Design and Implementation of CRONE Controller for Automatic Voltage Regulator (AVR) System

Pritesh Shah
Symbiosis Institute of Technology (SIT)
Symbiosis International (Deemed University) (SIU)
Pune, India
pritesh.ic@gmail.com

Ravi Sekhar
Symbiosis Institute of Technology (SIT)
Symbiosis International (Deemed University) (SIU)
Pune, India
ravi.sekhar@sitpune.edu.in

Margi Shah
Department of Mechanical Engineering
AISSMS College of Engineering
Pune, India
mpshah@aissmscoe.com

***Abstract*—Automatic voltage regulator (AVR) systems are critically required in many systems such as hydro, gas, steam turbines and engines. Effective control of an AVR system is complex and challenging due to its unstable open loop response characteristics. The AVR system is required to sustain appropriate voltage levels in spite of fluctuations in the main supply. Hence, the AVR system needs to be primarily designed for stability. This paper presents design implementation of the first and second generations of CRONE controllers (Commande Robuste d'Ordre Non Entier) for an AVR system. CRONE is a non-integer order robust controller which is far more effective than the standard PID controllers as it offers better tuning and flexibility in controlling the AVR process. In the present study, various time-domain performance criteria with and without controller were simulated to validate the accomplishment of AVR CRONE controllers. The proposed control procedure for enhancing AVR systems' efficiency has been shown to be effective and better in terms of improved phase and gain margins.**

***Index Terms*—Automatic voltage regulator (AVR), First generation CRONE controller, Second generation CRONE controller, Robustness, PID controller**

I. INTRODUCTION

Nowadays, voltage variations occur in many locations because of fluctuations in load on the supply system. To overcome such voltage variations, automatic voltage regulators (AVR) can be utilised. The AVR system converts voltage variations into a constant voltage supply. The AVR system is used in industrial applications with a fast transient response and needs to be as robust as possible [1]. To improve its time domain specifications and for relatively better stability, the AVR system is generally added with a controller in closed loop control. Initially, proportional integrative derivative (PID) controllers have been implemented on AVR system [1]–[3]. A PID controller takes three variables into account, namely a proportional value, an integral value and a derivative value. The vector sum of these three variables results in the final controller output fed to the plant [4]. The PID controller's tuning can be achieved based on system parameters by minimizing the error functions such as ISE (integral square error) performance function. However, the PID controller performance is sluggish for long time delay processes, higher order systems, integrating processes etc. The phase and gain margins achieved using the PID controllers were not up to the mark as expected [5], [6]. Therefore, CRONE controllers (non-integer order robust controller) are suggested for AVR systems. This controller is competent in increasing the robustness and stability of AVR while taking into account all uncertain parameters that PID controller couldn't handle. This technique has a shorter computation time and provides excellent frequency domain results. In this paper, first and second generation CRONE controller methods are proposed for AVR application. The proposed CRONE methods are simulated and their results are correlated with those of the classical PID controller. The simulation results indicate that CRONE robustness is much higher than PID for AVR implementation.

This paper is structured as follows. In next Section briefs about the AVR system and its control challenges. Section 3 discusses the various generations of CRONE controllers and tools for implementing the same. In the subsequent section, experimental work is described with PID and 1^{st} and 2^{nd} generation CRONE controllers. Finally, conclusions are presented based on the investigations carried out in this work.

II. AVR SYSTEM

The AVR is mainly used for start-up, testing and catering to circumstances where the AC regulator is faulty [7]. The life of electronic components or instruments gradually decays if the supply voltage suffers from fluctuations [8]. An well controlled AVR system provides a constant voltage level. Moreover, it also protects electronic instruments from electrical surges, spikes and lightning. A typical AVR system block diagram

978-1-6654-9291-1/22/$31.00 ©2022 IEEE

is shown in figure 1. The figure shows AVR comprised of an amplifier, an exciter and a generator. Figure 2 depicts the simulated open loop response of an AVR system. The system is under-damped and the steady state error persists.

