# Digital Control in Power Electronics

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

## <u>Simulation results</u>

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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 $\alpha$ 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, $\alpha$=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.
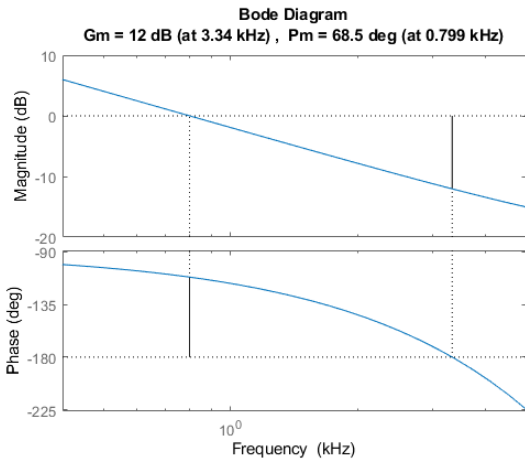


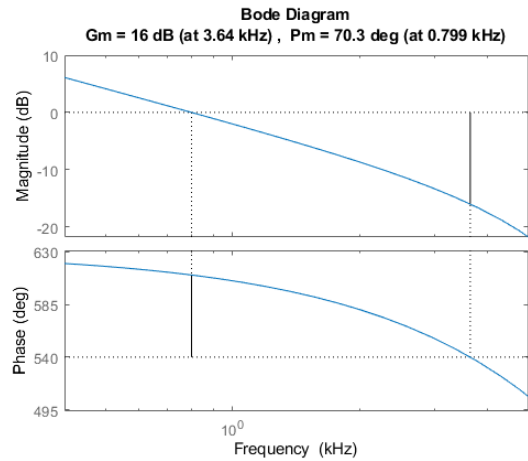Fig. 1. Open-loop Bode plots: UR=2 no MAF $\alpha = 0.25$.



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 |

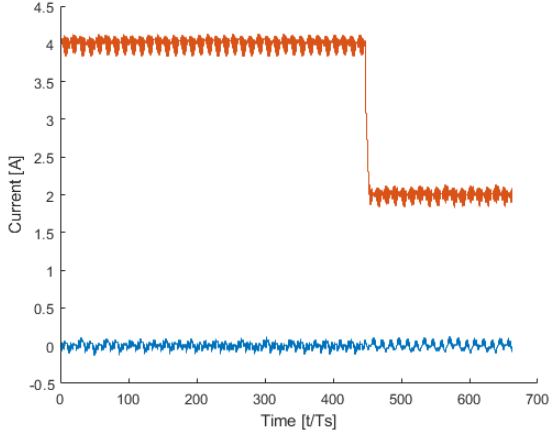Table 1. Our controller: Step response characteristics.

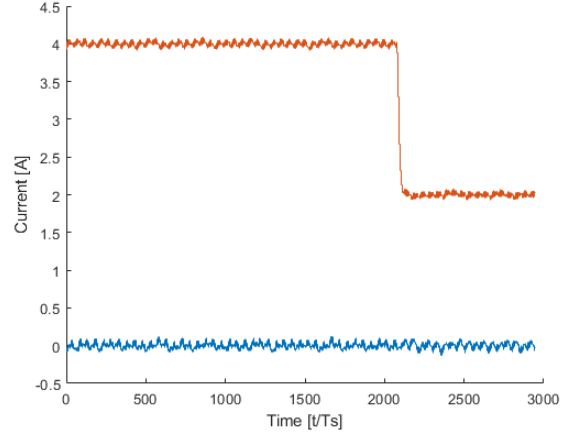Fig. 3. Sim.step response: UR=2 no MAF $\alpha = 0.25$.



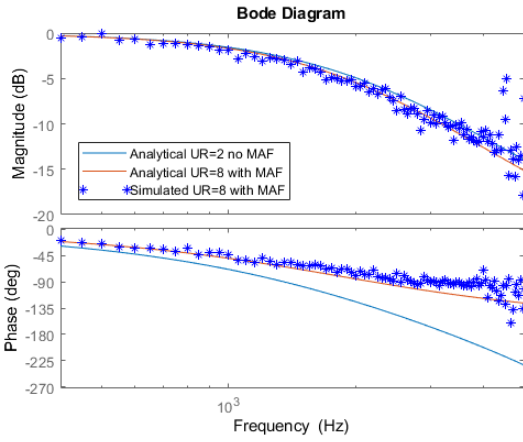Fig. 4. Sim. step response: UR=8 with MAF $\alpha = 0.0636$.



