Digital Control in Power Electronics

Analysis and implementation of Multisampled PWM for high bandwidth and output frequency current control of electrical drives

Simulation results

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1 Our controller: UR=8 with MAF, IMC

A goal of this section is to show that our controller can achieve the same performance as an IMC controller with double update rate without MAF, whose parameter α is set to the highest value which results in the response without an overshoot [1]. Parameter $\alpha = 0.0636$ for our controller is set to obtain the same cross-over frequency as with UR=2 no MAF, α=0.25. Open-loop Bode plots for two cases of interest are shown in Fig. 1-2. Corresponding step responses from simulation with dead-time at 270Hz output frequency are shown in Fig. 3-4. Comparison between analytical and simulated rise times are shown in Table 1. Comparison between analytical and simulated open and closed loop frequency response at 270Hz output frequency is shown in Fig. 5-6. The most important characteristics of the system (cross-over frequency f_c, phase margin pm and -3dB closed loop bandwidth f_{bw}) obtained by analytical calculation and simulated frequency response analysis (FRA) are shown in Tab. 2. Note that the FRA in Simulink is done without dead-time.

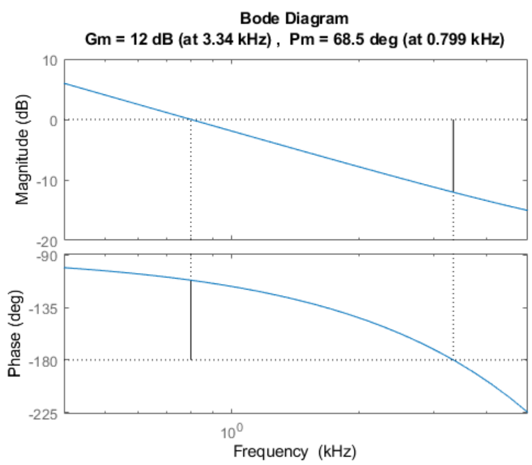

Fig. 1. Open-loop Bode plots: UR=2 no MAF $\alpha = 0.25$.

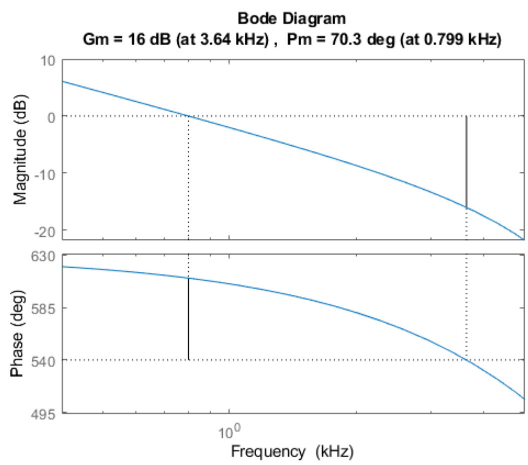

Fig. 2. Open-loop Bode plots: UR=8 with MAF $\alpha = 0.0636$.

Characteristics		UR=2 no MAF $\alpha = 0.25$	UR=8 with MAF $\alpha = 0.0636$
analytical	$f_{bw} - 3dB[kHz]$	1.4607	1.3871
	t_{rise}/T_{pwm}	2.1542	2.2685
simulated	t_{rise}/T_{pwm}	2.4	2.75

Table 1. Our controller: Step response characteristics.

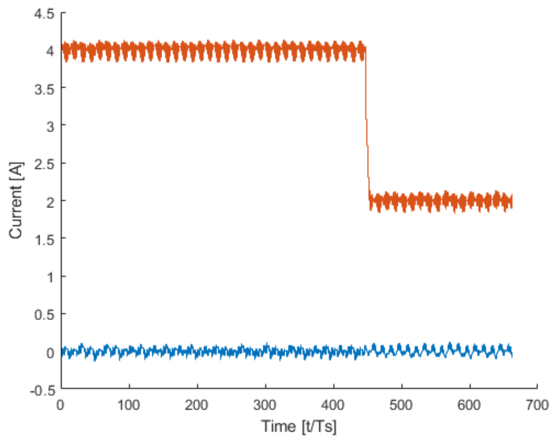

Fig. 3. Sim.step response: UR=2 no MAF $\alpha = 0.25$.

