Final Exam Project Advanced Power Electronics

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24/552146/PTK/16435

Task 1

In this task, we should design and specified all the parameter of given a synchronous buck converter, as shown in Figure 1, thus it could meet the specified ripple current and could keep the performance within load variation scenarios.

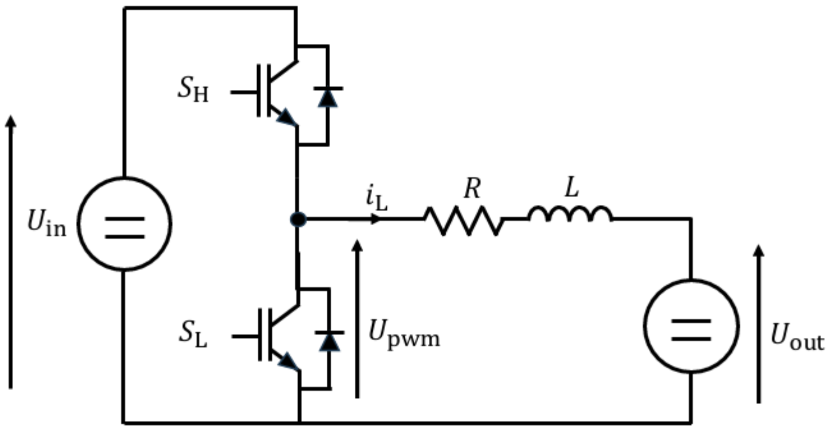

Figure 1 Synchronous Buck Converter

1.1 Operation range of topology

There are four quadrant operation of a converter, as shown in Figure 2. Operation in Quadrant I give positive voltage and positive current, usually for motoring or forward power flow. Operation in Quadrant II give positive voltage and negative current (acting as a load), thus could be used to perform regenerative braking and reverse power flow. In Quadrant III, converter give negative voltage and negative current, thus could perform reverse motoring. In Quadrant IV, converter give negative voltage and positive current, thus could be used to perform reverse braking. The synchronous buck converter operates only in a **single quadrant** (quadrant I: positive voltage and positive current) as a step-down power source. The output voltage is always positive and lower than the input voltage, while the current flows from the converter to the load (it acts as a power source).

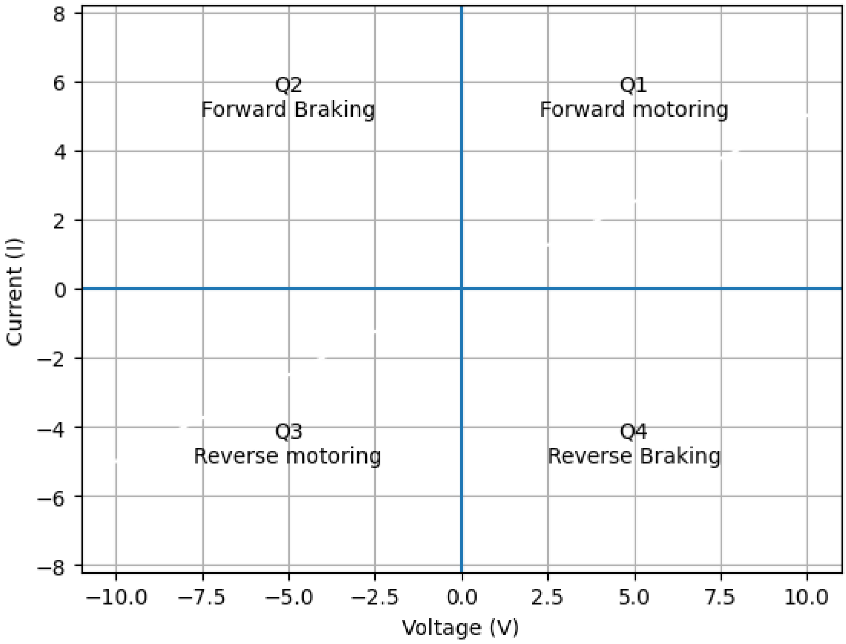

Figure 2 Four-Quadrant Operation of Converter

1.2 Steady-state duty cycle required

For a synchronous buck converter that operates in continuous conduction mode (CCM) and have a perfect efficiency, the duty cycle (d) is just simply ratio between output voltage (V_{out}) and input voltage (V_{in}), as given in (1).