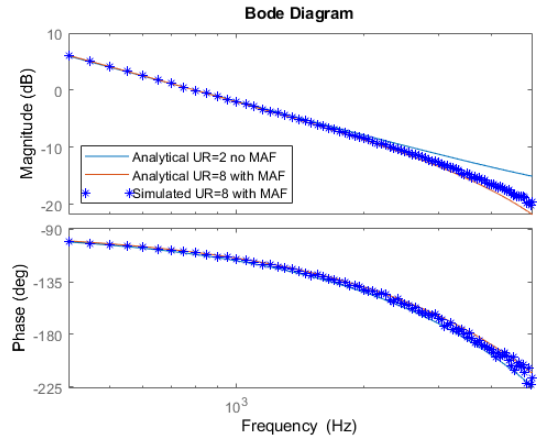Fig. 5. Sim. closed-loop FRA: UR=8 with MAF $\alpha = 0.0636$.



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 | 800 |
| $pm[°]$ | 68.4572 | 70.2667 | 70 |
| $f_{bw} - 3dB[kHz]$ | 1.4607 | 1.3871 | 1.35 |

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 $(\alpha, d)$ 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.
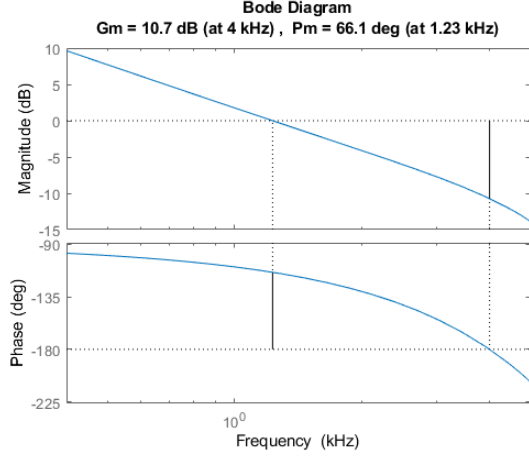


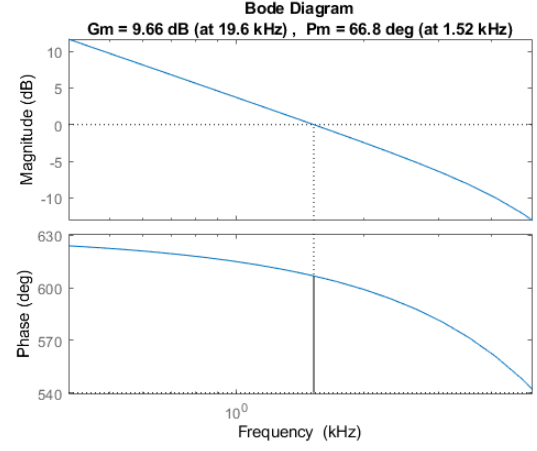Fig. 7. Open-loop Bode plots: benchmark.
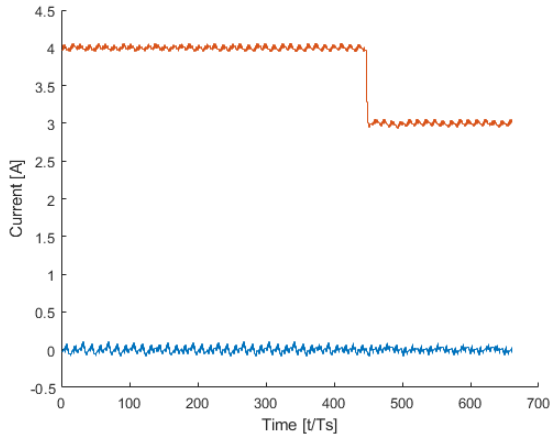


Fig. 8. Open-loop Bode plots: our dif. controller.
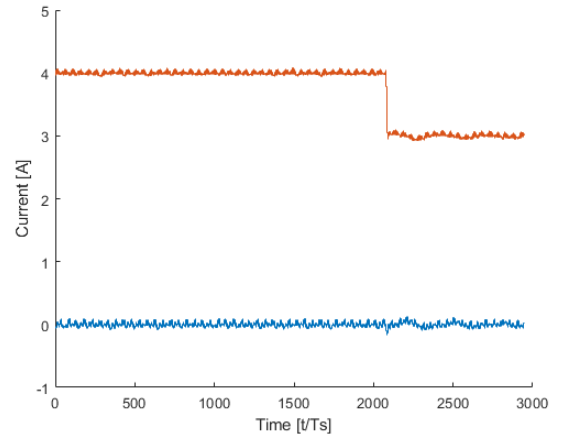


