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Transitioning to Fractional Order PID Controllers from Conventional Integer Order PID Control

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ABSTRACT

Control interest in fractional-order (FO) dates to the late nineteenth century, when verifiable foundations were laid. A large part of the reason fractional-order proportional-integral-derivative (FOPID) is growing is due to its additional tuning parameters, which make it possible to fine-tune the dynamics of the control system. In comparison to standard PID controllers, fractional-order PID (FOPID) controllers have two additional parameters. By contrast, differential and integral orders allow for greater flexibility in fine tuning the controller's performance. To address design complexities, fractional calculus has gained significant interest in control theory. Firstly, fractional-order dynamic models offer a more accurate representation of real dynamic systems than integer-order models. Fractional Order (FO) controllers frequently show better execution over Integer Order (IO) controllers in different situations. However, the existing literature often overlooks several key aspects. These include: (1) How do FOPID controllers compare to conventional integer-order (IO) PID controllers, especially when considering the complexities involved in their implementation? (2) In real-time implementation of FOPID controllers, approximations are often employed that really transform them into high-order linear controllers. For practical control applications, what benefits may be obtained from using FOPID controllers in such cases? Finally, (3) How can we achieve near-ideal fractional-order behaviour? A comprehensive survey of relevant distributions within the rapidly growing field of fractional-order control will be conducted in this paper to address these concerns. We aim to clarify the significant accomplishments, obstacles, and provide perspectives on the future potential of applying fractional-order control in industrial applications.

INDEX TERMS Fractional-order (FO) control, tuning parameters, fractional calculus, dynamic systems.

I. INTRODUCTION

Conventional integer order PID controllers have tracked down broad use in industrial applications and have set up a good foundation for themselves as an industry process control standard. While more advanced control methods are accessible, the PID controller's persevering through fame is simple and adaptable to industrial environments. Regardless, it is broadly perceived that only a portion of the PI/PID controller-based loops are tuned to accomplish their maximized operation.

In the rapidly evolving field of innovation and design, control systems assist in maintaining stability and effectiveness of diverse processes and applications. Among the various control techniques available, Proportional-Integral-Derivative (PID) controllers traditionally serve as the bedrock of control theory, offering reliable and versatile solutions for a variety of industries. With industrial processes becoming increasingly complex and requiring more sophisticated control solutions, it is clear their necessity. The interest for advanced controllers within control systems emerges because of the requirements innate in fundamental control techniques, like Proportional Integral Derivative (PID) controllers.

Within the industrial and engineering domains, the proportional-integral-derivative (PID) controller remains the prevailing choice due to its uncomplicated structure and ease of tuning. In the pursuit of enhanced reliability and performance, Podlubny introduced a generalized PID controller known as FOPID, incorporating fractional integration and differentiation. Podlubny initially presents the generalized transfer function of the FOPID controller, articulated as follows:

$$G_c(s) = K_p + \frac{K_i}{s^{\lambda}} + K_d s^{\mu} \tag{1}$$

This novel FOPID configuration has gained traction in research circles for its adaptability and robust characteristics.

In contrast to integer-order calculations, fractional-order calculation's differential operators represent an extension that is both global and infinitely dimensional. Fractional-order differentials have the capacity to capture not only the present system information but also historical information at a specific time. This attribute proves particularly advantageous when describing numerous systems with nonlinear behaviour, the flow of data in a network and the characteristics of nonlinear materials like rubber isolators, resulting in a more precise representation with fractional-order models. Fractional-order controllers exhibit broader applications and superior performance compared to conventional integer-order controllers. Additionally, it is evident that fractional-order control effectively compensates for pole assignment challenges induced by spatial relative acceleration.

Within the ever-changing terrain of control systems, a transformative wave is making its mark on the realm of industrial automation. This wave is propelled by the advent of Fractional Order Proportional-Integral-Derivative (FOPID) controllers. This survey initiates an in-depth investigation into the industrial applications and forthcoming possibilities of FOPID controllers in Fractional-Order Control Systems, casting light on their crucial role in redefining the control methodologies that form the foundation of contemporary industries.

Leading the way in this fractional-order revolution is the FOPID controller—a refined extension of the conventional PID controller, distinguished by its fractional order parameters. While FOPID controllers retain the fundamental proportional, integral, and derivative actions of their integer-order counterparts, the fractional orders bestow upon them heightened adaptability and precision. This survey delves into the profound influence of FOPID controllers on industrial applications, unravelling their transformative impact on the regulation of systems and the optimization of performance.

