Feedback Control Design Report

“Advanced Electric Drives and Power Converter Systems” – Digital Automation Engineering

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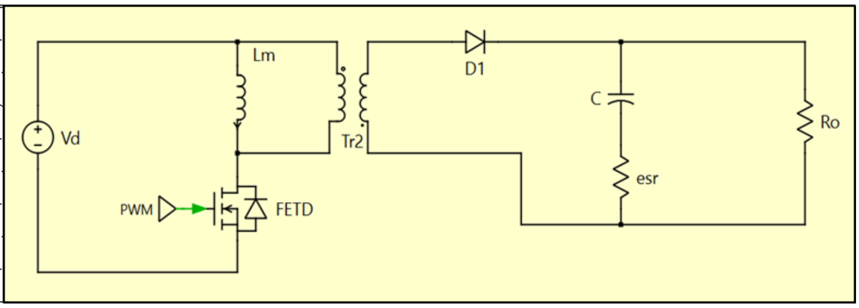
1. Introduction

Building upon the validated design from the previous project, this work focuses on implementing a current mode control strategy for the flyback converter. The reference signal for the current loop is set to the peak inductor current, obtained from the simulation of the converter operating under voltage mode control. Following this, a Type 2 compensator is designed to shape the system's response, ensuring adequate stability margins. The compensator is tuned to achieve a desired phase margin and gain margin, while targeting a specific crossover frequency. The final step involves closing the feedback loop, verifying the system’s frequency response, and ensuring that the converter operates efficiently within the expected stability criteria. The converter’s design data, topology and required feedback stability specifications are shown below:

- Crossover frequency: $f_c = 500 \div 700\ Hz$
- Feedback stability: Phase margin $> 45°$ - Amplitude margin $> 10\ dB$

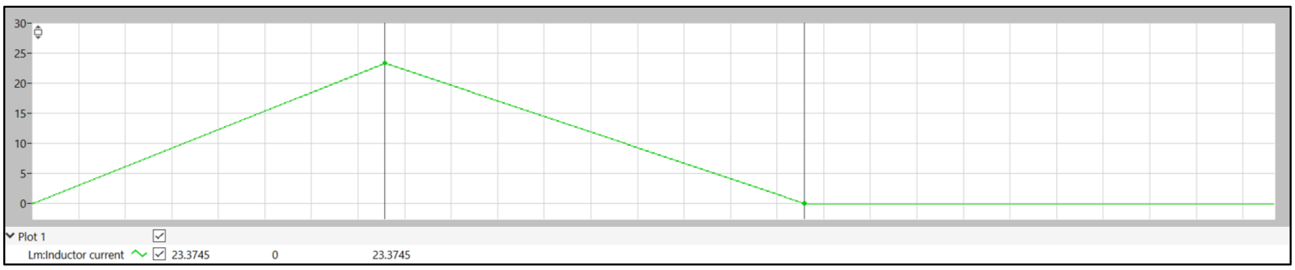
Flyback design data

Input Voltage	*15 V*
Output Voltage	*19 V*
Rated Power	*50 W*
Switching frequency	*75 kHz*
C	*1.662e-4 F*
Lm	*2.43e-6 H*
N1	*4*
N2	*6*
Dmax	*0.45*



2. Open loop: Voltage Mode Control

The very first step consists of evaluating the peak current on the converter inductance at rated operating point. As previously said this measurement comes from the simulation carried out using voltage mode control PWM. At rated power, imposing a duty cycle $D = 0.284$, the following current waveform was obtained:



The peak current on the inductor at rated operating point is $I_{pk} = 23.37\ A$.

3. Open loop: Current Mode Control

Current mode control is implemented to directly control the peak inductor current, with the duty cycle emerging as a byproduct of this process. This allows to obtain a first order system, basically canceling out the pole associated to the inductor dynamics. To analyze the system behavior under this control scheme, a small perturbation to simulate an overload or more in general a disturbance is introduced, and the response is observed. Performing an impulse response analysis allows obtaining the converter transfer function specific to current mode control, providing insight into system stability.

