

Chapter 6

Result analysis

6.1 Introduction

In the previous chapters, performance of the proposed controllers are validated by comparing Step Responses i.e Controller Outputs of the closed-loop system with classical ZN-PID controller. In this chapter, performance of proposed controllers obtained through NM-algorithm, GWO-algorithm and MGWO-algorithm for various examples are summarized.

6.2 Result Analysis

In this section, results of FOPID controllers designed using three different optimization algorithms for each of the system are compared with each other and with other existing controller in the literature.

6.2.1 Third order linear plant

This section considers the third order linear plant discussed in section 3.3. The performance of the system with different controllers proposed in chapter 3, 4 and 5 (i.e. ZN-PID, NM-FOPID, GWO-FOPID and MGWO-FOPID) is compared together through Controller Outputs of the closed-loop system as shown in Figure 6.1. The GWO-FOPID shows better time-domain performance than the other three classical PID and FOPID controllers. Frequency response of the system with different controllers is compared in Figure 6.2 that justify the better performance of GWO-FOPID controller in whole bandwidth of the system.

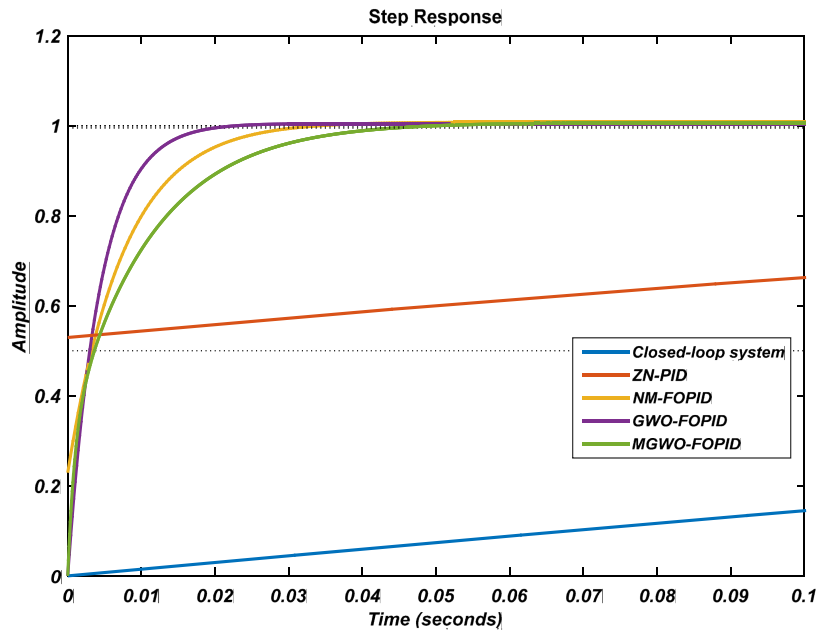


Fig. 6.1. Comparison of Controller Outputs of the closed-loop system with ZN-PID, NM-FOPID, GWO-FOPID and MGWO-FOPID controllers