Fig. 9. Sim.step response: benchmark.
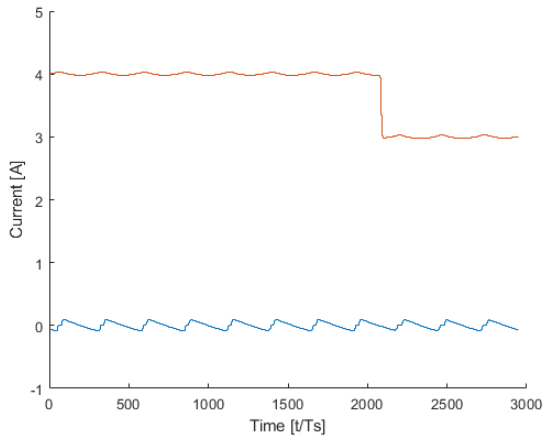


Fig. 10. Sim. step response: our dif. controller.



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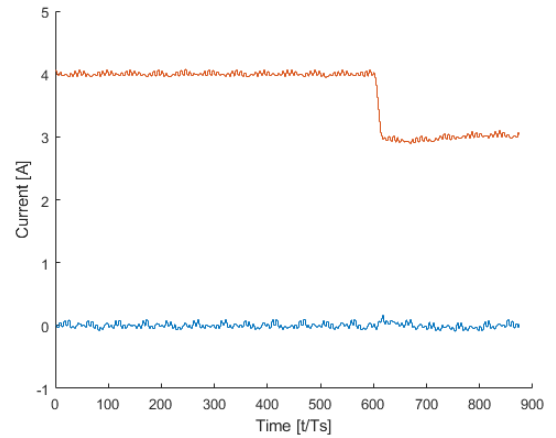


Fig. 12. Sim. step response with Rs=3*Rs: our dif. controller.

| 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 |

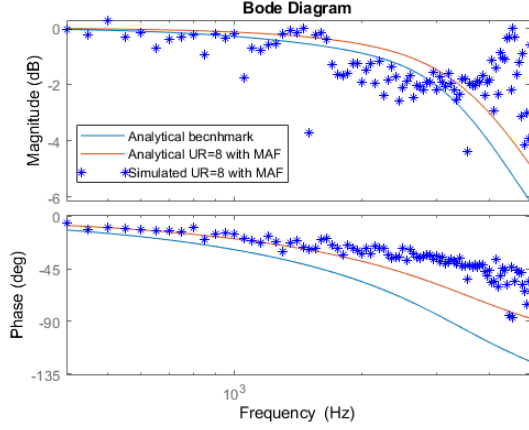Table 3. Our dif. controller: Step response characteristics.



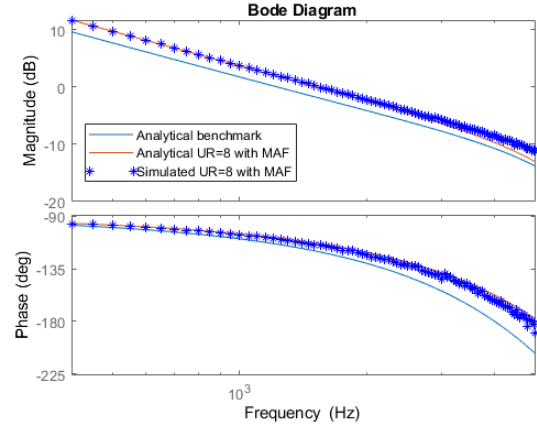Fig. 13. Sim. closed-loop FRA: our dif. controller.
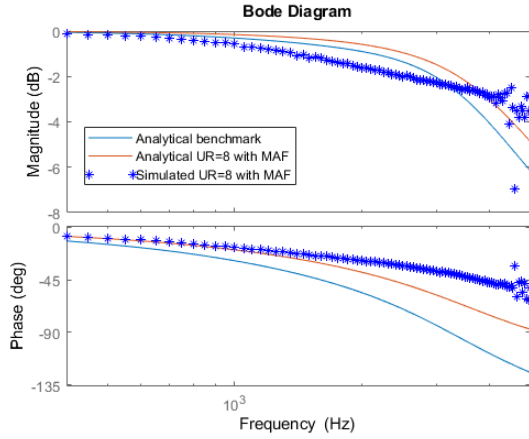


Fig. 14. Sim. open-loop FRA: our dif. controller.