Fig. 1. Block diagram of AVR system

Fig. 2. AVR open loop step response without any controller

A. AVR system linear model

The main function of an AVR system is to constantly maintain the generator's voltage output in a specified range. The Simulink model of an AVR consists of the error amplifier, silicon controlled rectifier (SCR) power amplifier and a generator as presented in figure 3. The AVR system variables for this model were referred from [7], [9].

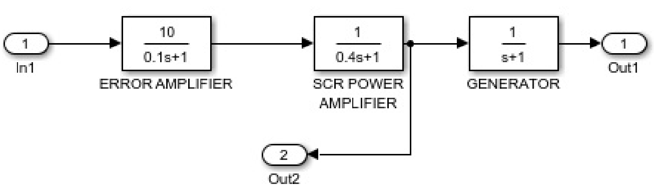

Fig. 3. AVR system block diagram

III. PID Controller

The AVR process needs to be effectively controlled to achieve and maintain better quality and working life of electronic products. The PID controller, which is proportional, integral and derivative, considers an error between the actual output and set-point value. A PID controller is extensively used in the process industry as it has a straightforward structure, availability of various tuning methods, simple electronic circuits, etc. The tuning of a controller can be achieved by minimizing the performance function (a function of error) over time using various optimization methods. Using three different proportional, integral and derivative terms removes dynamic response damping, and steady-state error and thus increases system stability [10]–[13]. In this study, PID controller was implemented on the above mentioned AVR linear model.

IV. CRONE Controller

CRONE control-system is a type of controller designed according to the frequency-domain methodology. CRONE controller is a non-integer type controller. The concept of fractional calculus was applied for the first time in control system through a CRONE controller [14]–[17]. CRONE controller satisfies various needs of controller design such as effective handling of gain variations around different frequencies as well as model uncertainties. The controller's nominal transfer function is determined from the open loop transfer function [18]–[20]. There are three generations of the CRONE controller. These are known as the first, second, and third generation CRONE controllers [14]. A featured summary of these controllers is presented in table I [21].

TABLE I
Feature summary of CRONE generations

Sr. No.	CRONE Generation	Useful
1	1^{st} Generation	Robust against plant gain variations provided constant phase around corner frequency
2	2^{nd} Generation	Robust against plant gain variations in spite of phase around corner frequency not being constant
3	3^{rd} Generation	Robust against all plant gain variations as well as model uncertainties

One of the significant advantages of CRONE controllers is that the plant disturbances are considered without knowing the actual structure of these disturbances [22], [23]. These non-integer controllers can be implemented using various approximation approaches [24]. The 1^{st} generation of CRONE controller is a fractional derivative or integration controller. It is represented by

$$C(s) = C_0 S^{\beta} \tag{1}$$

where, β and $C_0 \in \mathbb{R}$. The first generation controller is useful for achieving constant plant phase around the operating frequency. It is useful for handling plant disturbance models as well. The second generation CRONE's transfer function is the same as that of the Bode's ideal loop [21], [25], [26]. It is determined based on the Nichols chart curve, which is defined by

$$c(s) = \frac{O(s)}{p(s)} \tag{2}$$

where O(s) and p(s) are the open loop and plant transfer functions respectively. The 3^{rd} generation CRONE controller is robust against model uncertainty, which is a unique characteristic as compared to the CRONE's second generation controller. The third generation controller structure can be effectively attained based on the desired open loop frequency response. The following section presents the results of PID and CRONE controllers for the AVR plant model.

V. Results and discussions

A. AVR system design with PID controller

Figure 4 shows a standard PID controller block added to the AVR plant closed loop model. The AVR system subsystem was created in Simulink. The PID controller block was also obtained from the Simulink library. The negative loop feedback system was used in this PID controller Simulink model. The tuning of PID controller was achieved by employing the auto-tuning feature of PID block in Simulink. The resultant step response obtained with PID tuning is demonstrated in figure 5.