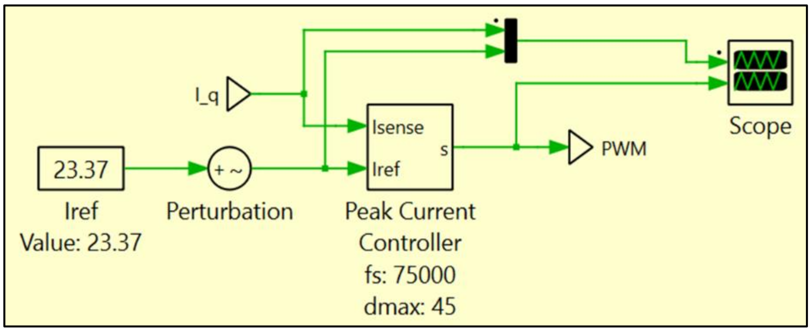


Figure 1. Current mode control scheme

The Bode diagrams obtained from the impulse response analysis are the following ones:

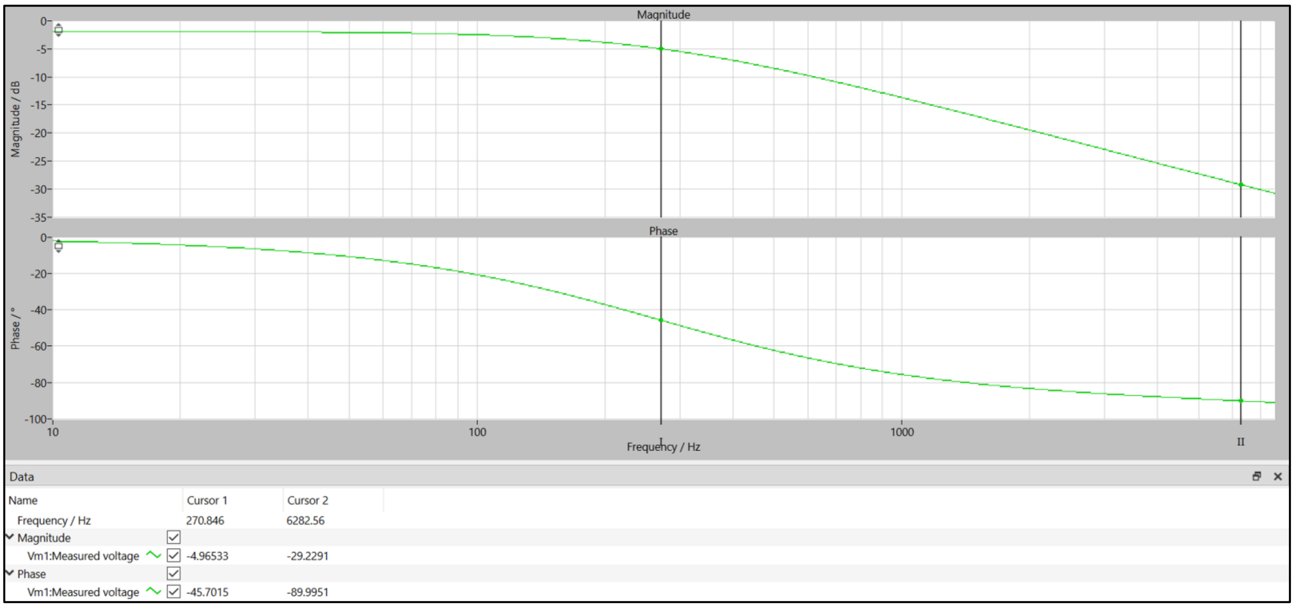


Figure 2. Flyback Bode diagrams in Current Mode Control and DCM operation

From the diagrams, it is possible to verify that the transfer function $G(s)$ of the flyback converter exhibits just a dominant pole, which aligns with the expected frequency behavior of this converter operating in DCM. By using cursors, it is possible to determine the dominant pole frequency, which is approximately $\omega_p = 2\pi * 270\ Hz = \ 1696.5\, rad/s$. The open-loop gain is actually yet negative at low frequencies, meaning the system is naturally stable. To improve dynamic response and set crossover frequency at a target value a compensator is needed.