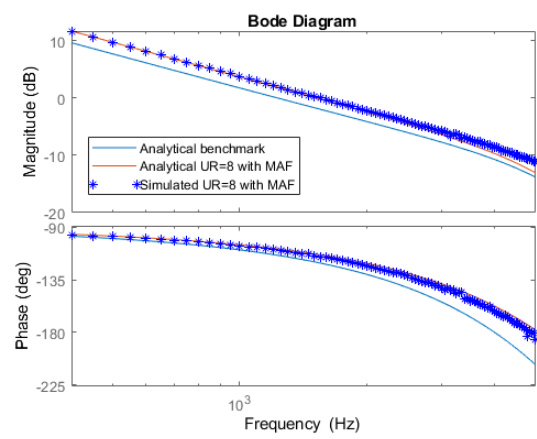Fig. 15. Sim. closed-loop FRA at 50Hz: our dif. controller.



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

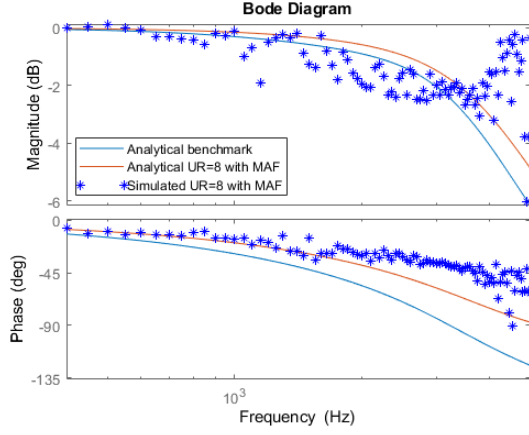| Characteristics | benchmark | UR=8 with MAF $\alpha = 0.12038, d = 2.1948$ | | | |
|---|---|---|---|---|---|
| | analytical | analytical | simulated | | |
| | | | fe=270Hz | fe=50Hz | Rs=3*Rs |
| $f_c[kHz]$ | 1.2283 | 1.5209 | 1.55 | 1.55 | 1.55 |
| $pm[°]$ | 66.068 | 66.838 | 65.135 | 64.9 | 65.633 |
| $f_{bw} - 3dB[kHz]$ | 3.5105 | 3.9846 | 4.1 | 4.3 | 3.8 |

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

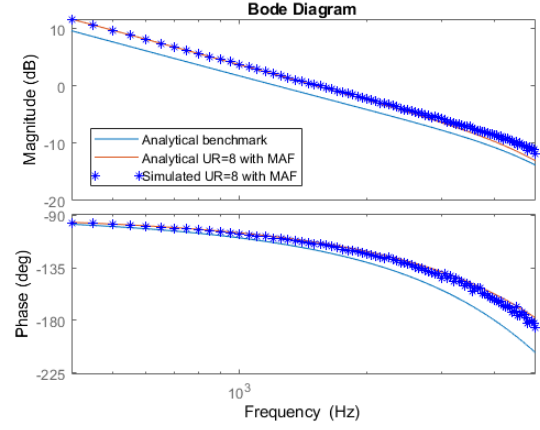Fig. 17. Sim. closed-loop FRA with Rs=3*Rs: our dif. controller.



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 $\alpha$ 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.
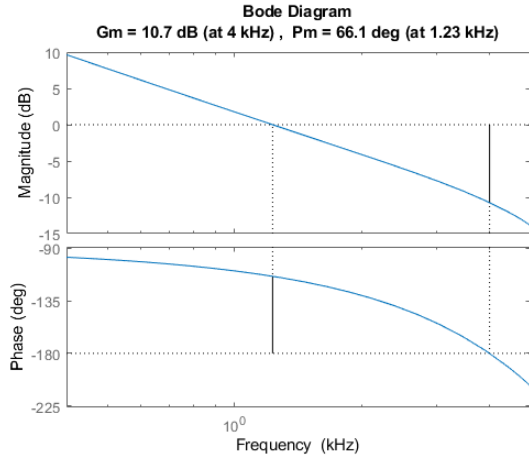