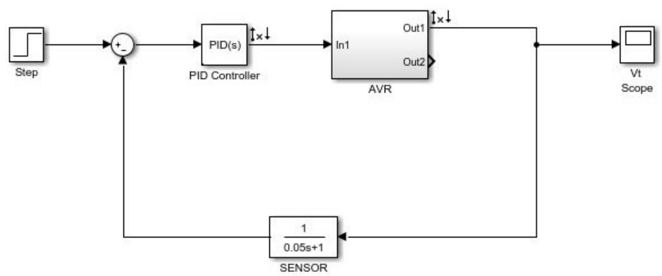

Fig. 4. Simulation model of AVR system with PID block in Simulink

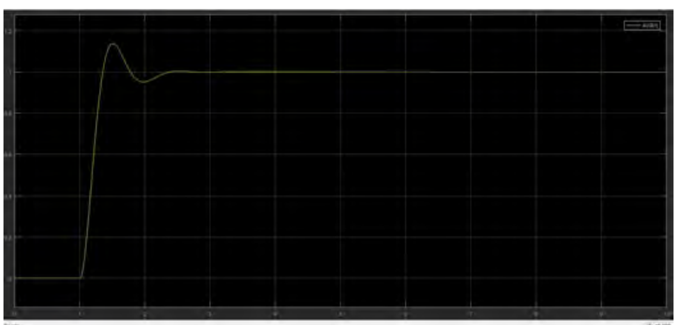

Fig. 5. Step response of the PID controller for AVR system

It is evident that the system becomes critically damped as compared to its under damped characteristics in figure 2. The open-loop stability parameters for this PID controlled AVR model were determined and presented in table 2. This table shows PID gain margin of 13.13 dB, phase margin 34 deg., gain crossover frequency 12.9217 red/sec and phase crossover frequency 4 rad/sec. In order to further increase response robustness in terms of the phase and gain margins, the first and second generation CRONE controllers were implemented.

B. AVR system design with 1^{st} generation CRONE controller

In this study, CRONE controller was implemented with the help of the CRONE toolbox of Matlab Simulink. The CRONE toolbox has various GUI models that can be implemented as per various applications. These models have extensive guideline documentations attached within the toolbox, to help controller designers use these models effectively. Firstly, the original AVR plant wass used as inputs to the CRONE toolbox. Thereafter, the required nominal open lop gain crossover frequency was provided. Fractional control design as well as rational controller design are based on the inputs received from the plant model. Figure 6 depicts the fractional open loop Bode plot of CRONE's first generation controller. It shows the phase and magnitude plots for the first generation CRONE AVR controller system. The fractional and rational Nichols charts for the same are shown in figure 7. Table 2 shows that the first generation CRONE attained infinite gain margin and phase crossover frequency as compared to the PID controlled AVR system. The phase margin of the first generation CRONE was also higher than that of the PID controller. However, the gain crossover frequency was much reduced in case of the first generation CRONE as compared to its PID counterpart.