$$d = \frac{V_{out}}{V_{in}} \tag{1}$$

1.3 PWM and Inductor Voltage waveform

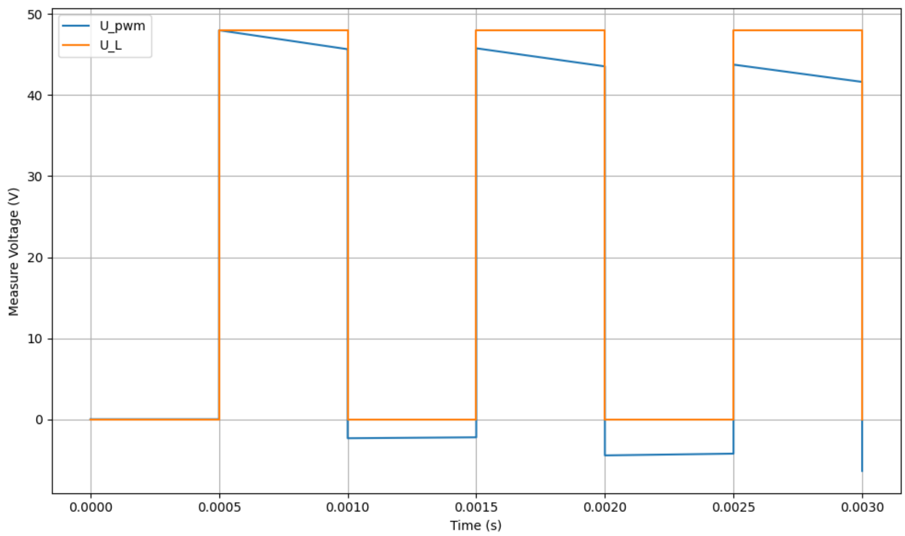

Figure 3 PWM and Inductor Voltage Waveform over three switching cycles

1.4 Relation between voltage and current ripple in inductor

In steady-state, these two quantities are linked by the fundamental principle of Inductor Volt-Second Balance. The voltage across an inductor (v_L) and the change in its current (i_L) are related by Faraday's Law of Induction:

$$v_L(t) = L\frac{di_L(t)}{dt} \tag{2}$$

From this formula, we can see that the instantaneous voltage determines the slope of the inductor current. Then, the inductor ripple current (Δi_L) is the result of applying a specific voltage across the inductor for a specific duration of time.

In steady-state operation, the average voltage across the inductor over a full switching period (T_s) must be zero. This is known as the Inductor Volt-Second Balance.

$$\langle v_L \rangle = \frac{1}{T_s}\int_0^{T_s} v_L(t)dt = 0 \tag{3}$$

If the average voltage were not zero, the current would increase or decrease indefinitely every cycle, meaning the converter would not be in a "steady" state.

1.5 Design system with customized ripple

In this section, we want to discuss about the ripple in the inductor current and what is the mathematical expression that determine inductor ripple current. In the end of this section, we want to design the converter with customized ripple by determine the right inductance value.

1.5.1 Expression of current ripple

The ripple current is calculated by observing the inductor voltage during the two main switching intervals:

- **Interval 1: Switch ON (Duration $\boldsymbol{DT_s}$)**
  The inductor is connected between $V_{in}\ and\ V_{out}$.
- Inductor Voltage: $v_{L,on} = V_{in} - V_{out}$
- The current rises with a positive slope:

$$\Delta i_L = \frac{V_{in} - V_{out}}{L} \cdot DT_s \tag{4}$$

- **Interval 2: Switch OFF (Duration $\boldsymbol{(1-D)T_s}$)**
  The inductor is connected between Ground and V_{out}.
- Inductor Voltage: $v_{L,off} = -V_{out}$

- The current falls with a negative slope:

$$\Delta i_L = \frac{V_{out}}{L} \cdot (1 - D)T_s \tag{5}$$

Because the net change in current over one cycle is zero, the "area" of the positive voltage rectangle must exactly equal the "area" of the negative voltage rectangle.