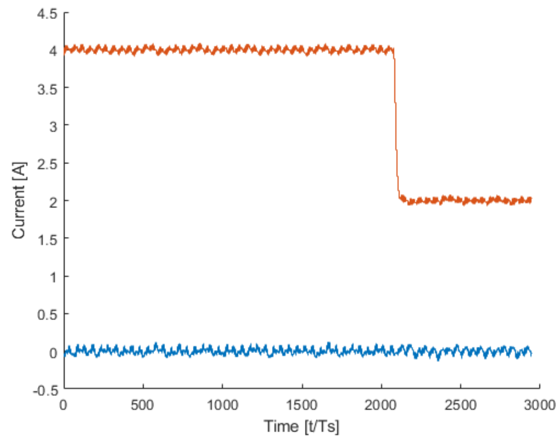

Fig. 4. Sim. step response: UR=8 with MAF $\alpha = 0.0636$.

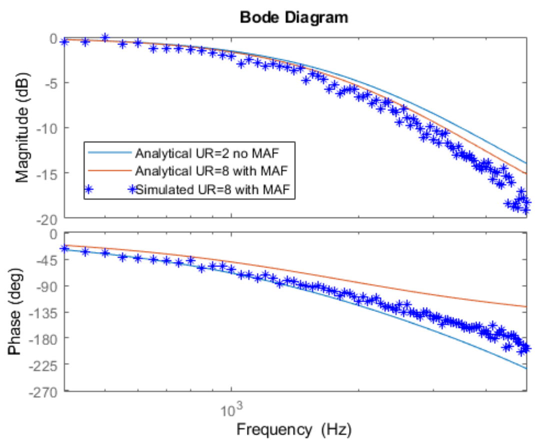

Fig. 5. Sim. closed-loop FRA: UR=8 with MAF $\alpha = 0.0636$.

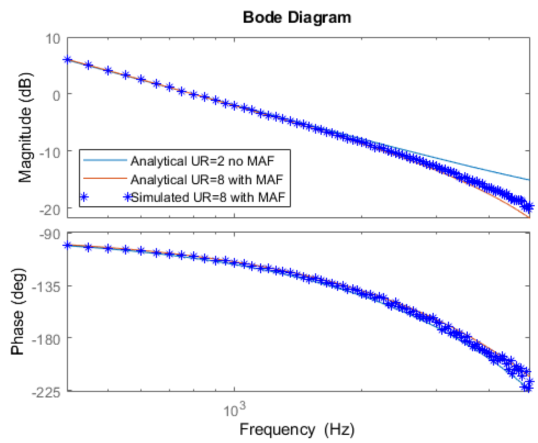

Fig. 6. Sim. open-loop FRA: UR=8 with MAF $\alpha = 0.0636$.

Characteristics	UR=2 no MAF $\alpha = 0.25$	UR=8 with MAF $\alpha = 0.0636$	
	analytical	analytical	simulated
$f_c[Hz]$	799.1594	798.5845	700
$pm[^\circ]$	68.4572	70.2667	70
$f_{bw} - 3dB[kHz]$	1.4607	1.3871	1.25

Table 2. Our controller: FRA open & closed loop performance.

2 Our dif. controller: UR=8 with MAF, IMC + dif.

A goal of this section is to compare performance of our differential controller with the performance of the controller proposed in [2] (UR=2 with MAF & advanced scheduling $\alpha = 0.38, d = 0.444$), further on denoted as benchmark. Optimum pair of parameters $\alpha = 0.12038, d = 2.1948$ for our differential controller are found by performing a numerical search for the optimum along the (α, d) plane [2]. Open-loop Bode plots for two cases of interest are shown in Fig. 7-8.