4. Type 2 Compensator design

The type 2 compensator design has the objective of shaping the dynamics response of the system by combining the effects of a PI controller and a high-frequency pole. The proportional term of the PI controller compensates the open-loop gain, a pole in the origin is needed to reduce error at steady state. A high-frequency pole allows attenuating the loop gain at high frequencies, namely attenuating noise and disturbances; in this case, it is set at half PWM switching cycle ($\omega_{hf} = 2\pi * 37.5\ kHz$). The loop-gain transfer function is therefore given by: $L(s) = C(s) * G(s)$.

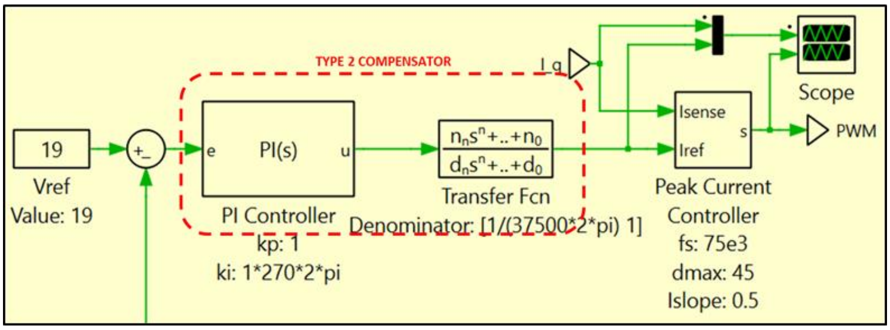


Figure 3. Type 2 Compensator

To compute the values of the proportional and integral terms of the PI controller, and be able to adjust them in order to target a desired cross over frequency, a starting step is carried out by setting:

$$K_P = 1 \qquad K_I = K_P * \omega_{zc} = 1 * \omega_p = 1696.5\ rad/s$$

This hypothesis holds since the actual dominant pole frequency is lower than the targeted crossover ($\omega_p = 270\ Hz \ll 500 \div 700\ Hz$). In this way it is possible to lift up the loop gain transfer function being able to evaluate the compensatory action needed to target a specific crossover frequency. A loop gain meter is needed to measure the loop gain. From this moment the desired output voltage is used as a reference and the discrepancy at output is fed to the compensator. Once the loop is closed it is possible to perform an AC Sweep analysis and observe the Bode's diagrams obtained in this first control design:

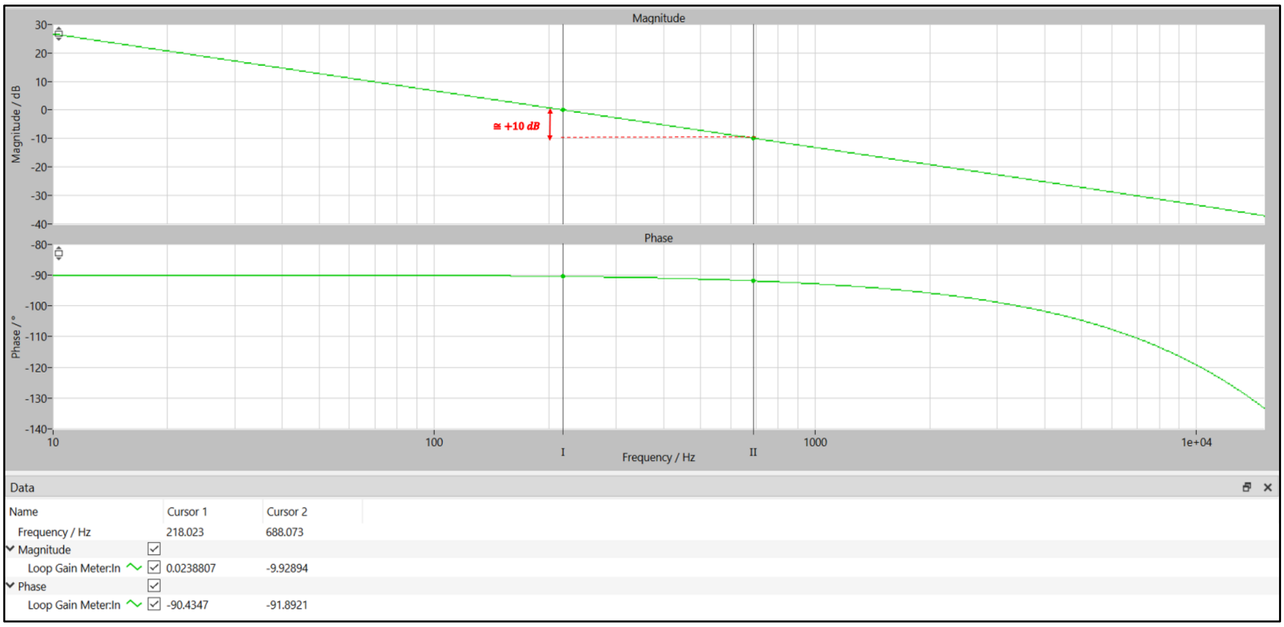


Figure 4. First AC Sweep Analysis with Kp = 1

The amplitude diagram shows that crossover frequency happens at approximately 218 Hz. As a first instance, it is possible to target a new desired crossover frequency $\omega_{cr} = 2\pi * 688\,Hz$. The compensator has to compensate with $G_{mid} \cong 10\,dB$ to achieve the target crossover. Knowing that, it is possible to adjust the compensator parameters as:

$$K_P = 10^{\left(\frac{|-10|\,dB}{20\,dB}\right)} = 3.16 \qquad\qquad K_I = K_P * \omega_{zc} = 3.16 * 1696.5\frac{rad}{s} = 5364.8\frac{rad}{s}$$

Following this reasoning it is possible to target different crossover frequencies across the desired interval $(500 \div 700\,Hz)$ and assess if they satisfies the desired stability criteria in terms of phase and amplitude margins.

5. Loop gain analysis and feedback stability

The stability analysis for the feedback loop control implemented so far has been carried out targeting different target crossover frequencies, evaluating if the desired design guarantees stability criteria. The tab below shows the compensator parameter computed for each target crossover frequency:

	Target crossover frequency		
	688 Hz	**600 Hz**	**500 Hz**
G_{mid}	(+10 dB)	(+8.8 dB)	(+7.25 dB)
ω_{zc}	1696 rad/s	1696 rad/s	1696 rad/s
K_P	3.16	2.75	2.30
K_I	5364.8 rad/s	4672.5 rad/s	3908.8 rad/s

PLECS Simulation

$\omega_{zc} = \omega_p$

The results of the AC Sweep analysis carried out for each scenario are below reported and evaluated in terms of stability margins:

- ***fcr* = 688 Hz**

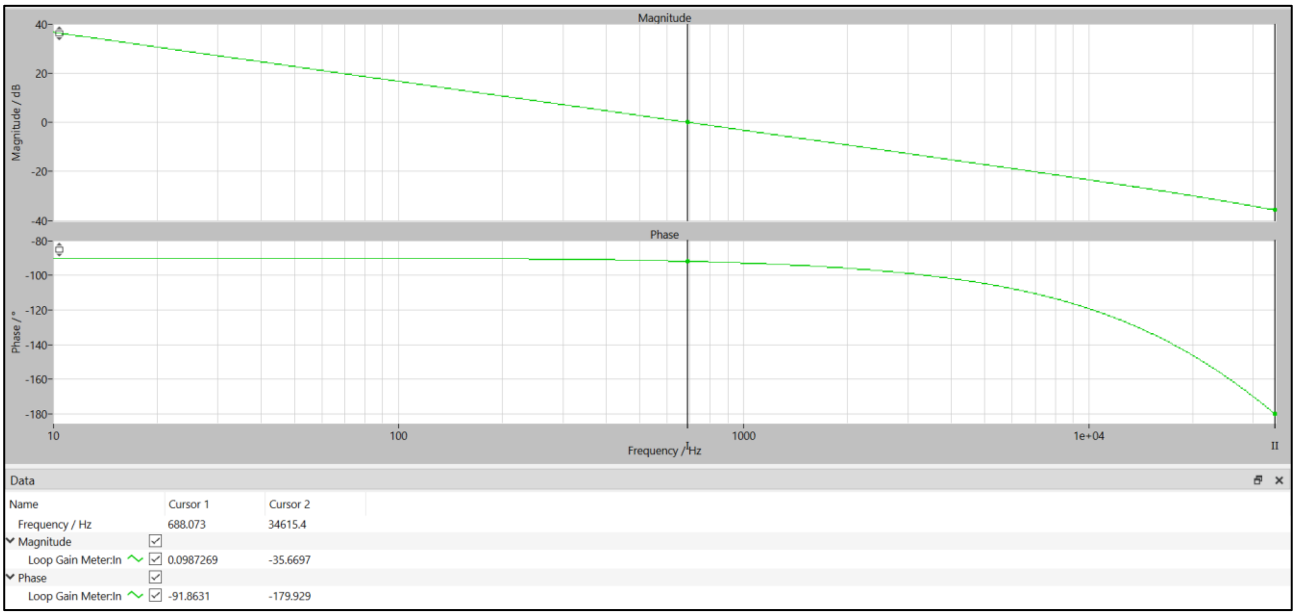


Figure 5. Loop gain TF for target crossover frequency of 688Hz

As can be deduced by both phase and amplitude diagrams, stability margins are far beyond satisfied, the phase margin is $\varphi_c = 180° - 91° = 89° \gg 45°$ and the amplitude margin is higher than 30 dB.