II. An Emerging Shift from Traditional PID Controllers to FOPID Controllers

The transition from traditional Proportional-Integral-Derivative (PID) controllers to Fractional Order PID (FOPID) controllers' signals a rising trend in control systems engineering. This shift is propelled by the demand for heightened performance, adaptability, and robustness across various applications. While classical PID controllers have historically served as the backbone of control systems, offering a dependable framework for process regulation, the evolving landscape of industries and advancing technologies has exposed their limitations.

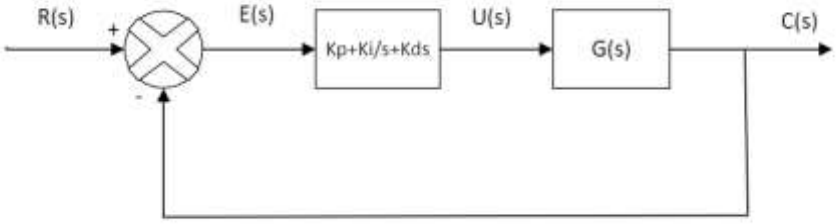

FIGURE 1. Schematic of Traditional PID Controller Circuit.

The output of a PID controller is calculated as,

$$u(t) = K_P.e(t) + K_I.\int e(t)dt + K_D.\frac{de(t)}{dt} \tag{2}$$

PID Controller's transfer function in s-domain is:

$$G_c(s) = \frac{U(s)}{E(s)} = K_p + K_i\frac{1}{s} + K_d s \tag{3}$$

In the face of complex, nonlinear, and time-varying systems, classical PID controllers encounter challenges, prompting the exploration of alternative strategies, with fractional order control gaining prominence.

Table 1. An analysis of the effects of increasing the value of each parameter in a conventional PID controller

Parameter	**Rise time**	**Overshoot**	**Settling time**	**Steady state error**	**Stability**
K_p	Decrease	Increase	Small change	Decrease	Degrade
K_i	Decrease	Increase	Increase	Eliminate	Degrade
K_d	Minor change	Decrease	Decrease	No effect in theory	Improve if K_d small

Traditional PID controllers have served as the backbone of control systems, offering a dependable framework for process regulation over an extended period. However, the evolving landscape of industries and the increasing sophistication of technologies have exposed the limitations of classical PID controllers when dealing with intricate, nonlinear, and time-varying systems. Recognizing this challenge, the exploration of alternative control strategies has gained momentum, with fractional order control taking centre stage. FOPID controllers mark an extension of the classical PID paradigm by integrating fractional order calculus into the controller parameters. In contrast to classical PID controllers utilizing integer orders (1 for proportional, 2 for integral, and 1 for derivative), FOPID controllers introduce non-integer orders denoted as $PI^{\lambda}D^{\mu}$. This innovation allows for a more nuanced and flexible approach to system regulation, addressing the complexities posed by modern industrial processes.

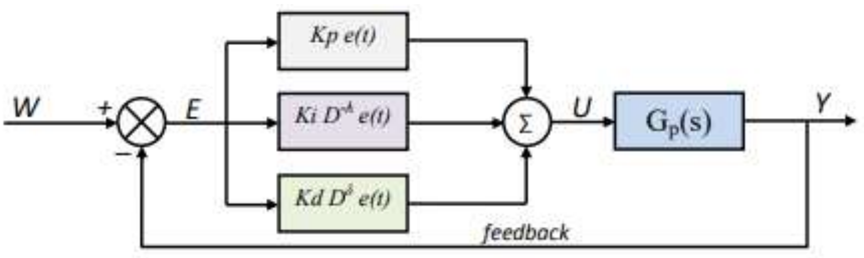

FIGURE 2. Feedback Control System with the Fractional order PID Controller (20).

In a $PI^{\lambda}D^{\mu}$ controller, the differential equation is as follows:

$$U(t) = K_p e(t) + K_i D^{-\lambda} e(t) + K_d D^{\mu} e(t) \tag{4}$$

The above equation written in s-domain as,

$$U(s) = K_p E(s) + K_i s^{-\lambda} E(s) + K_d s^{\mu} E(s) \tag{5}$$

In this expression, K_p represents the proportional gain, K_i denotes the integration gain, and K_d signifies the derivative gain. The integral and derivative orders, λ and μ, respectively, adhere to the condition, $0 < \lambda, \mu < 2$. Notably selecting $\lambda = \mu = 1$ yields a standard IOPID controller. The FOPID controller possesses a crucial characteristic allowing an adjustment for continuous slopes in the Bode plot of the controller, with adjustments occurring at both low and high frequencies based on the values of λ and μ. This distinctive feature can be harnessed improved control performance and loop shaping.