Simulation step responses at 270Hz output electrical frequency for our differential and benchmark controller are shown Fig. 9-10. In order to examine origin of the oscillations at fundamental frequency which are present in the step response of our dif. controller, simulation was run at smaller electrical frequency (50Hz) and with 3 times higher phase resistance (Fig. 11-12). Comparison between analytical and simulated rise times are shown in Table 3 Note that when used for analytical calculation, the same transfer function for the benchmark controller as in [2] is assumed, whereas for the simulation, execution time of approximately 12us is modelled, in order to represent a more realistic case which corresponds to the implementation of the benchmark controller where execution time is not negligible.

Comparison between analytical and simulated open and closed loop frequency response at 270Hz output frequency is shown in Fig. 13-14. Simulation was run at smaller electrical frequency (50Hz) and with 3 times higher phase resistance, and the resulting open and closed loop frequency responses are shown in Fig. 15-18. The most important characteristics of the system (cross-over frequency f_c, phase margin pm and -3dB closed loop bandwidth f_{bw}) obtained by analytical calculation and simulated frequency response analysis are shown in Tab. 4.

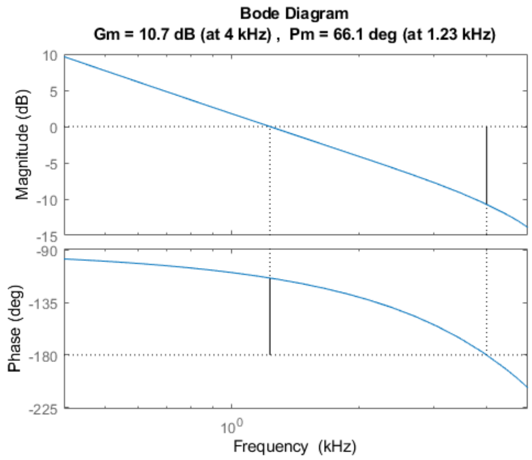

Fig. 7. Open-loop Bode plots: benchmark.

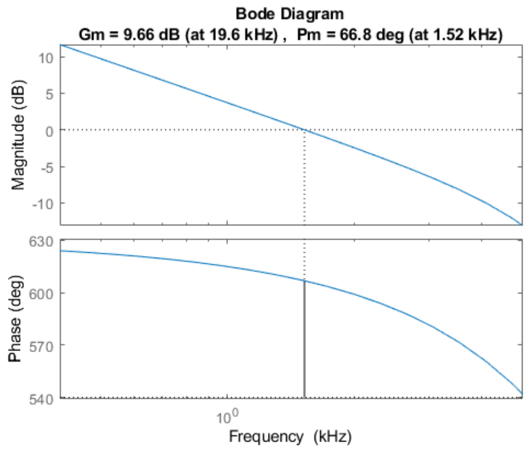

Fig. 8. Open-loop Bode plots: our dif. controller.

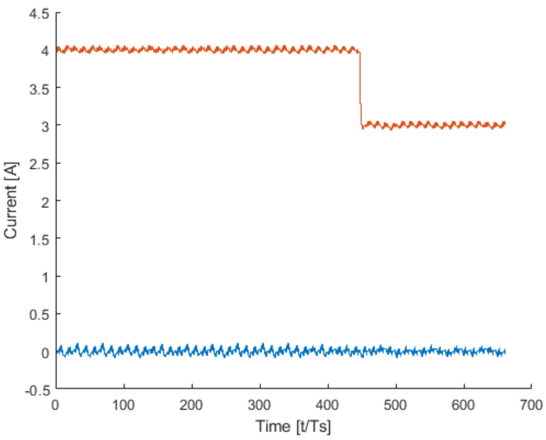

Fig. 9. Sim.step response: benchmark.