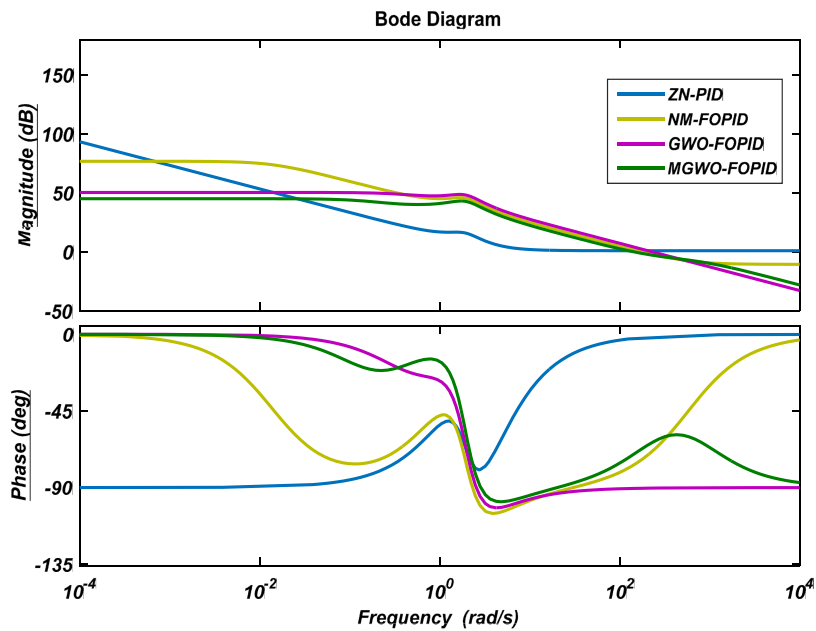


Fig. 6.2. Comparison of frequency response of the third order linear system with ZN-PID, NM-FOPID, GWO-FOPID and MGWO-FOPID controllers

Table 6.1 Comparison of performance characteristics of third order linear plant with different controllers.

Controller	Rise-time	Settling-time	Peak Overshoot	Gain Margin	Phase Margin
ZN-PID	0.5491	3.2580	0.9997	∞	∞
TE-PID	0.0280	0.1662	17.47	∞	∞
NM-FOPID	0.0159	0.0264	0.7313	∞	107
GWO-FOPID	0.0100	0.0176	0.6753	∞	89.7
MGWO-FOPID	0.0188	0.0339	1.1442	∞	110

The performance characteristics of the third order linear plant with different controllers are compared in Table 6.1. Here it is clear that the performance of GWO-FOPID controller performs better as compared to other proposed controllers. It improves both the time-domain as well as frequency domain performance of the third order linear plant and shows minimum rise-time, settling-time and peak overshoot.

6.2.2 Time-delay system

6.2.2.1 Second order system with time delay

System under consideration is from section 3.4.1. Comparison of Controller Outputs of the closed-loop system with different controllers (i.e. ZN-PID, NM-FOPID, GWO-FOPID and MGWO-FOPID) proposed in chapter 3, 4 and 5 is shown in Figure 6.3. In this case, the MGWO-FOPID controller shows better time-domain performance than the other three classical PID and FOPID controllers.

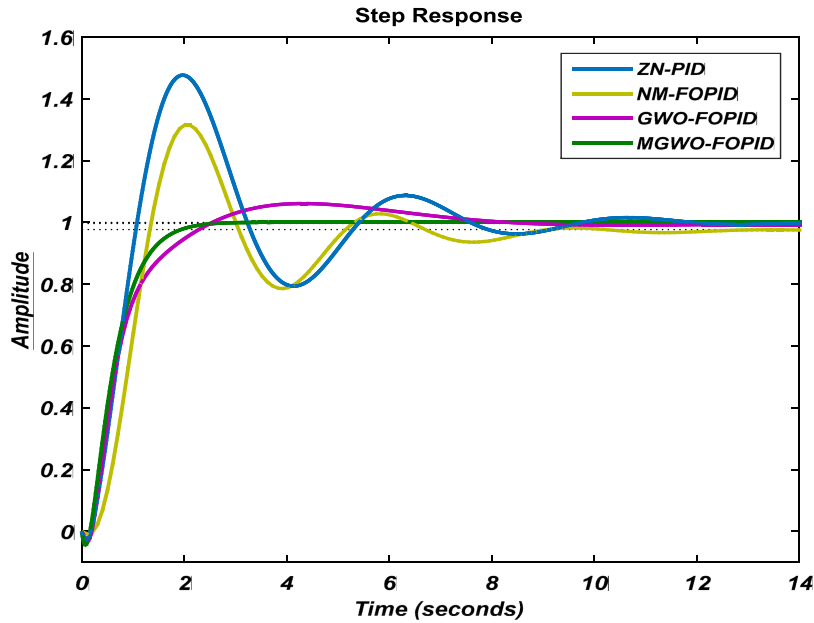


Fig. 6.3. Comparison of Controller Outputs of the second order time-delayed system with ZN-PID, NM-FOPID, GWO-FOPID and MGWO-FOPID controllers

Table 6.2 Comparison of performance characteristics of the second order time-delayed system with different controllers.