In summary, the shift from classical order PID controllers to FOPID controllers marks a paradigmatic transformation in control systems engineering. Fuelled by the imperative for heightened performance, adaptability, and resilience amidst evolving technologies, FOPID controllers present a sophisticated and versatile solution. The ongoing exploration and integration of FOPID controllers across diverse industries unequivocally affirm their pivotal role in shaping the future landscape of advanced control strategies.

III. A Deep Dive into Frequency Domain Tuning for FOPID Controllers

In the realm of control systems engineering, the optimization techniques for Fractional Order Controllers (FOC) tailored for time-delay systems constitute a crucial domain of both research and practical application. Given that time delays are intrinsic to diverse processes and systems, the adept adjustment of controllers to effectively manage these delays is imperative for attaining peak performance and stability. The stability and performance of control systems can be notably influenced by time delays. These delays introduce intricacies like phase lag, and if not appropriately managed, they can result in oscillations, instability, and a compromised system response.

Specialized in its approach, frequency domain tuning for Fractional Order Proportional-Integral-Derivative (FOPID) controllers is geared towards enhancing the performance and stability of control systems across the frequency spectrum. Diverging from traditional integer-order controllers, FOPID controllers integrate fractional calculus, introducing added flexibility for tuning parameters. The emphasis in frequency domain tuning lies in precisely adjusting these K_p, K_i and K_d parameters to attain specific characteristics in the frequency response of the control system. The transfer function of the FOPID controller is:

$$G_c(s) = K_p + \frac{K_i}{s^{\lambda}} + K_d s^{\mu} \tag{6}$$

Where K_p, K_i and K_d are proportional, integral, and derivative gains, λ and μ are fractional orders of integration and differentiation.

One widely adopted approach for Fractional-order PID controller fine-tuning involves establishing the controller parameters through the resolution of a collection of non-linear equations that articulate specifications concerning phase margin, gain crossover frequency, responsiveness capabilities, and resilience to gain variations within a defined range. The parameters of FOPID controllers encompass fractional orders related to the proportional, integral, and derivative actions. The objective of frequency domain tuning is to fine-tune these parameters, aiming to optimize the system's performance concerning stability, gain margin, and phase margin. The specific characteristics of the system under regulation dictate the criteria the controller must meet, influencing the selection of tuning specifications. The mathematical expressions for the phase margin and gain crossover frequency are as follows:

$$\angle\left(C(j\omega_{cg})G(j\omega_{cg})\right) = -\pi + \emptyset_m \tag{7}$$

$$\left|C(j\omega_{cg})G(j\omega_{cg}\right| = 1 \tag{8}$$

The tuning procedure typically commences with a thorough examination of the system's frequency response, employing Bode plots. These graphical representations illustrate both the amplitude and phase of the system's transfer function as frequencies change. The objective of tuning is to modify the fractional order parameters, like λ and μ with the aim of attaining desired characteristics. Frequency domain tuning guarantees the robustness of the control system throughout a spectrum of operating frequencies. Tools such as Nyquist plots play a role in evaluating this stability. Enhancing robustness through frequency domain optimization contributes to the stability of FOPID controllers.

V. Industrial Utilization of FOPID Control

FOPID control finds application in power systems and electronics for the regulation of voltage, power factor, and motor control. The inclusion of fractional-order components enhances the stability and efficiency of power distribution networks. The flexibility of FOPID controllers proves especially beneficial in managing load fluctuations and ensuring a steady power quality, establishing them as essential elements for the stability and dependability of electrical systems. The incorporation of Fractional Order Proportional Integral Derivative (FOPID) controllers into power systems has emerged as a revolutionary influence, providing sophisticated control capabilities surpassing conventional methods. Securing a consistent and dependable source of electricity is of utmost importance in power systems, making voltage regulation a critical aspect. Controllers in this field are dedicated to preserving consistent voltage levels, even in the face of demand fluctuations and external factors. Despite notable progress in power system controller advancements, challenges persist. The incorporation of sophisticated controllers, including FOPID controllers, demands robust tuning methods and meticulous implementation for optimal performance. Furthermore, ongoing research is dedicated to developing controllers capable of effectively managing the escalating complexity of interconnected power systems. In industrial power systems, where precise control over motor speed and torque is crucial, FOPID controllers excel in providing enhanced adaptability. The fractional-order nature allows for a more nuanced adjustment to changes in load and operating conditions. This adaptability results in smoother and more efficient motor operation, contributing to energy savings and improved overall performance in industrial processes.