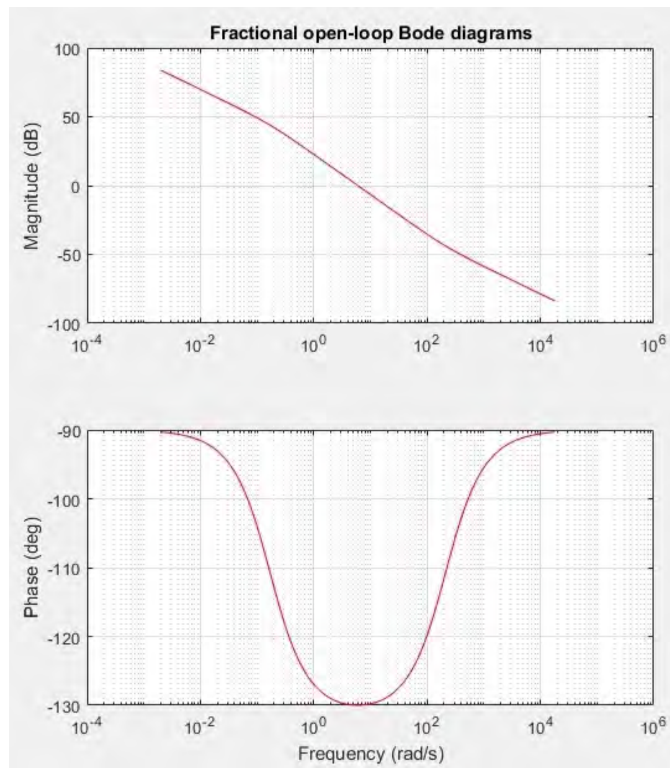

Fig. 6. Bode plot of AVR with first generation CRONE controller

The time response of first generation CRONE controller is shown in Figure 8. It has a rise time of 1.2 seconds, settling time of 4.6 seconds, peak time of 2.3 seconds and suffers from 22 % overshoot. The sensitivity function for the first generation CRONE controller is shown in figure 9.

C. AVR system design with 2^{nd} generation CRONE controller

This section presents the results of the second generation CRONE controller implemented for the AVR plant. It is evident from table 2 that the phase margin of the second generation CRONE controlled plant was improved over the PID controller, thus increasing the overall stability of the plant. The gain margin, gain crossover frequency and phase crossover frequency of the second generation CRONE were

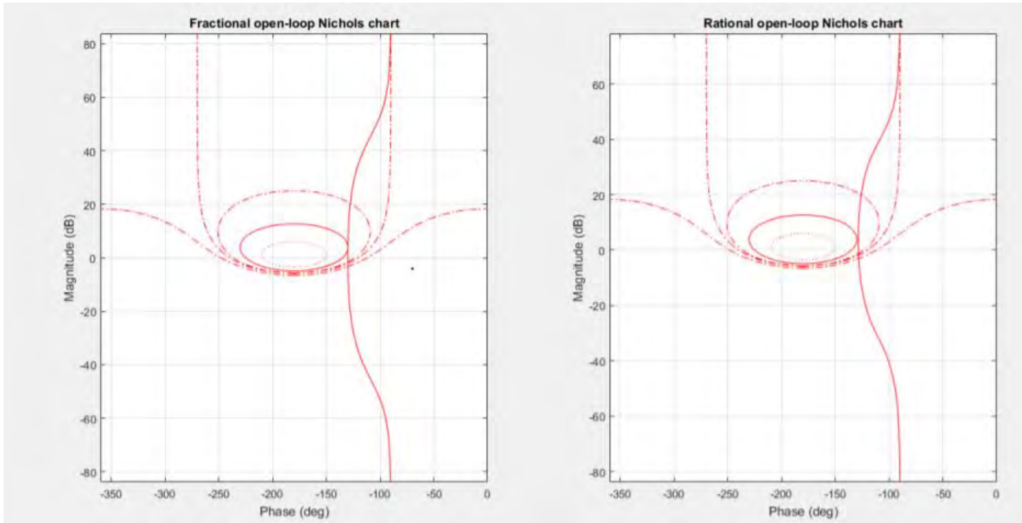

Fig. 7. Nichols chart of AVR with first generation CRONE controller

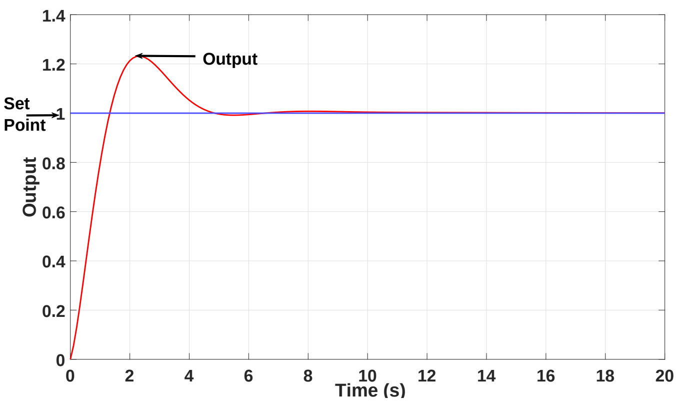

Fig. 8. First generation CRONE controller time response characteristics for AVR system

exactly similar as that attained by its first generation counterpart. The GUI used for the implementation of the CRONE 2^{nd} generation controller is depicted in figure 10.