1.5.2 Minimum inductance

From (4) and (5), we could determine the value of inductance to achieve our desired ripple current. The inductance value of L could be determined by rearrange (5) into (6).

$$L = \frac{V_{out}}{\Delta i_L} \cdot (1 - D)T_s \tag{5}$$

$$L = \frac{D * V_{in}}{\Delta i_L} \cdot \frac{(1 - D)}{fw} \tag{6}$$

Let we use these parameter:

V_in = 48 V

fw = 1000 Hz

D = 0.5

R_1 = 0.1 Ω

$\mathrm{R_{Load}}$ = 1000 Ω

To achieve ripple current of 5%, means that the Δi_L = $(\mathrm{V_{out}}/(\mathrm{R_{Load}} + \mathrm{R_1})) * 5\%$, then the value of L could be determined by (7). The result is a big inductance, because the switching frequency is relatively low. Once we use high switching frequency, we can minimize the value of inductor.

$$L = \frac{D * V_{in}}{(\mathrm{V_{out}}/(\mathrm{R_{Load}} + \mathrm{R_1})) * 5\%,} \cdot \frac{(1 - D)}{fw} = 10\ H \tag{7}$$

1.5.3 Inductor current waveform

Since we want the ripple current is 5% of its nominal value, then the $\Delta i_L = 1.2\ x\ 10^{-3}\ A$. Figure 4 shows us about the inductor current waveform. In Figure 5, seen that using the calculated inductance value, the ripple is 5%.