Controller	Rise-time	Settling-time	Peak Overshoot
ZN-PID	0.6871	9.2096	47.6680
TE-PID	1.5675	7.1597	6.4811
NM-FOPID	0.7799	8.4589	34.6049
GWO-FOPID	1.3195	7.0761	6.4650
MGWO-FOPID	1.0731	1.9603	0.0801
FOPID [59]	≈0.8	≈12	19

The performance characteristics of the system with different controllers is compared in Table 6.2. The comparison validates the better performance of the MGWO-

FOPID controller over other proposed controller and an FOPID controller present in the literature [59] for the second order time-delayed system.

6.2.2.2 Non-minimum phase system with time delay:

In this subsection, the performance of the NMP-system [160] discussed in section 3.4.2 with different controllers (i.e. ZN-PID, NM-FOPID, GWO-FOPID and MGWO-FOPID) are compared together. The comparison of Controller Outputs for the unit step input for the closed-loop system with different controllers are shown in Figure 6.4. Here, although the performance of the MGWO-FOPID controller is slower than the GWO-FOPID. It gives lesser settling-time and minimum peak overshoot than the other three classical PID and FOPID controllers.

Table 6.3 Comparison of performance characteristics of the second order time-delayed system with different controllers.

Controller	Rise-time	Settling-time	Max. Overshoot
ZN-PID	3.3664	77.4635	39.7292
TE-PID	117.84	$1.53 \times 10^{+3}$	45.58
NM-FOPID	3.8213	13.6168	4.3293
GWO-FOPID	7.9301	22.9301	2.4970
MGWO-FOPID	8.5241	17.4682	1.7015

The performance characteristics of the NMP-system with different controllers is compared in Table 6.3. The comparison shows the better performance of the MGWO-FOPID controller over other proposed controller for NMP-system with time-delayed.

The overall performance the MGWO-FOPID controller is better than other classical PID, NM-FOPID and GWO-FOPID controllers for both second order time-

delayed system and NMP-system with time delay. Thus, it can be stated that the MGWO-algorithm gives better results than the other three techniques for optimization of FOPID controller parameters.

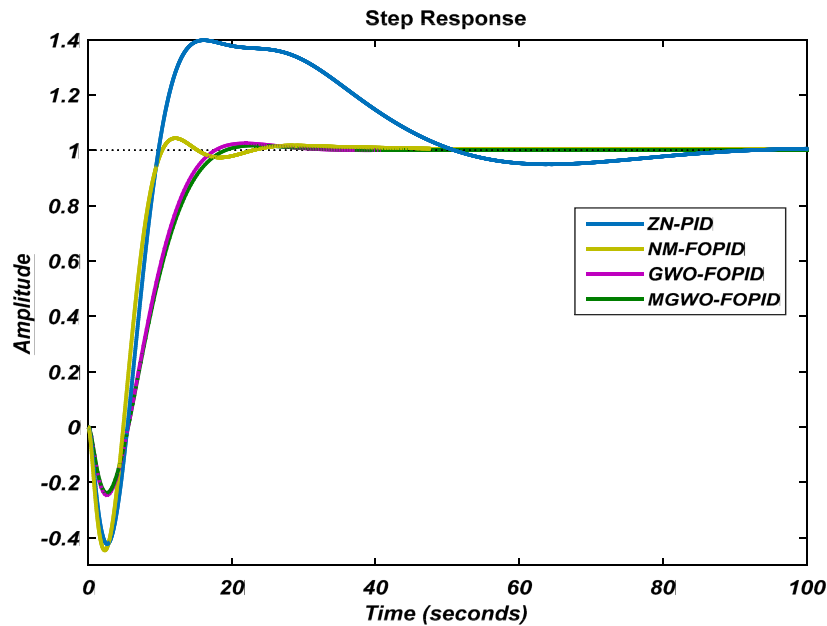


Fig. 6.4. Comparison of Controller Outputs of the NMP system with ZN-PID, NM-FOPID, GWO-FOPID and MGWO-FOPID controllers

6.2.3 Magnetic levitation system

The performance of the MLS [162], [163] with different controllers (i.e. ZN-PID, NM-FOPID, GWO-FOPID and MGWO-FOPID) proposed in chapter 3, 4 and 5 is summarised here. The Controller Outputs of the closed-loop MLS is shown in Figure 6.5. it is observed that the closed-loop MLS with MGWO-FOPID controller gives faster response than the other existing classical PID and FOPID controllers.

