

List of Figures

Figure	Caption	Page No.
Fig. 2.1.	Stability region of the fractional order system	28
Fig. 2.2.	Location of roots and the corresponding time-domain responses of fractional order system	31
Fig. 2.3.	The plane of FOPID controller	39
Fig. 2.4.	Generalized form of closed-loop system with FOPID controller	40
Fig. 2.5.	Fractional-calculus based toolbox relations	45
Fig. 2.6.	FOMCON toolbox module overview	47
Fig. 2.7.	GUI for fotfid	48
Fig. 2.8.	GUI for iopid_tune	48
Fig. 2.9.	GUI for fpid_optim	49
Fig. 2.10.	Simulation blocks available in FOMCON toolbox	50
Fig. 3.1.	Different steps of simplex upgradation	55
Fig. 3.2.	Step response of the closed-loop system without controller	58
Fig. 3.3.	Step response of the closed-loop system with ZN-PID	58
Fig. 3.4.	Frequency response of the system with ZN-PID	58
Fig. 3.5.	Step-response comparison of ZN-PID and NM-FOPID	60
Fig. 3.6.	Frequency response of the system with NM-FOPID	60
Fig. 3.7.	Step response of the closed-loop time-delayed system without controller.	62
Fig. 3.8.	Step response comparison of the time-delayed system ZN-PID controller and system without controller.	63
Fig. 3.9.	Step response comparison of the time-delayed system with ZN-PID and NM-FOPID controller.	64

Fig. 3.10.	Step response of the closed-loop NMP-system without controller.	67
Fig. 3.11.	Comparison of step response of the NMP-system with ZN-PID controller and the system without controller.	68
Fig. 3.12.	Comparison of step response of the NMP-system with NM-FOPID and ZN-PID controller.	68
Fig. 3.13.	Magnetic levitation system	70
Fig. 3.14.	Step response of the open-loop MLS without controller	73
Fig. 3.15.	Step response of the MLS with ZN-PID and TE-PID controllers	74
Fig. 3.16.	Comparison of step response of the closed-loop MLS with NM-FOPID, ZN-PID and TE-PID controllers	74
Fig. 3.17.	Circuit diagram of DC-Buck converter with a voltage controller.	76
Fig. 3.18.	Step response of the closed-loop DC-buck regulator without controller	78
Fig. 3.19.	Step response of the DC-buck regulator with ZN-PI controller	78
Fig. 3.20.	Comparison of step response of the DC-buck regulator with ZN-PI and NM-FOPI controller	79
Fig. 3.21.	Comparison of frequency response of the DC-buck regulator with ZN-PI and NM-FOPI controller	80
Fig.3.22.	Experimental model of STS	81
Fig. 3.23.	Step response of closed-loop STS without controller.	82
Fig. 3.24.	Comparison of step response of STS with ZN-PID and system without controller	83
Fig. 3.25	Comparison of step response of STS with ZN-PID and NM-FOPID controllers	83
Fig. 3.26	Block diagram of an AVR system	85
Fig. 3.27.	Step response of the closed-loop AVR system without controller	86

Fig. 3.28.	Frequency response of open-loop AVR system without controller	87
Fig. 3.29.	Comparison of step response of AVR system with ZN-PID and system without controller.	87
Fig. 3.30.	Comparison of step response of AVR system with ZN-PID and NM-FOPID controller	88
Fig. 4.1.	Social leading hierarchy of grey wolves	91
Fig. 4.2.	(A) Chasing, approaching, and tracking prey (B–D) Pursuing, harassing, and encircling (E) Stationary situation and attack	93
Fig. 4.3.	Two-dimensional position vector and few of the feasible neighbors of the wolves	95
Fig. 4.4.	The probable updated locations of the wolf in 3D space	95
Fig. 4.5.	Process of updating the position according to the best search agents	97
Fig. 4.6.	(a) the wolves who are compelled to attach the prey, (b) The wolves who are compelled to separate from the prey to find a better solution	98
Fig. 4.7.	Flowchart of the GWO algorithm	100
Fig. 4.8.	Pseudo code of the GWO algorithm	101
Fig. 4.9.	Comparison of step response of the closed-loop system with GWO-FOPID controller with ZN-PID and the system without controller	103
Fig. 4.10.	Frequency response of the system with GWO-FOPID controller	103
Fig. 4.11.	Comparison of step response of the closed-loop time-delayed system with GWO-FOPID and ZN-PID controller	105
Fig. 4.12.	Comparison of step response of the closed-loop NMP-system with ZN-PID and GWO-FOPID controller	106
Fig. 4.13.	Comparison of step response of the closed-loop MLS with ZN-PID, TE-PID and GWO-FOPID controller	107