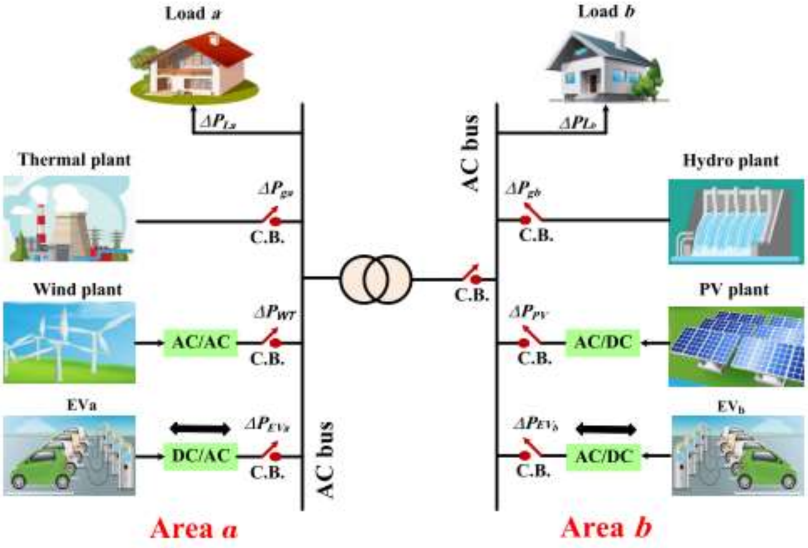

FIGURE 3. Comprehensive depiction of the analysed two-area power system diagram (8).

Smart grids embody a revolutionary strategy for power distribution, amalgamating cutting-edge technologies to elevate efficiency, reliability, and sustainability. A pivotal element propelling the effectiveness of smart grids lies in the utilization of Fractional Order Proportional Integral Derivative (FOPID) controllers. Ensuring stable voltage levels is pivotal for smart grids, particularly given the growing incorporation of sustainable energy sources and the dynamic nature of contemporary power demand. FOPID controllers provide a notable edge in adaptive voltage control.

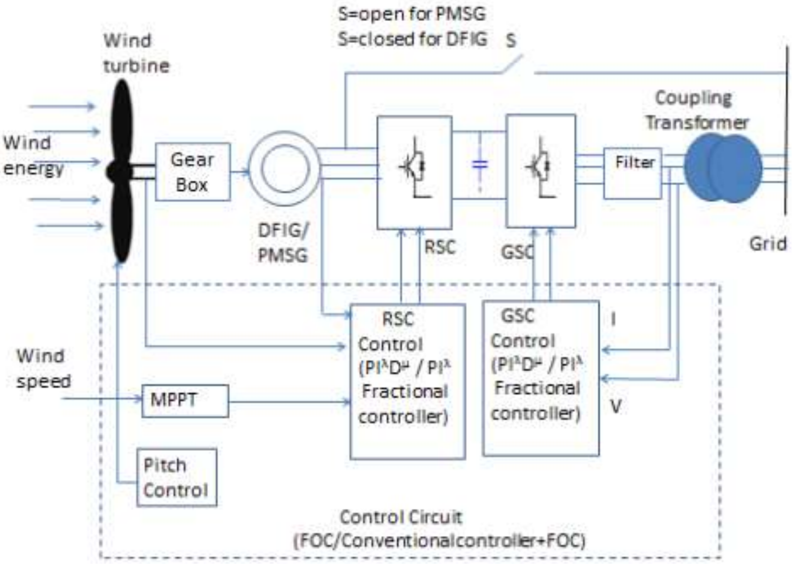

FIGURE 4. Diagram illustrating a wind energy conversion system featuring fractional control (3).

Wind Energy Conversion Systems (WECS) are pivotal in capturing renewable energy from the wind, thereby contributing significantly to sustainable power generation. Recent advancements have incorporated Fractional Order Proportional Integral Derivative (FOPID) controllers to enhance the performance and efficiency of these systems. Wind energy possesses inherent variability, posing challenges for conventional control systems. FOPID controllers stand out in effectively handling the fluctuations in wind conditions.