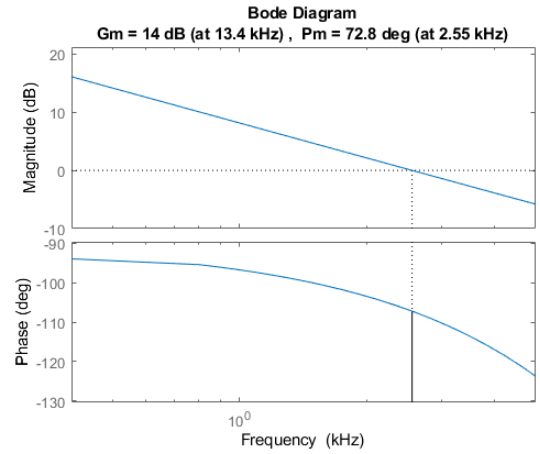Fig. 19. Open-loop Bode plots: benchmark.



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 |

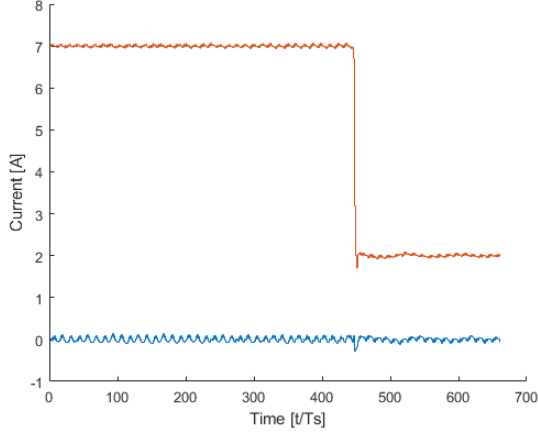Table 5. Our controller without MAF: Step response characteristics.

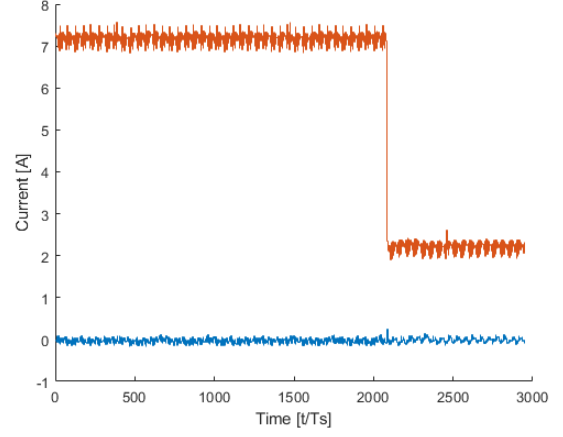Fig. 21. Sim.step response: benchmark (7A-¿2A).



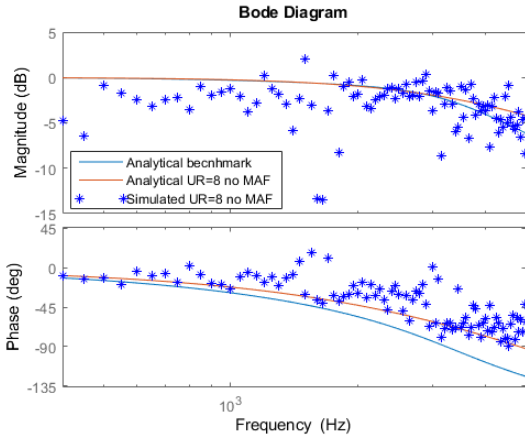Fig. 22. Sim. step response: UR=8 no MAF $\alpha = 0.2$.



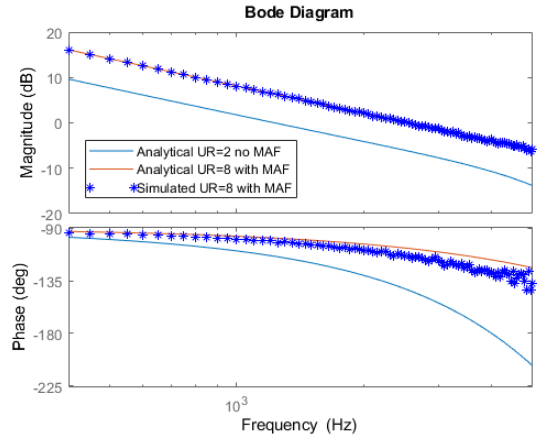Fig. 23. Sim. closed-loop FRA: UR=8 no MAF $\alpha = 0.2$.



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.