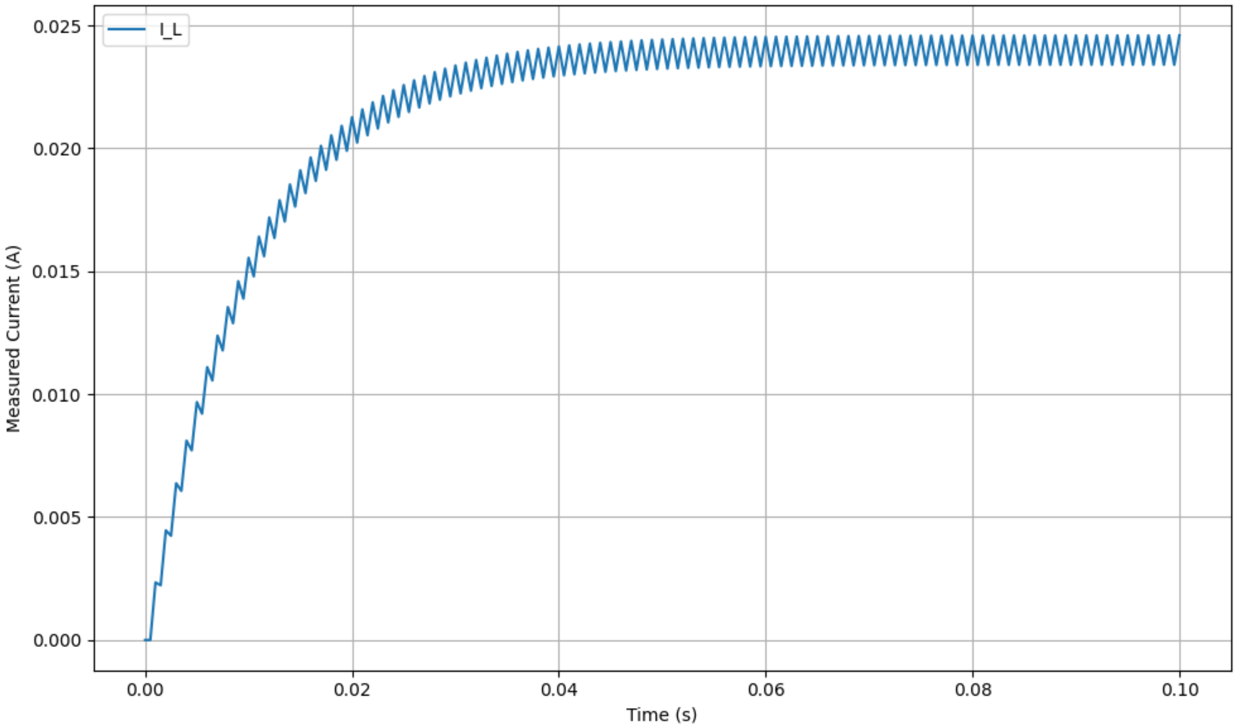

Figure 4 Inductor Current Waveform

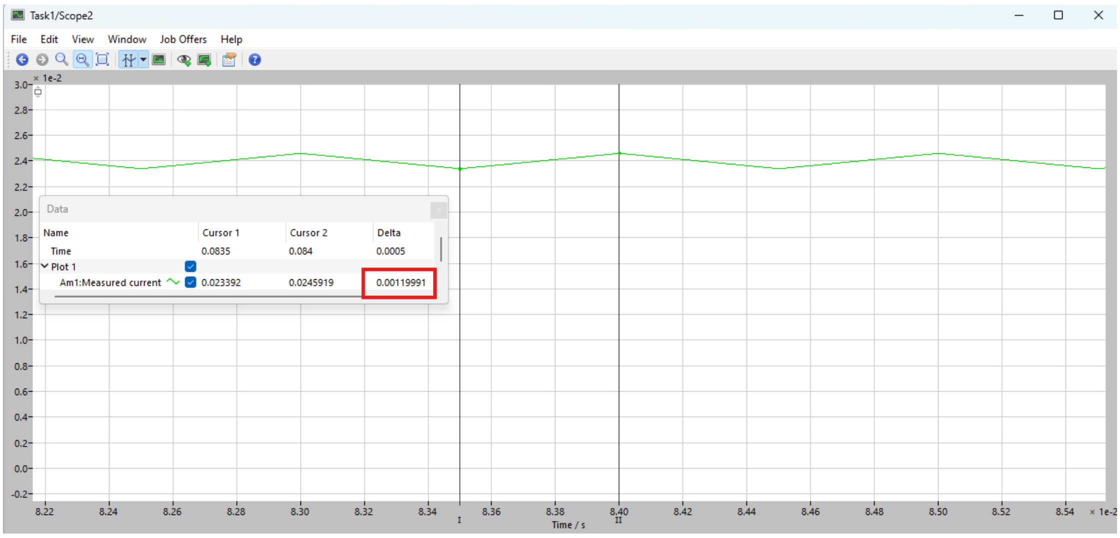

Figure 5 Ripple Current of Inductor

1.5.4 Operating condition of the system during load variation

Continous conduction mode is rely so much with comparison between average load current (I_{out}) and half of the inductor ripple current $\left(\frac{\Delta i_L}{2}\right)$. Converter is said to still in CCM Condition when $I_{out} > \frac{\Delta i_L}{2}$. If the load current I_{out} drops below half of the ripple current, the inductor current will hit zero before the next switching cycle begins, causing the converter to enter Discontinuous Conduction Mode (DCM). In Figure 4 and Figure 5, it is seen that $I_{out} > \frac{\Delta i_L}{2}$ when the load is in 100% of its nominal load. Similiarly, in Figure 6 and Figure 7, it is seen that $I_{out} > \frac{\Delta i_L}{2}$ when the load is in 75% of its nominal load. Also, in Figure 4 and Figure 5, it is seen that $I_{out} > \frac{\Delta i_L}{2}$ when the load is in 25% of its nominal load. So, with the variation of load, converter is still in the CCM mode.