- ***fcr* = 600 Hz**

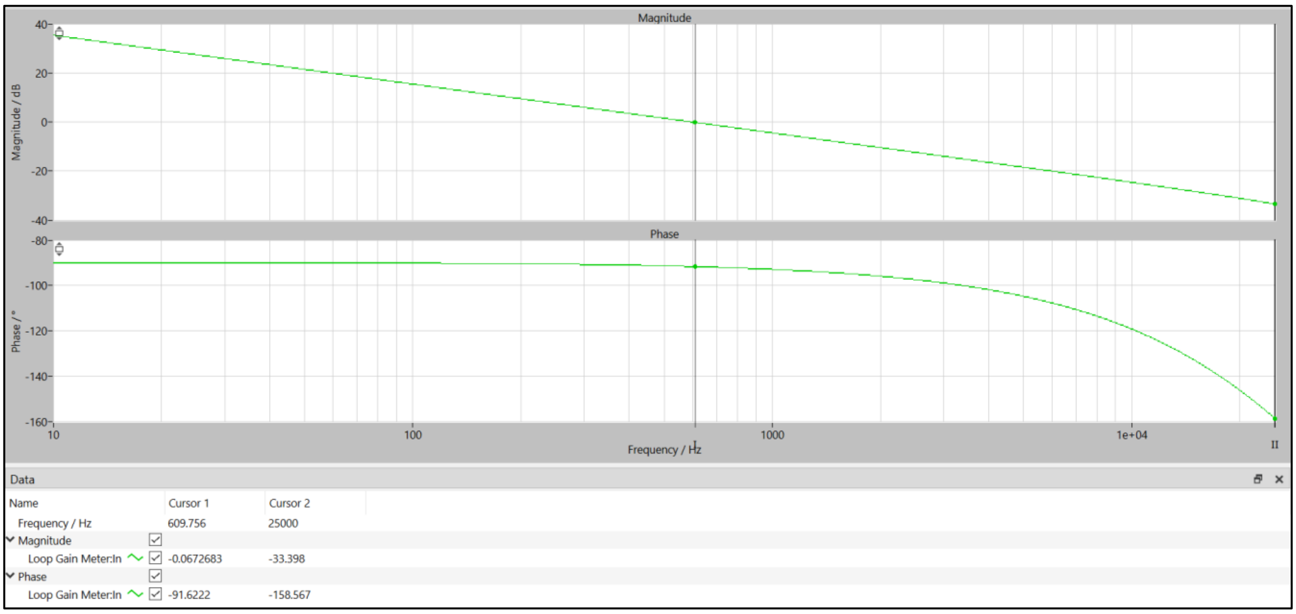


Figure 6. Loop gain TF for target crossover frequency of 600Hz

Targeting a crossover frequency of nearly 600 Hz, an actual 609 Hz frequency is met, which can be considered as a fair approximation. The loop-gain transfer function shows sufficient margins, it is not possible to visualize the point at -180° phase but stability is ensured by the fact that the transfer function it is not increasing and the margin is already satisfied at -160° phase.