This second generation of CRONE controller for the AVR model considered in the current study is represented as follows -

$$C_F(s) = C_0 \left(1 + \frac{\omega_1}{s}\right)^{n_1} \left(\frac{1 + \frac{s}{\omega_l}}{1 + \frac{s}{\omega_h}}\right)^{n} \frac{1}{\left(1 + \frac{s}{\omega_f}\right)^{n_f}} \tag{3}$$

$$C_F(s) = 155.3191 \left(1 + \frac{0.2}{s}\right) \left(\frac{1 + \frac{s}{0.18974}}{1 + \frac{s}{189.7367}}\right)^{-1.46}$$

$$\frac{1}{(1 + \frac{s}{189.7367})} \tag{4}$$

The fractional and rational bode plots and Nichols chart plots are shown in figures 11 and 12 respectively.

TABLE II
COMPARISON OF DIFFERENT CONTROLLERS ON AVR BLOCK

Parameter	**PID**	**1st generation CRONE**	**2ND generation CRONE**
Gain margin (in dB)	13.13	Infinite	Infinite
Phase margin (deg.)	34	50	49
Gain crossover frequency (rad/sec)	12.9217	6	6
Phase crossover frequency (rad/sec)	4	infinite	infinite

VI. CONCLUSIONS

The main function expected from an automatic voltage regulator (AVR) system is to stabilize output voltage inspite of input load fluctuations. This paper presents an implementation of first and second generation CRONE controllers for an automatic voltage regulator (AVR) system. The AVR system was also controlled by a conventional auto tuned PID controller for performance comparisons. Primary results show that the gain margins of PID, first and second generations of CRONE controller are 13.13 dB, infinite and infinite respectively. A greater gain margin indicates better stability, hence proving the CRONE controllers to be more stable as compared to PID. Similarly, the CRONE controllers outperformed the PID controller in terms of the phase margin as well. Hence, the CRONE first and second generation controllers provide much more stable AVR performance inspite of input voltage fluctuations as compared to the conventional PID controlled AVR plants.

REFERENCES

[1] Ching-Chang Wong, Shih-An Li, and Hou-Yi Wang. Optimal PID controller design for avr system. *Tamkang Journal of Science and Engineering*, 12(3):259–270, 2009.