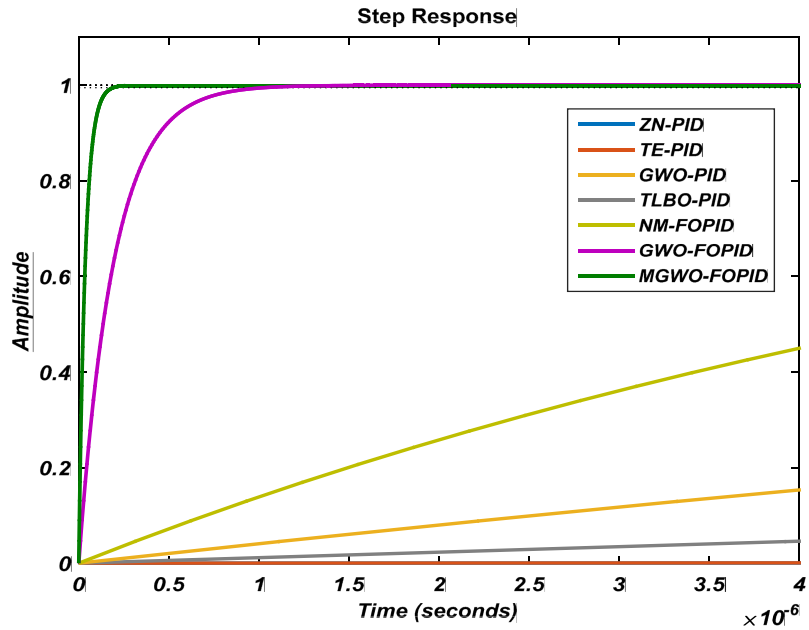


Fig. 6.5. Comparison of Controller Outputs of the MLS with ZN-PID, NM-FOPID, GWO-FOPID and MGWO-FOPID controllers

Table 6.4 Comparison of performance characteristics of the MLS with different controllers.

Controller	Rise-time	Settling-time	Peak Overshoot
ZN-PID	0.0096	0.503	37.692
TE-PID	0.0068	0.2637	22.113
GWO-PID [176]	$1.27 * 10^{-4}$	$1.4 * 10^{-4}$	0.0207
TLBO-PID [162]	0.007	0.012	1.28
NM-FOPID	$1.46 * 10^{-5}$	$2.58 * 10^{-5}$	0.0976
GWO-FOPID	$4.27 * 10^{-7}$	$7.61 * 10^{-7}$	0.0157
MGWO-FOPID	$7.8089 * 10^{-8}$	$1.338 * 10^{-7}$	0.4096

Table 6.4 shows the comparison of performance characteristics of the MLS with different proposed controller and a classical PID controller present in the literature. The comparison present the better performance of the MGWO-FOPID controller over other proposed and existing controllers for magnetic levitation system.

Hence, the MGWO-algorithm also gives better results than the other three techniques for optimization of FOPID controller parameters for highly unstable magnetic levitation system.