- ***fcr* = 500 Hz**

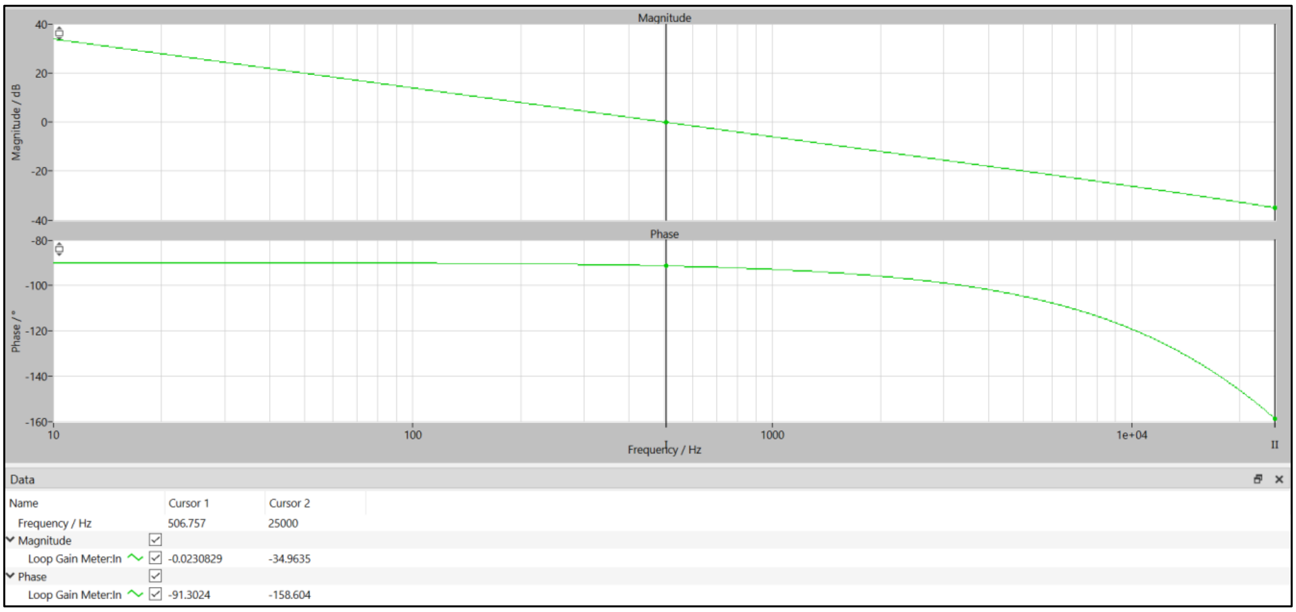


Figure 7. Loop gain TF for target crossover frequency of 500Hz

Even targeting a crossover frequency of nearly 500 Hz the system guarantees wide stability margins for both amplitude and phase. The exact crossover frequency is 506 Hz, which again may be a fair approximation. This is quite expected since the converter was already showing a stable behavior (attenuation at low frequency) without considering the effect of the type 2 compensator.

The desired output voltage is met at rated operating point and it remains nearly constant at steady state. The following waveforms are referred to this last scenario ($f_{cr} = 500\,Hz$), but same performances hold for the other ones:

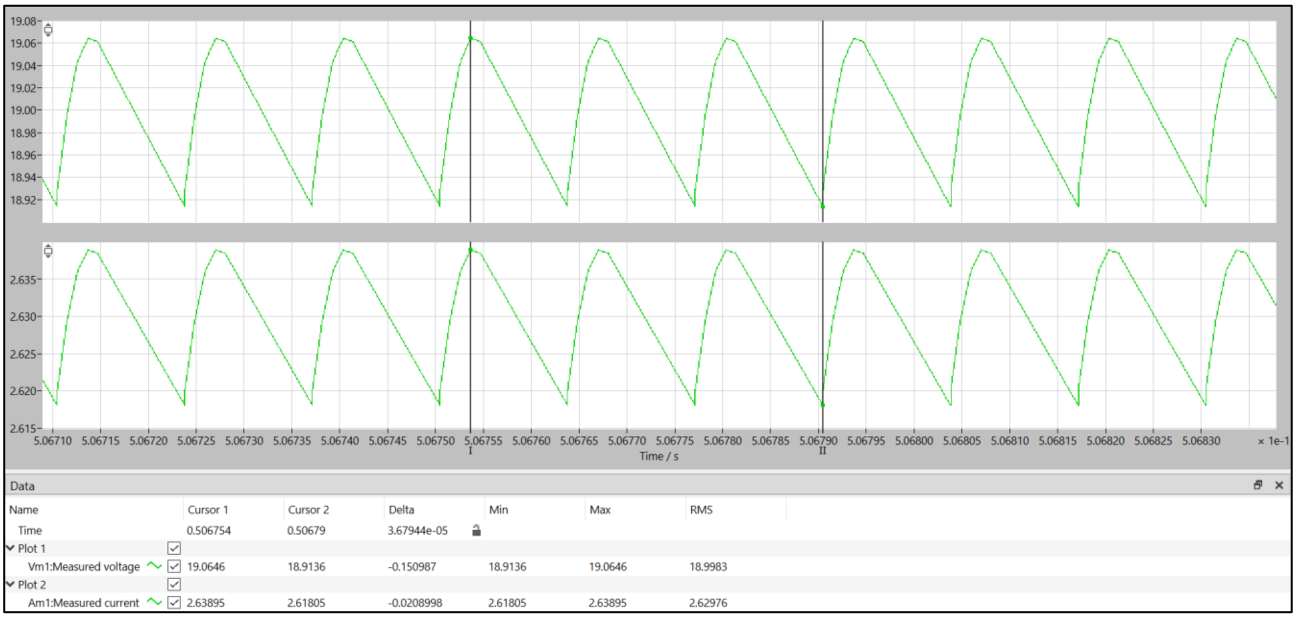


Figure 8. Output Voltage and current in feedback-loop current control mode

The current controlled feedback loop implemented so far appears to be operating as intended. Must be stressed that, since the control loop is based on linearization around a specific operating point, those results – especially those related to stability – are only valid for the considered operating point and may just hold for very small variation around it.