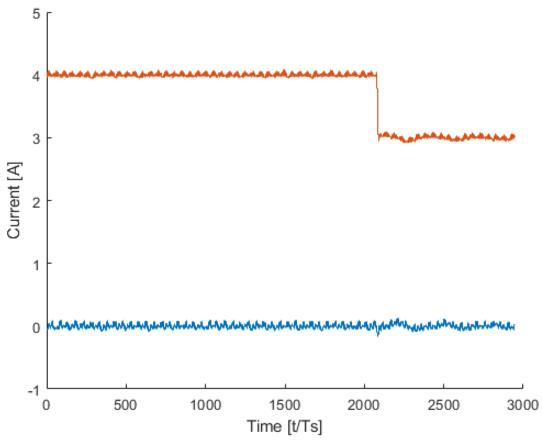

Fig. 10. Sim. step response: our dif. controller.

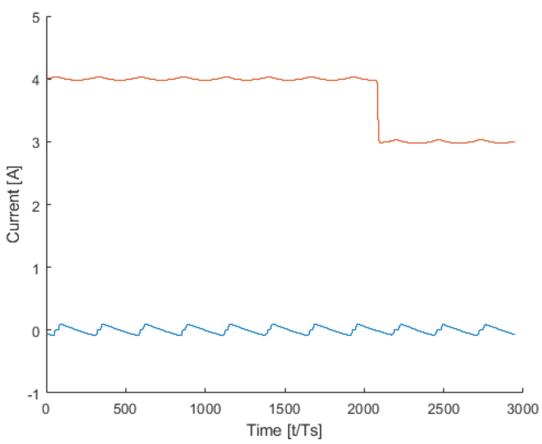

Fig. 11. Sim. step response at 50Hz: our dif. controller.

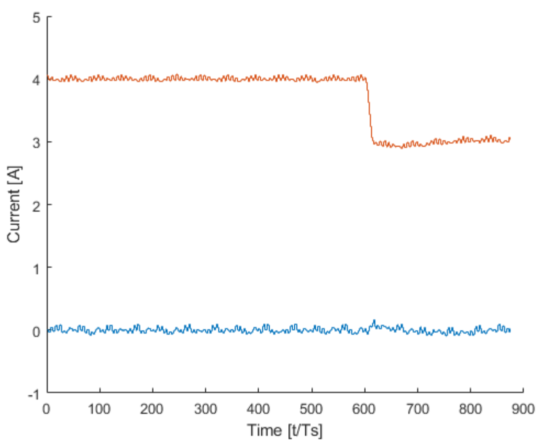

Fig. 12. Sim. step response with Rs=3*Rs: our dif. controller.

Characteristics		benchmark	UR=8 with MAF $\alpha = 0.12038, d = 2.1948$		
		fe=270Hz	fe=270Hz	fe=50Hz	Rs=3*Rs
analytical	$f_{bw} - 3dB[kHz]$	3.5105	3.9846		
	t_{rise}/T_{pwm}	0.8964	0.7897		
simulated	t_{rise}/T_{pwm}	1.21	0.875	1.25	1.067

Table 3. Our dif. controller: Step response characteristics.

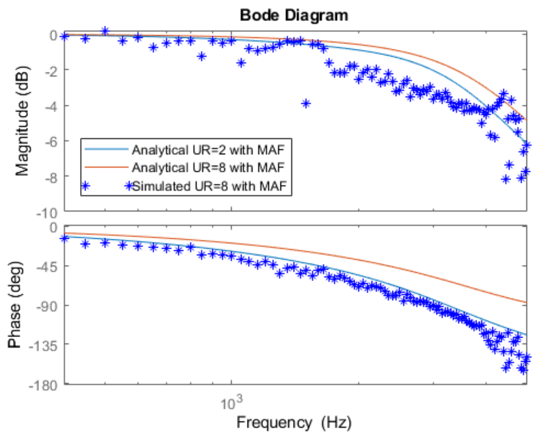

Fig. 13. Sim. closed-loop FRA: our dif. controller.