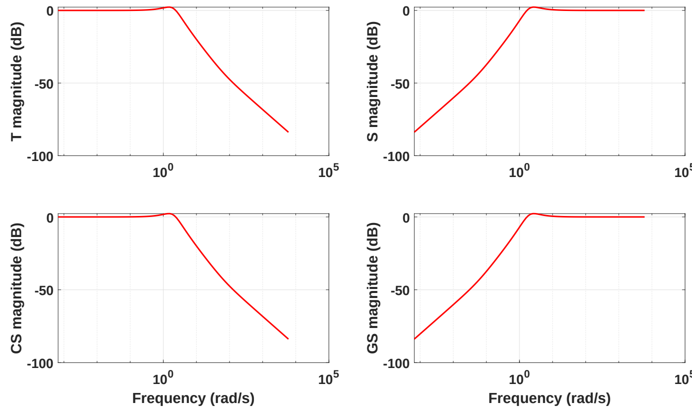

Fig. 9. Sensitivity functions for first generation CRONE controller

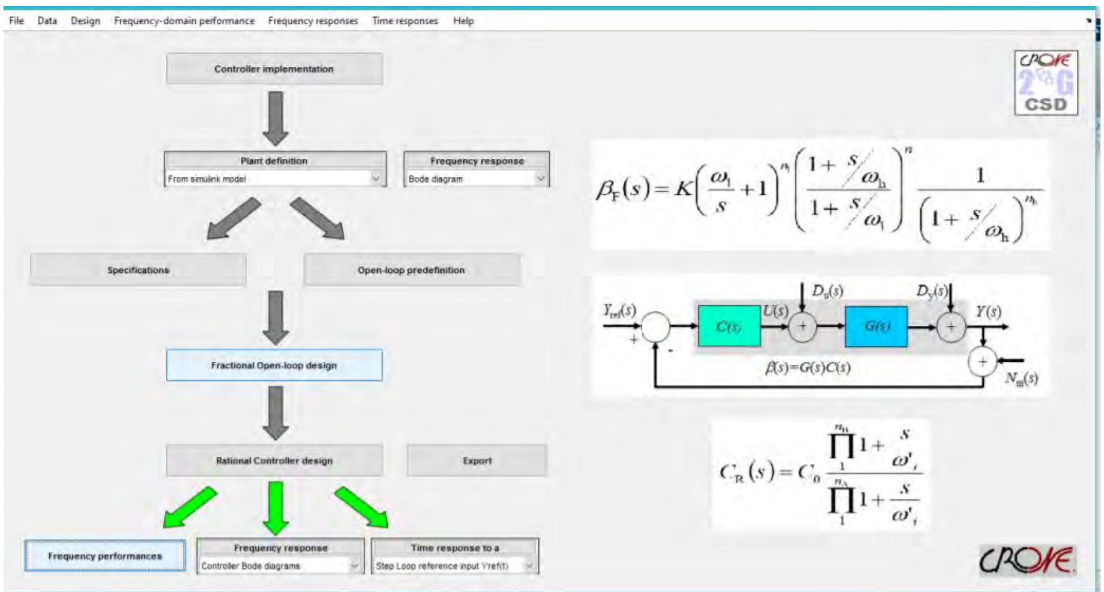

Fig. 10. Second generation CRONE toolbox

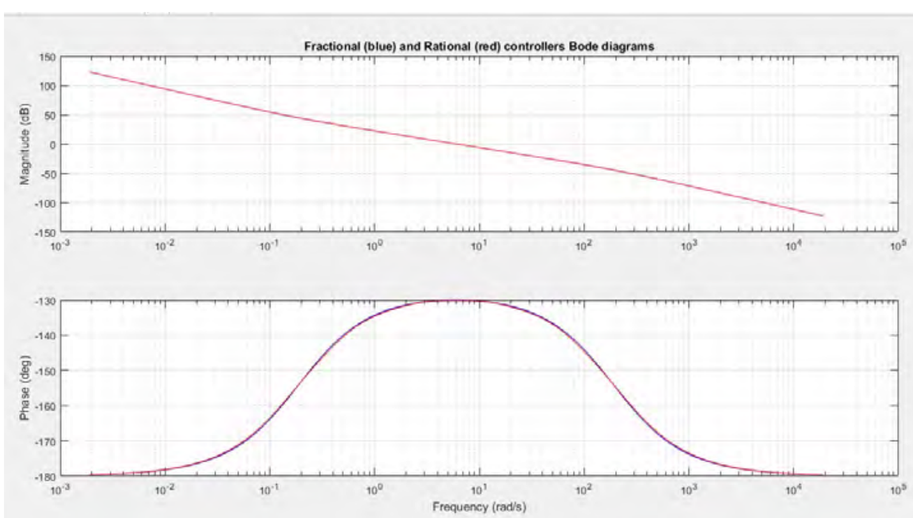

Fig. 11. Bode plot of AVR with 2^{nd} Gen CRONE

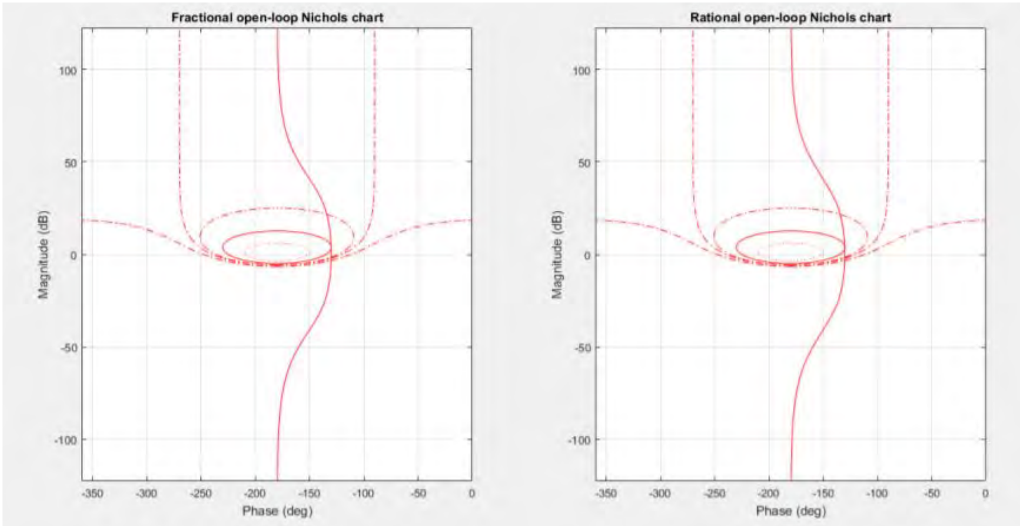

Fig. 12. Nichols chart of AVR with 2^{nd} Gen CRONE

[2] Zwe-Lee Gaing. A particle swarm optimization approach for optimum design of PID controller in AVR system. *IEEE transactions on energy conversion*, 19(2):384–391, 2004.

[3] Dong Hwa Kim. Hybrid GA–BF based intelligent PID controller tuning for avr system. *Applied soft computing*, 11(1):11–22, 2011.

[4] Karl Johan Åström and Tore Hägglund. *PID controllers: theory, design, and tuning*, volume 2. Instrument society of America Research Triangle Park, NC, 1995.

[5] Su Whan Sung and In-Beum Lee. Limitations and countermeasures of PID controllers. *Industrial & engineering chemistry research*, 35(8):2596–2610, 1996.