TABLE 1. Lists some industrial applications of FOPID control

Industrial Application	Description
Voltage Regulation in Power Systems	Power distribution networks aim to regulate voltage levels, ensuring efficient management of changing circumstances and improved stability, as well as increased flexibility in handling load variations.
Motor Control in Manufacturing	In manufacturing, the goal of FOPID control is to optimize motor performance in industrial processes, leading to smoother and more efficient motor operation, with improved flexibility in dealing with load changes.
Power Factor Correction in Industries	Enhance power quality, minimize energy losses, and optimize industrial power usage by dynamically adjusting power factor correction.
Oil and Gas Drilling Operations	Enhance drilling efficiency and safety by regulating pressure and flow rates. Adaptability to dynamic conditions is improved.
Chemical Reactors in Manufacturing	Control temperature, pressure, and concentration accurately. Reduce waste in chemical processes, and increase manufacturing control capabilities.
Temperature Control in Heat Exchangers	Temperatures can be accurately regulated in heat exchange processes. Nonlinearity and variations in thermal dynamics can be handled efficiently, resulting in an improvement in energy efficiency.
Chemical Dosing in Water Treatment	Achieve precise chemical dosing in water treatment, reducing chemical consumption while maintaining optimal water quality.
Precision Agriculture in Farming	Improve irrigation systems and crop management by adapting to changing environmental conditions.
Robotics in Manufacturing	Streamline motor performance in automated systems. Upgraded versatility for exact movement control and trajectory tracking, further developing effectiveness in industrial automation settings.
Biomedical Systems	Maintain desired conditions for drug delivery and physiological parameter control. Adaptability to the dynamic nature of biological systems, ensuring precise and controlled applications.

The above table offers a short outline of the uses of FOPID controllers in various industrial sectors, exhibiting their flexibility and productivity in handling a scope of control difficulties.

VI. CONCLUSION

This research paper has dive into the execution of Fractional Order Proportional Integral Derivative (FOPID) controllers when contrasted with conventional integer-order controllers, denoting a critical step towards the transitioning of FOPID controllers.

FOPID controllers offer a significant improvement in adaptability and accuracy compared to their conventional integer-order counterparts. The fractional-order elements provide a more nuanced response to dynamic and nonlinear systems, which is particularly advantageous in industrial applications characterized by complex and changing conditions. The use of FOPID controllers in power systems has been shown to enhance voltage regulation, power factor correction, and motor control. The fractional-order components contribute to stable and efficient operation, addressing challenges posed by load fluctuations and ensuring consistent power quality. In various industrial processes, ranging from chemical reactors to heat exchangers, FOPID controllers demonstrate increased efficiency. The knowledge acquired from this study provides valuable information on the potential for implementing FOPID controllers in industry. The adaptability, efficiency improvements, and reliable performance seen in different industrial applications establish FOPID controllers as valuable assets for advancing control strategies in large-scale implementation.

While the study highlights the benefits of FOPID controllers, it also recognizes the difficulties, particularly in terms of adjustment and implementation. Future paths should concentrate on improving adjustment methods and investigating integration with emerging technologies, such as artificial intelligence, to further improve the flexibility and usefulness of FOPID controllers in industrial settings. Essentially, the investigation of implementing FOPID controllers compared to conventional controllers not only confirms their effectiveness in various industrial sectors but also offers a roadmap for their wider industrial use. This study adds to the increasing knowledge base driving the adoption of fractional-order control strategies in practical industrial applications.

REFERENCES

[1] Tepljakov *et al*., "Towards Industrialization of FOPID Controllers: A Survey on Milestones of Fractional-Order Control and Pathways for Future Developments," in *IEEE Access*, vol. 9, pp. 21016-21042, 2021.

[2] N. Zhuo-Yun, Z. Yi-Min, W. Qing-Guo, L. Rui-Juan, and X. Lei-Jun, "Fractional-Order PID Controller Design for Time-Delay Systems Based on Modified Bode’s Ideal Transfer Function," in *IEEE Access*, vol. 8, pp. 103500-103510, 2020.

[3] P. Warrier and P. Shah, "Fractional Order Control of Power Electronic Converters in Industrial Drives and Renewable Energy Systems: A Review," in *IEEE Access*, vol. 9, pp. 58982-59009, 2021.

[4] R. Cajo, T. T. Mac, D. Plaza, C. Copot, R. De Keyser and C. Ionescu, "A Survey on Fractional Order Control Techniques for Unmanned Aerial and Ground Vehicles," in *IEEE Access*, vol. 7, pp. 66864-66878, 2019.