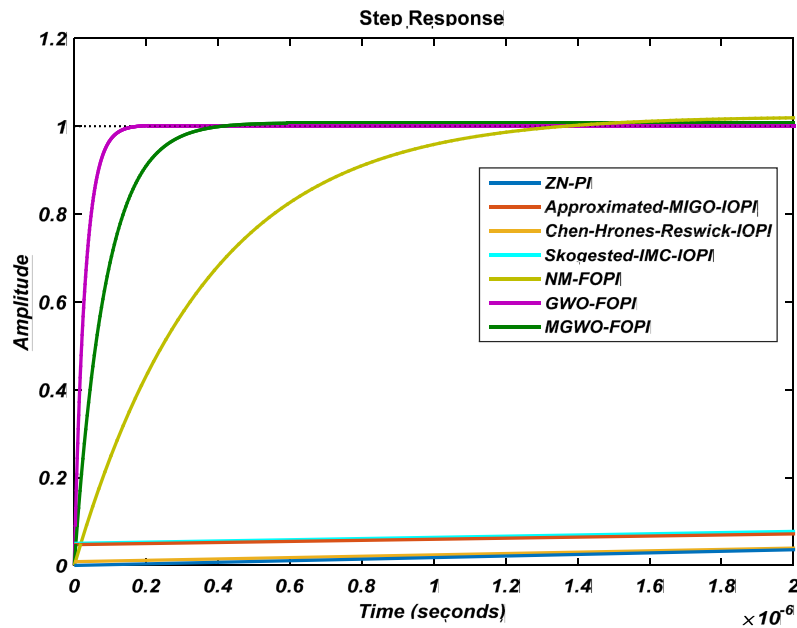


Fig. 6.6. Comparison of Controller Outputs of the closed-loop DC-buck regulator system with ZN-PI, NM-FOP, GWO-FOP and MGWO-FOP controllers

6.2.4 DC-buck regulator system

The performance of the DC-buck regulator system discussed in chapter 3 with different controllers (i.e. ZN-PI, NM-FOP, GWO-FOP and MGWO-FOP) is summarised here. The comparison is shown with the Controller Outputs in Figure 6.6. The response of the system with GWO-FOP controller is faster than the other proposed FOP and existing

IOPI controllers. The frequency response of the DC-buck regulator with different controllers is compared in Figure 6.7 which shows almost similar response of all three proposed FOPI controllers.

Table 6.5 compares the performance characteristics of the closed-loop DC-buck regulator with different controllers. Although the frequency response of the DC-buck regulator is almost similar with all the three proposed FOPI controllers but time-domain specifications of the GWO-FOPI controller dominates over other controllers. Hence, the overall performance of GWO-FOPI controller is better than the other proposed controllers in the present work.

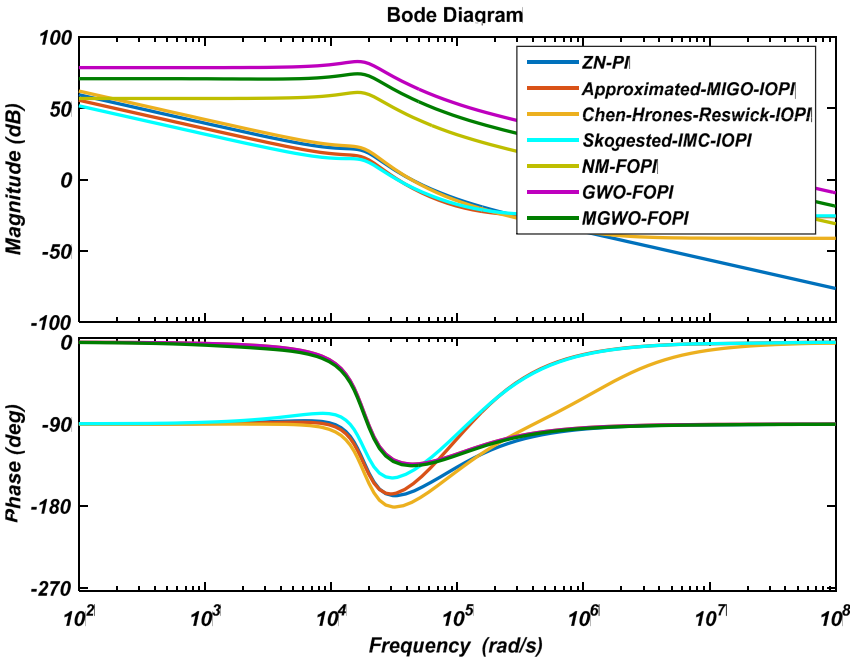


Fig. 6.7. Comparison of frequency response of the DC-buck regulator system with ZN-PI, NM-FOPI, GWO-FOPI and MGWO-FOPI controllers

Table 6.5 Comparison of performance characteristics of DC-buck regulator with different controllers.