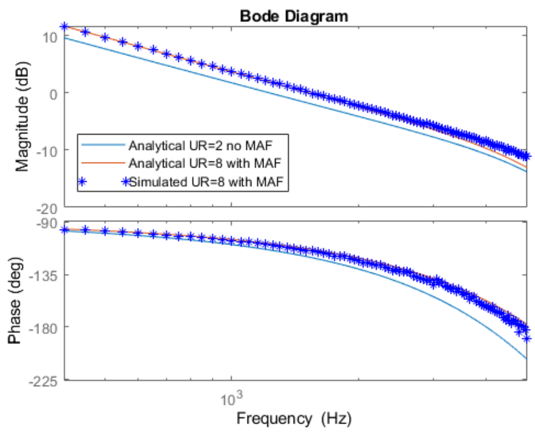

Fig. 14. Sim. open-loop FRA: our dif. controller.

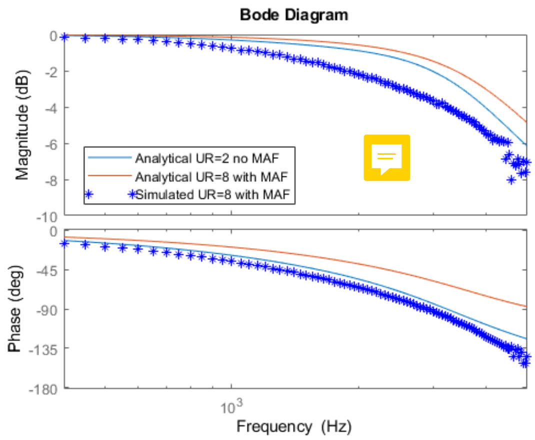

Fig. 15. Sim. closed-loop FRA at 50Hz: our dif. controller.

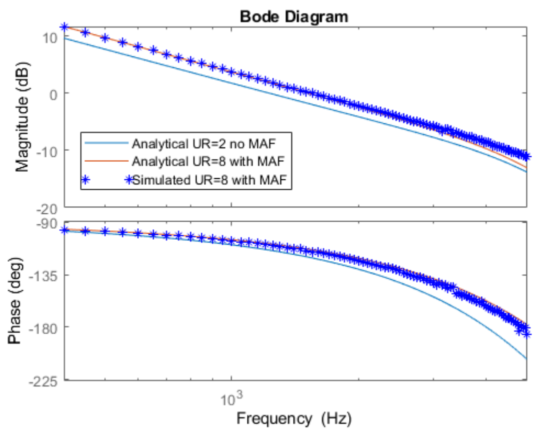

Fig. 16. Sim. open-loop FRA at 50Hz: our dif. controller.

Characteristics	benchmark	UR=8 with MAF $\alpha = 0.12038, d = 2.1948$			
	analytical	analytical	simulated		
			fe=270Hz	fe=50Hz	Rs=3*Rs
$f_c[kHz]$	1.2283	1.5209	1.55	1.55	1.55
$pm[°]$	66.068	66.838	65.135	64.9	65.633
$f_{bw} - 3dB[kHz]$	3.5105	3.9846	2.525	2.5	2.3

Table 4. Our dif. controller: FRA open & closed loop performance.

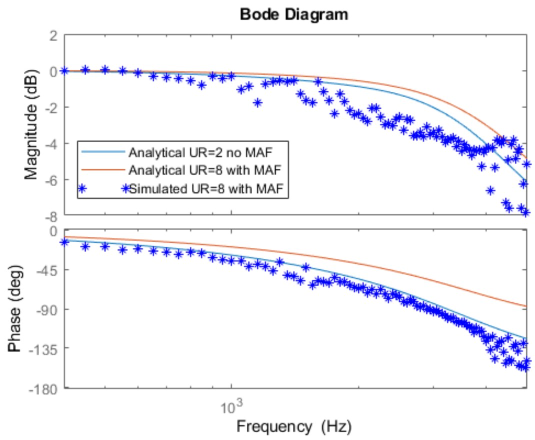

Fig. 17. Sim. closed-loop FRA with Rs=3*Rs: our dif. controller.