[5] S. H. Nguyen, V. N. L. Truong, and L. N. P. Nguyen, "Analytical Tuning Rules for Cascade Control Systems Based on Fractional-Order PI Controller in Frequency Domain," in *IEEE Access*, vol. 11, pp. 76196-76201, 2023.

[6] Birs, C. Muresan, I. Nascu and C. Ionescu, "A Survey of Recent Advances in Fractional Order Control for Time Delay Systems," in *IEEE Access*, vol. 7, pp. 30951-30965, 2019.

[7] J. Zhang *et al*., "Design and Implementation of Novel Fractional-Order Controllers for Stabilized Platforms," in *IEEE Access*, vol. 8, pp. 93133-93144, 2020.

[8] E. M. Ahmed, E. A. Mohamed, A. Elmelegi, M. Aly and O. Elbaksawi, "Optimum Modified Fractional Order Controller for Future Electric Vehicles and Renewable Energy-Based Interconnected Power Systems," in *IEEE Access*, vol. 9, pp. 29993-30010, 2021.

[9] R. Stanisławski, M. Rydel and Z. Li, "A New Reduced-Order Implementation of Discrete-Time Fractional-Order PID Controller," in *IEEE Access*, vol. 10, pp. 17417-17429, 2022.

[10] Birs, C. Muresan, M. Mihai, E. Dulf and R. De Keyser, "Tuning Guidelines and Experimental Comparisons of Sine Based Auto-Tuning Methods for Fractional Order Controllers," in *IEEE Access*, vol. 10, pp. 86671-86683, 2022.

[11] I. Podlubny. “Fractional-order systems and PIλD μ controllers [J].” Automatic Control IEEE Transactions on, vol. 44, no.1, pp. 208– 214, Jan. 1999.

[12] Idir, H. Akroum, S. A. Tadjer and L. Canale, "A Comparative Study of Integer Order PID, Fractionalized Order PID and Fractional order PID Controllers on a Class of Stable System," *2023 IEEE International Conference on Environment and Electrical Engineering and 2023 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, Madrid, Spain, 2023, pp. 1-6.

[13] K. Mohapatra, D. K. Gupta and C. K. Panigrahi, "FOPID controller for Load Frequency Control of Hybrid Power System under Deregulated regime using Improved Firefly Algorithm (IFA)," *2022 1st IEEE International Conference on Industrial Electronics: Developments & Applications (ICIDeA)*, Bhubaneswar, India, 2022, pp. 175-180.

[14] R. Maurya and M. Bhandari, "Design of Optimal PID[FOPID] Controller for Linear System," *2016 International Conference on Micro-Electronics and Telecommunication Engineering (ICMETE)*, Ghaziabad, India, 2016, pp. 439-443.

[15] M. A. George, D. V. Kamath, and I. Thirunavukkarasu, "An Optimized Fractional-Order PID (FOPID) Controller for a Non-Linear Conical Tank Level Process," *2020 IEEE Applied Signal Processing Conference (ASPCON)*, Kolkata, India, 2020, pp. 134-138.

[16] Q G. Wang, T H. Lee, and H W. Fung. “PID tuning for improved performance [J].” IEEE Trans.contr.syst.technol, vol. 7, no. 4, pp. 457–465, Apr. 1994.

[17] R. Pradhan and B. B. Pati, "Optimal FOPID Controller for an Automobile Cruise Control System," *2018 International Conference on Recent Innovations in Electrical, Electronics & Communication Engineering (ICRIEECE)*, Bhubaneswar, India, 2018, pp. 1436-1440.

[18] P. Kaushik and P. D. Dewangan, "Model Order Reduction by Teaching Learning Based Optimization and FOPID Controller Designing," *2020 First International Conference on Power, Control and Computing Technologies (ICPC2T)*, Raipur, India, 2020, pp. 166-170.

[19] S. P. Arunachalam, S. Kapa, S. K. Mulpuru, P. A. Friedman and E. G. Tolkacheva, "Intelligent fractional-order PID (FOPID) heart rate controller for cardiac pacemaker," *2016 IEEE Healthcare Innovation Point-Of-Care Technologies Conference (HI-POCT)*, Cancun, Mexico, 2016, pp. 105-108.

[20] Mohamed, Mohamed Jasim, and Amjad Khashan. "Comparison between PID and FOPID controllers based on particle swarm optimization." *The Second Engineering Conference of Control, Computers and Mechatronics Engineering (ECCCM2, 2014)*. 2014.