Controller	Rise-time	Settling-time	Peak Overshoot	Gain Margin	Phase Margin
ZN-PI	$2.75 * 10^{-5}$	$7.57 * 10^{-4}$	51.5141	∞	46.9
TE-PI	$1.92 * 10^{-5}$	$2.36 * 10^{-4}$	35.1	∞	36.0
NM-FOPI	$7.28 * 10^{-7}$	$4.50 * 10^{-6}$	2.2698	∞	88.5
GWO-FOPI	$6.42 * 10^{-8}$	$1.12 * 10^{-7}$	0.1160	∞	89.9
MGWO-FOPI	$1.83 * 10^{-7}$	$3.06 * 10^{-7}$	0.6896	∞	89.3
Approximate MIGO-IOPI [176]	$5.84 * 10^{-5}$	$12 * 10^{-4}$	30.82	∞	14.7
Chen-Hrones-Reswick-IOPI [176]	$3.64 * 10^{-5}$	$8.15 * 10^{-4}$	41.4965	-3.88	3.78
Skogested IMC-IOPI [176]	$4.04 * 10^{-5}$	$8.65 * 10^{-4}$	38.4285	∞	31.5

6.2.5 Spherical Tank System

The performance of the spherical tank system discussed in chapter 3 with different controllers (i.e. ZN-PID, NM-FOPID, GWO-FOPID and MGWO-FOPID) is summarised together. Comparison of the Controller Outputs of the closed-loop STS system is shown in Figure 6.8. The step response of both GWO-FOPID and MGWO-FOPID controllers seem to be similar and faster than NM-FOPID controller.

The performance characteristics of the closed-loop STS with different proposed and existing controllers is compared in Table 6.6. The performance of GWO-FOPID and MGWO-FOPID controllers are far better than NM-FOPID, ZN-PID and FOPI controllers

present in the literature. Performance of MGWO-FOPID controller leads in terms on rise-time and settling-time of the closed-loop system but it lags behind GWO-FOPID in terms of percentage peak overshoot of the system.

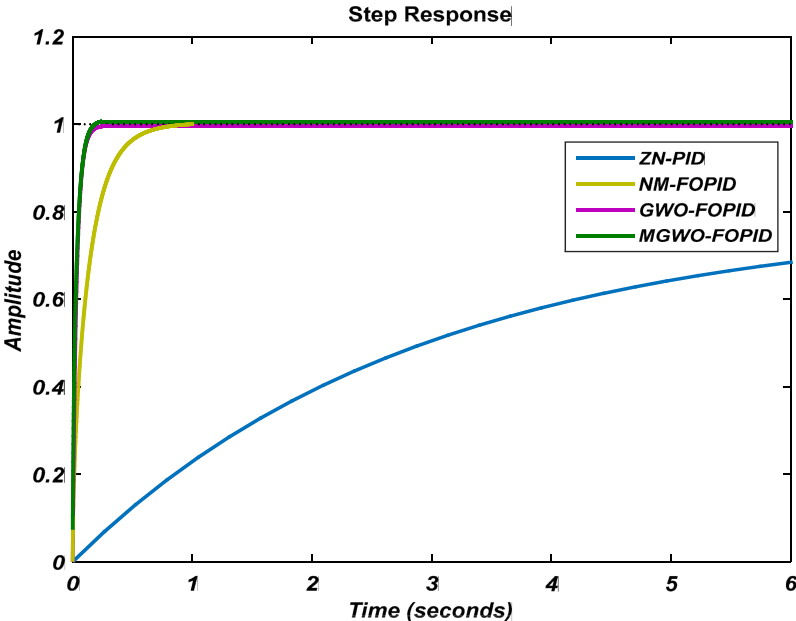


Fig. 6.8. Comparison of Controller Outputs of the closed-loop STS with ZN-PI, NM-FOPID, GWO-FOPID and MGWO-FOPID controllers

Table 6.6 Comparison of performance characteristics of STS with different controllers.