Fig. 4.14.	Comparison of step response of the closed-loop DC-buck regulator with ZN-PI and GWO-FOPI controller	108
Fig. 4.15.	Comparison of frequency response of the DC-buck regulator with ZN-PI and GWO-FOPI controller	109
Fig. 4.16.	Comparison of step response of the closed-loop STS with ZN-PID and GWO-FOPID controller	110
Fig. 4.17.	Comparison of step response of the closed-loop AVR system with GWO-FOPID controller for both values of β is compared and ZN-PID controller	112
Fig. 4.18.	Comparison of step response of AVR system with uncertainty in amplifier	114
Fig. 4.19.	Comparison of step response of AVR system with uncertainty in exciter	115
Fig. 4.20.	Comparison of step response of AVR system with uncertainty in generator	115
Fig. 5.1.	Flowchart of MGWO-algorithm	120
Fig. 5.2.	Pseudo code of the MGWO-algorithm	121
Fig. 5.3.	Comparison of step responses of the closed-loop system with MGWO-FOPID, ZN-PID and the system without controller	122
Fig. 5.4.	Comparison of frequency response of the system without controller and the system with ZN-PID and MGWO-FOPID controller	122
Fig. 5.5.	Comparison of step response of the closed-loop time-delayed system with MGWO-FOPID and ZN-PID controller	124
Fig. 5.6.	Comparison of step response of the closed-loop NMP-system with ZN-PID and MGWO-FOPID controller	125
Fig. 5.7.	Comparison of step response of the closed-loop MLS with ZN-PID, TE-PID and MGWO-FOPID controller	126
Fig. 5.8.	Comparison of step response of the closed-loop DC-buck regulator with ZN-PI and GWO-FOPI controller	127

Fig. 5.9.	Comparison of frequency response of the DC-buck regulator with ZN-PI and GWO-FOPID controller	128
Fig. 5.10	Comparison of step response of the closed-loop STS with ZN-PID and GWO-FOPID controller	129
Fig. 5.11.	Comparison of step response of the closed-loop AVR system with MGWO-FOPID controller and ZN-PID controller	130
Fig. 5.12.	Comparison of step response of original and altered AVR system due to uncertainty in amplifier	132
Fig. 5.13.	Comparison of Step response of original and altered AVR system due to uncertainty in exciter	132
Fig. 5.14.	Comparison of Step response of original and altered AVR system due to uncertainty in generator	133
Fig. 6.1.	Comparison of Controller Outputs of the closed-loop system with ZN-PID, NM-FOPID, GWO-FOPID and MGWO-FOPID controllers	136
Fig. 6.2.	Comparison of frequency response of the third order linear system with ZN-PID, NM-FOPID, GWO-FOPID and MGWO-FOPID controllers	136
Fig. 6.3.	Comparison of Controller Outputs of the second order time-delayed system with ZN-PID, NM-FOPID, GWO-FOPID and MGWO-FOPID controllers	138
Fig. 6.4.	Comparison of Controller Outputs of the NMP system with ZN-PID, NM-FOPID, GWO-FOPID and MGWO-FOPID controllers	140
Fig. 6.5.	Comparison of Controller Outputs of the MLS with ZN-PID, NM-FOPID, GWO-FOPID and MGWO-FOPID controllers	141
Fig. 6.6.	Comparison of Controller Outputs of the closed-loop DC-buck regulator system with ZN-PI, NM-FOPID, GWO-FOPID and MGWO-FOPID controllers	142

Fig. 6.7.	Comparison of frequency response of the DC-buck regulator system with ZN-PI, NM-FOPI, GWO-FOPI and MGWO-FOPI controllers	143
Fig. 6.8.	Comparison of Controller Outputs of the closed-loop STS with ZN-PI, NM-FOPI, GWO-FOPI and MGWO-FOPI controllers	145
Fig. 6.9.	Comparison of Controller Outputs of the closed-loop AVR system with ZN-PID, NM-FOPID, GWO-FOPID, MGWO-FOPI and other controllers present in the literature for $\beta = 1$.	147
Fig. 6.10.	Comparison of Controller Outputs of the closed-loop AVR system with ZN-PID, NM-FOPID, GWO-FOPID, MGWO-FOPI and other controllers present in the literature for $\beta = 1.5$.	147

List of Tables

Table	Caption	Page No.
Table 1.1	Different forms of fractional order controllers.	6
Table 2.1	Steady-state errors and steady-state error coefficients	33
Table 2.2	List of tools and software for fractional order calculus and control application	43
Table 3.1	Comparison of performance characteristics of ZN-PID and NM-FOPID	61
Table 3.2	Comparison of performance characteristics of time-delayed system with ZN-PID and NM-FOPID	64
Table 3.3	Comparison of performance characteristics of NMP-system with NM-FOPID and ZN-PID	69
Table 3.4	Comparison of performance characteristics of MLS with NM-FOPID, ZN-PID and TE-PID controllers	75
Table 3.5	Comparison of performance characteristics of DC-buck regulator with NM-FOPI, ZN-PI controllers	79
Table 3.6	Comparison of performance characteristics of STS with NM-FOPID and ZN-PID controllers	84
Table 3.7	Comparison of performance characteristics of AVR system with NM-FOPID and ZN-PID controllers	88
Table 4.1	Comparison of performance characteristics of ZN-PID and GWO-FOPID	104
Table 4.2	Comparison of performance characteristics of time-delayed system with ZN-PID and GWO-FOPID controller	105
Table 4.3	Comparison of performance characteristics of ZN-PID and GWO-FOPID	106
Table 4.4	Comparison of performance characteristics of MLS with ZN-PID, TE-PID and GWO-FOPID controller	107