[6] Ravi Sekhar, TP Singh, and Pritesh Shah. ARX/ARMAX modeling and fractional order control of surface roughness in turning nano-composites. In *2019 International Conference on Mechatronics, Robotics and Systems Engineering (MoRSE)*, pages 97–102. IEEE, 2019.

[7] Majid Zamani, Masoud Karimi-Ghartemani, Nasser Sadati, and Mostafa Parniani. Design of a fractional order PID controller for an AVR using particle swarm optimization. *Control Engineering Practice*, 17(12):1380 – 1387, 2009. Special Section: The 2007 IFAC Symposium on Advances in Automotive Control.

[8] Pritesh Shah and Ravi Sekhar. Closed loop system identification of a DC motor using fractional order model. In *2019 International Conference on Mechatronics, Robotics and Systems Engineering (MoRSE)*, pages 69–74. IEEE, 2019.

[9] Vivek Kumar Bhatt and Sandeep Bhongade. Design of PID controller in automatic voltage regulator (AVR) system using PSO technique. *International Journal of Engineering Research and Applications (IJERA)*, 3(4):1480–1485, 2013.

[10] Piyush Mathur and Shyam K Joshi. Pid tuning of automatic voltage regulator. *international Journal of Research and Analytical Reviews*, 2(3):18–21, 2015.