Controller	Rise-time	Settling-time	Peak Overshoot
ZN-PID	84.644	193.0292	1.8564
TE-PID	92.2	656.0	6.2
NM-FOPID	0.3218	0.5910	0.1027
GWO-FOPID	0.0773	0.1481	0
MGWO-FOPID	0.0796	0.1383	0.5357
FOPI [165]	≈35	52	0

As the application of STS system is mostly in the chemical industry whether a minor change in amount of chemical may cause a disaster for whole process. Hence, percentage overshoot of the STS system must be negligible. So, the GWO-FOPID controller will be suitable controller for the STS system as it provides zero percentage overshoot. Although, the MGWO-FOPID controller will be preferred if minor overshoot is adaptable for the plant as it provides faster control action than GWO-FOPID.

Hence, in the case of STS system both GWO and MGWO-algorithm performs better than NM-algorithm for optimization of FOPID controller parameters.

6.2.6 Automatic voltage regulator system

Various PID and FOPID controller is proposed in the literature for controlling the terminal voltage of AVR system[71], [93], [116], [145], [147], [148], [177]–[182]. Performance of the AVR system with the proposed controllers (i.e. ZN-PID, NM-FOPID, GWO-FOPID and MGWO-FOPID) and different PID and FOPID controllers proposed in the literature are compared in this section. Comparison of step response of the closed-loop AVR system is shown in Figure 6.9 and Figure 6.10 for different values of parameter beta (β) in Equation 4.8.

From Figure 6.9 and Figure 6.10, it is clear that the Controller Outputs of AVR system with proposed MGWO-FOPID controller is faster than all the other existing PID and FOPID controllers for both values of beta. Moreover, MGWO-FOPID controller also show minimum percentage overshoot among all.

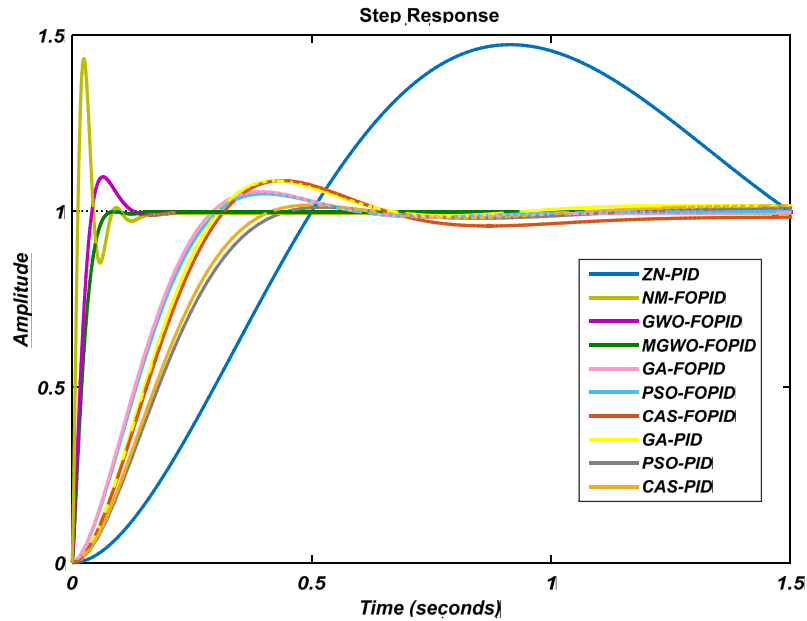


Fig. 6.9. Comparison of Controller Outputs of the closed-loop AVR system with ZN-PID, NM-FOPID, GWO-FOPID, MGWO-FOPID and other controllers present in the literature for $\beta = 1$ [178].