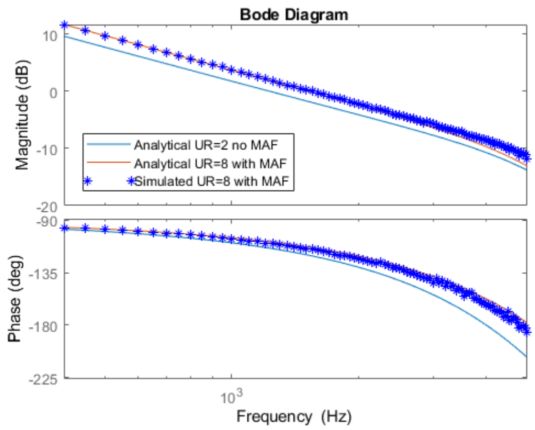

Fig. 18. Sim. open-loop FRA with Rs=3*Rs: our dif. controller.

3 Our controller without MAF: UR=8 no MAF, IMC

A goal of this section is to show that our controller without MAF (IMC only, no differential action) can achieve faster response than the benchmark controller. Parameter α for our controller is set analytically so that higher -3dB bandwidth is achieved than in case of the benchmark. Open loop Bode plots for two cases of interest are shown in Fig. 19-20. Corresponding simulated step responses at 270Hz output frequency are shown in Fig. 21-22. Comparison between analytical and simulated rise times are shown in Table 5. Comparison between analytical and simulated open and closed loop frequency response at 270Hz output frequency is shown in Fig. 23-24. The most important characteristics of the system (cross-over frequency f_c, phase margin pm and -3dB closed loop bandwidth f_{bw}) obtained by analytical calculation and simulated frequency response analysis (FRA) are shown in Tab. 6.

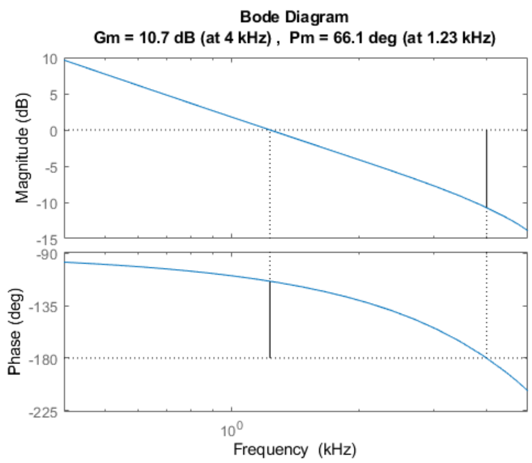

Fig. 19. Open-loop Bode plots: benchmark.

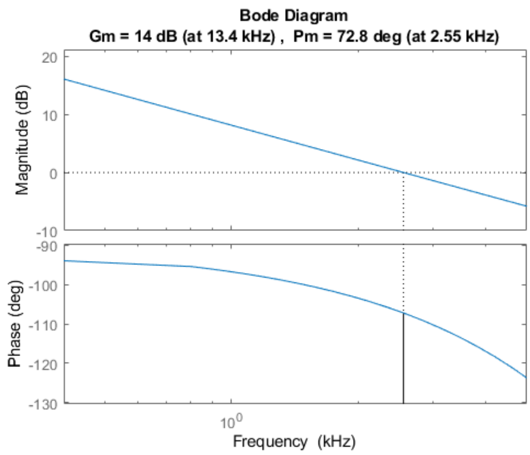

Fig. 20. Open-loop Bode plots: UR=8 no MAF $\alpha = 0.2$.

Characteristics		benchmark	UR=8 no MAF $\alpha = 0.2$
analytical	$f_{bw} - 3dB[kHz]$	3.5105	3.9467
	t_{rise}/T_{pwm}	0.8964	0.7973
simulated	t_{rise}/T_{pwm}	1.1875	0.8594

Table 5. Our controller without MAF: Step response characteristics.