[11] Hestikah Eirene Patoding, Eodia T Lobo, and Matius Sau. Modeling control of automatic voltage regulator with proportional integral derivative. *Volume: 04 Issue: 09. International Journal of Research in Engineering and Technology. Electrical Engineering, Paulus Chrystian University of Indonesia*, 2015.

[12] D Murugesan, Pritesh Shah, K Jagatheesan, Ravi Sekhar, and Anand J. Kulkarni. Cohort intelligence optimization based controller design of isolated and interconnected thermal power system for automatic generation control. In *2022 Second International Conference on Computer Science, Engineering and Applications (ICCSEA)*, pages 1–6, 2022.

[13] Ravi Sekhar, T. P. Singh, and Pritesh Shah. Machine learning based predictive modeling and control of surface roughness generation while machining micro boron carbide and carbon nanotube particle reinforced al-mg matrix composites. *Particulate Science and Technology*, 40(3):355–372, 2022.

[14] Pritesh Shah and Sudhir Agashe. Review of fractional PID controller. *Mechatronics*, 38:29–41, 2016.

[15] Xavier Moreau, Roy Abi Zeid Daou, and Fady Christophy. Comparison between the second and third generations of the CRONE controller: Application to a thermal diffusive interface medium. *Fractal and fractional*, 2(1):5, 2018.

[16] Tepljakov Aleksei, Petlenkov Eduard, and Belikov Juri. A flexible matlab tool for optimal fractional-order PID controller design subject to specifications. In *Proceedings of the 31st Chinese Control Conference*, pages 4698–4703. IEEE, 2012.

[17] Pritesh Shah, Ravi Sekhar, and Sudhir Agashe. Application of fractional PID controller to single and multi-variable non-minimum phase systems. *International Journal of Recent Technology and Engineering*, 8(2):2801–2811, 2019.

[18] Valerie Pommier, Jocelyn Sabatier, Patrick Lanusse, and Alain Oustaloup. CRONE control of a nonlinear hydraulic actuator. *Control Engineering Practice*, 10(4):391–402, 2002.

[19] O Cois, Alain Oustaloup, Thierry Poinot, and J-L Battaglia. Fractional state variable filter for system identification by fractional model. In *2001 European Control Conference (ECC)*, pages 2481–2486. IEEE, 2001.

[20] Ravi Sekhar, TP Singh, and Pritesh Shah. Micro and nano particle composite machining: Fractional order control of surface roughness. In *Third International Conference on Powder, Granule and Bulk Solids: Innovations and Applications PGBSIA 2020 February 26-28, 2020*, pages 35–42, 2020.

[21] Concepcion A Monje, YangQuan Chen, Blas M Vinagre, Dingyu Xue, and Vicente Feliu-Batlle. *Fractional-order systems and controls: fundamentals and applications*. Springer Science & Business Media, 2010.

[22] G Shabib, Mesalam Abdel Gayed, and AM Rashwan. Optimal tuning of PID controller for avr system using modified particle swarm optimization. In *Proceedings of the 14th International Middle East Power Systems Conference (MEPCON10), Cairo University, Egypt*, 2010.

[23] Sapna Bhati and Dhiiraj Nitnawwre. Genetic optimization tuning of an automatic voltage regulator system. *IJSET, Volume*, (1):120–124, 2012.

[24] Alain Oustaloup, Benoît Mathieu, and Patrick Lanusse. The CRONE control of resonant plants: application to a flexible transmission. *European Journal of control*, 1(2):113–121, 1995.

[25] Shah Pritesh, Sudhir Agashe, and Anand J Kulkarni. Design of a fractional PI$^{\lambda}$D$^{\mu}$ controller using the cohort intelligence method. *Frontiers of Information Technology & Electronic Engineering*, 19(3):437–445, 2018.

[26] Rohit Bhimte, Kalyani Bhole, and Pritesh Shah. Fractional order fuzzy PID controller for a rotary servo system. In *2018 2nd International Conference on Trends in Electronics and Informatics (ICOEI)*, pages 538–542. IEEE, 2018.