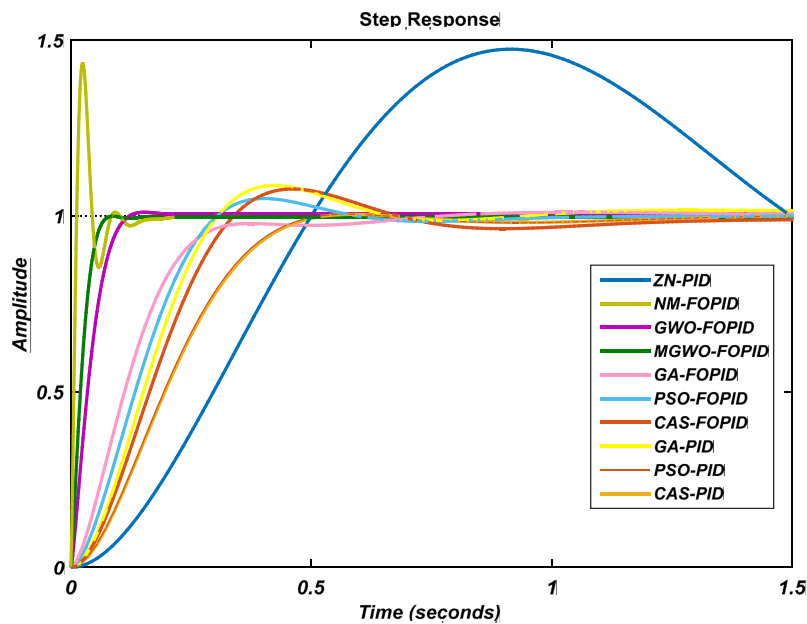


Fig. 6.10. Comparison of Controller Outputs of the closed-loop AVR system with ZN-PID, NM-FOPID, GWO-FOPID, MGWO-FOPID and other controllers present in the literature for $\beta = 1.5$ [178].

Table 6.7 Comparison of performance characteristics of AVR system with ZN-PI, NM-FOPI, GWO-FOPI, MGWO-FOPI and other controllers present in the literature [178].

Controller	Rise-time	Settling-time	Peak overshoot	Gain Margin	Phase Margin
ZN-PID	0.2607	6.9865	65.7226	4.62	16.1
MGWO-FOPID	0.0427	0.0653	0	29.8	71
$\beta = 1$					
GA-PID	0.2019	0.5980	8.6644	23.5	59.2
PSO-PID	0.2767	0.4025	1.16	25.8	67.6
CAS-PID	0.2425	0.3550	1.7678	25.4	66.9
CAS-FOPID	0.2223	0.3037	0.1678	26.6	57.7
GA-FOPID	0.1402	0.561	0	29.8	62.8
PSO-FOPID	0.1604	0.2657	0.02	30.2	63.5
$\beta = 1.5$					
GA-PID	0.2003	1.0517	3.6287	23.2	61.8
PSO-PID	0.2997	0.4156	0.4400	26.7	68.5
CAS-PID	0.3156	0.4212	0.4000	26.8	68.6
CAS-FOPID	0.2305	0.3187	0.0642	25.5	59
GA-FOPID	0.1444	0.4894	0.36	30.7	73.3
PSO-FOPID	0.1603	0.2655	0.01	30.2	63.6

The performance characteristics of the closed-loop AVR-system with different controllers is also compared in Table 6.7. The performance of MGWO-FOPID controllers is better in terms of rise-time, settling time, gain margin and phase margin of the AVR system. This support the validation for better performance off the MGWO-FOPID controller over other existing PID and FOPID controllers both in time-domain and frequency-domain for AVR system.

Hence, MGWO-algorithm present better FOPID controller for AVR system than NM-algorithm, GWO-algorithm and the other algorithms present in the literature.

6.3 Summary

Performance of all the proposed FOPID controller for various systems is summarised in this chapter. Effectiveness of the proposed algorithm is validated and discussed by comparing the simulation results of each controller. The performance check and effectiveness lead to the conclusion of the present work in the next chapter.