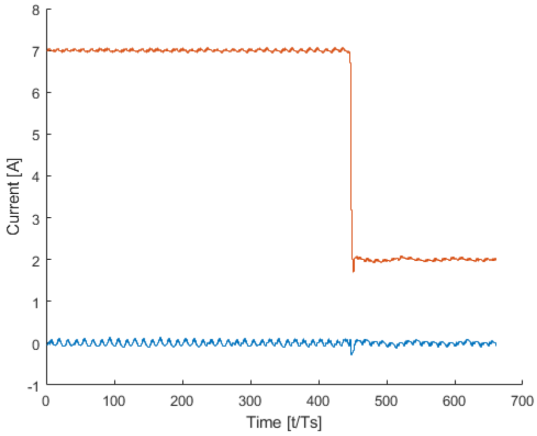

Fig. 21. Sim.step response: benchmark (7A-¿2A).

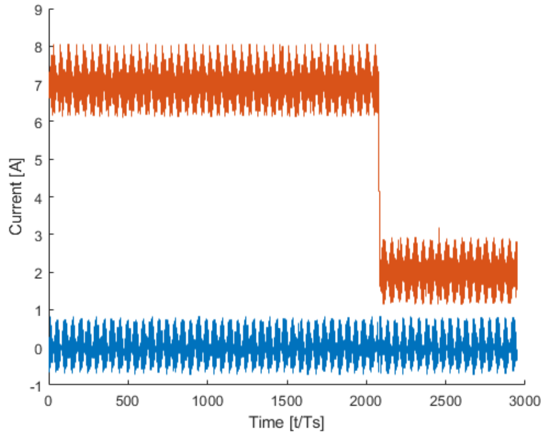

Fig. 22. Sim. step response: UR=8 no MAF $\alpha = 0.2$.

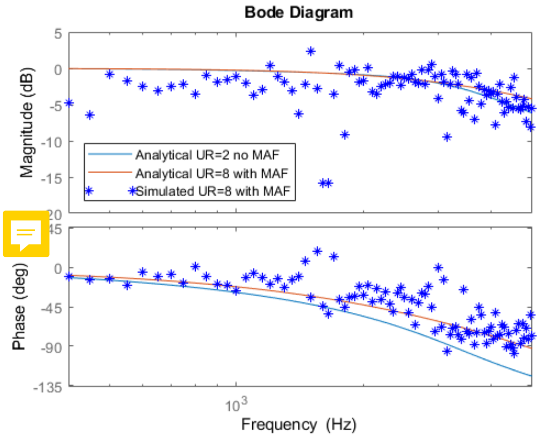

Fig. 23. Sim. closed-loop FRA: UR=8 no MAF $\alpha = 0.2$.

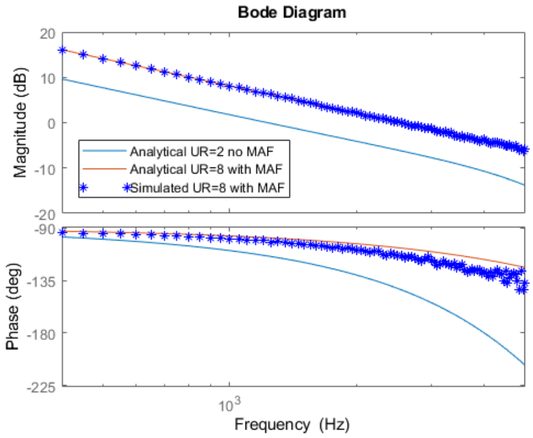

Fig. 24. Sim. open-loop FRA: UR=8 no MAF $\alpha = 0.2$.

Characteristics	benchmark	UR=8 no MAF $\alpha = 0.2$	
	analytical	analytical	simulated
$f_c[kHz]$	1.2283	2.5548	2.55
$pm[°]$	66.068	72.7824	66.5165
$f_{bw} - 3dB[kHz]$	3.5105	3.9467	3.85

Table 6. Our controller without MAF: FRA open & closed loop performance.

4 References

[1] S. Vukosavic, Grid Side Converters - Design and Control, Springer, 2018.

[2] S. N. Vukosavić, L. S. Perić and E. Levi, "A Three-Phase Digital Current Controller With Improved Performance Indices," in IEEE Transactions on Energy Conversion, vol. 32, no. 1, pp. 184-193, March 2017, doi: 10.1109/TEC.2016.2606663.