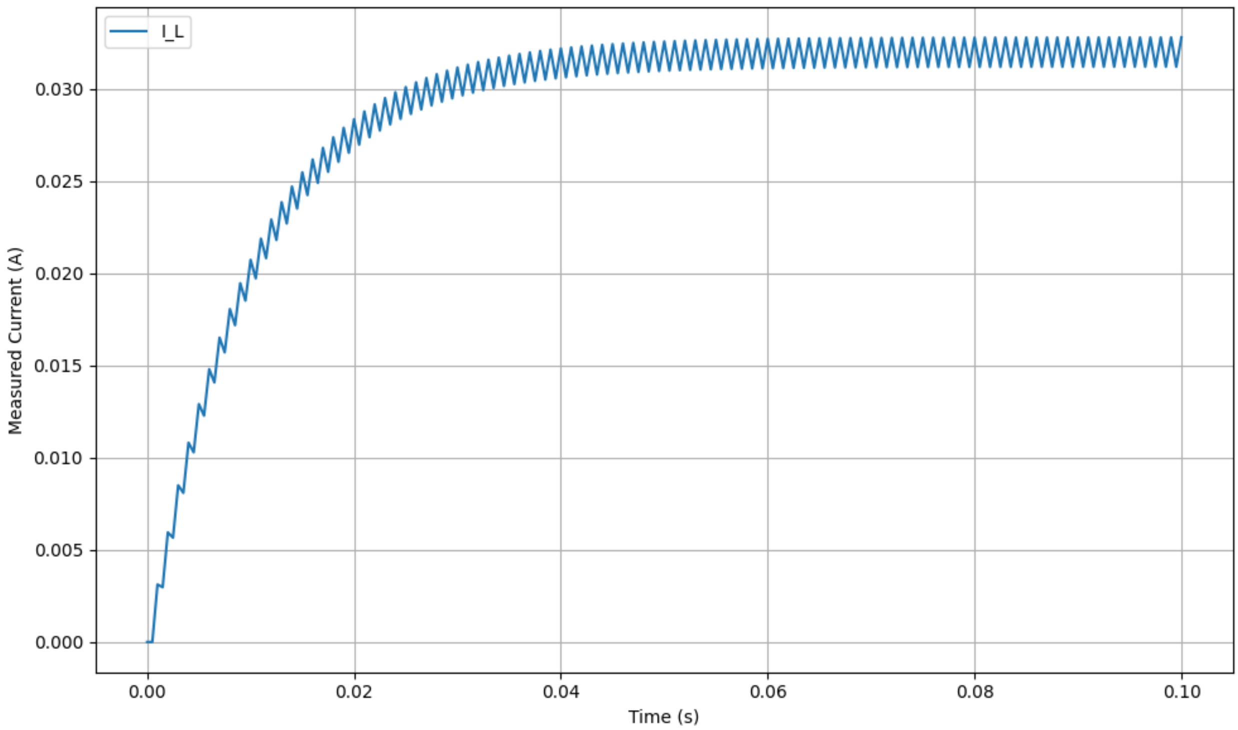

Figure 6 Inductor Current Waveform in 75% Load

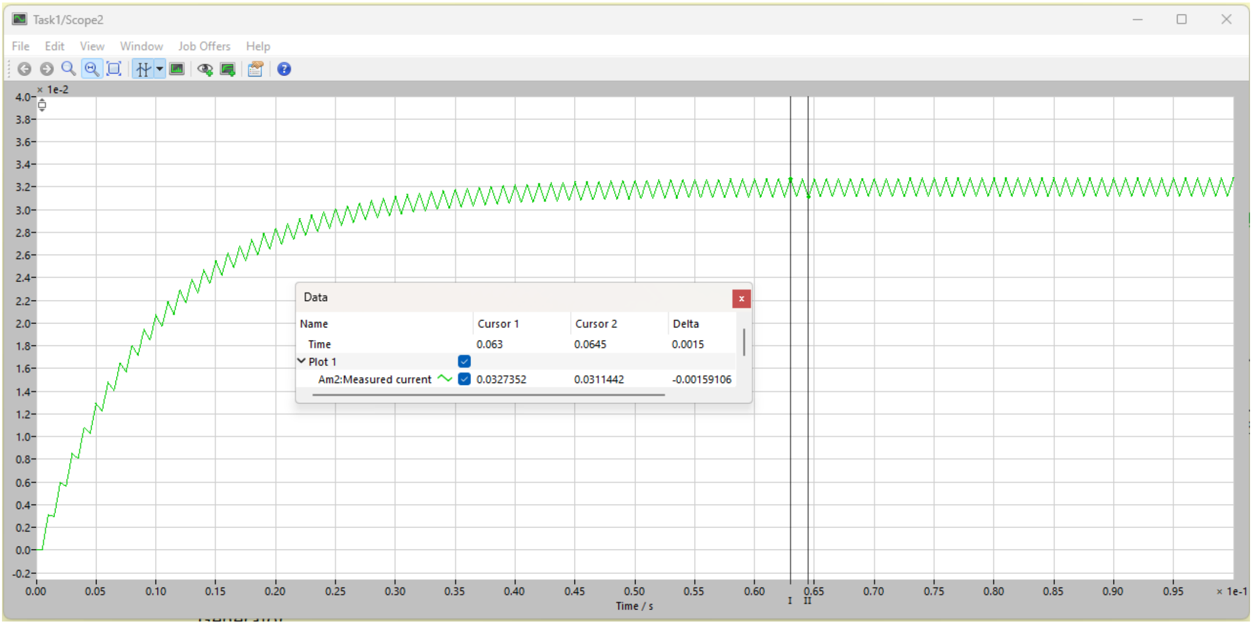

Figure 7 Ripple Current of Inductor in 75% Load

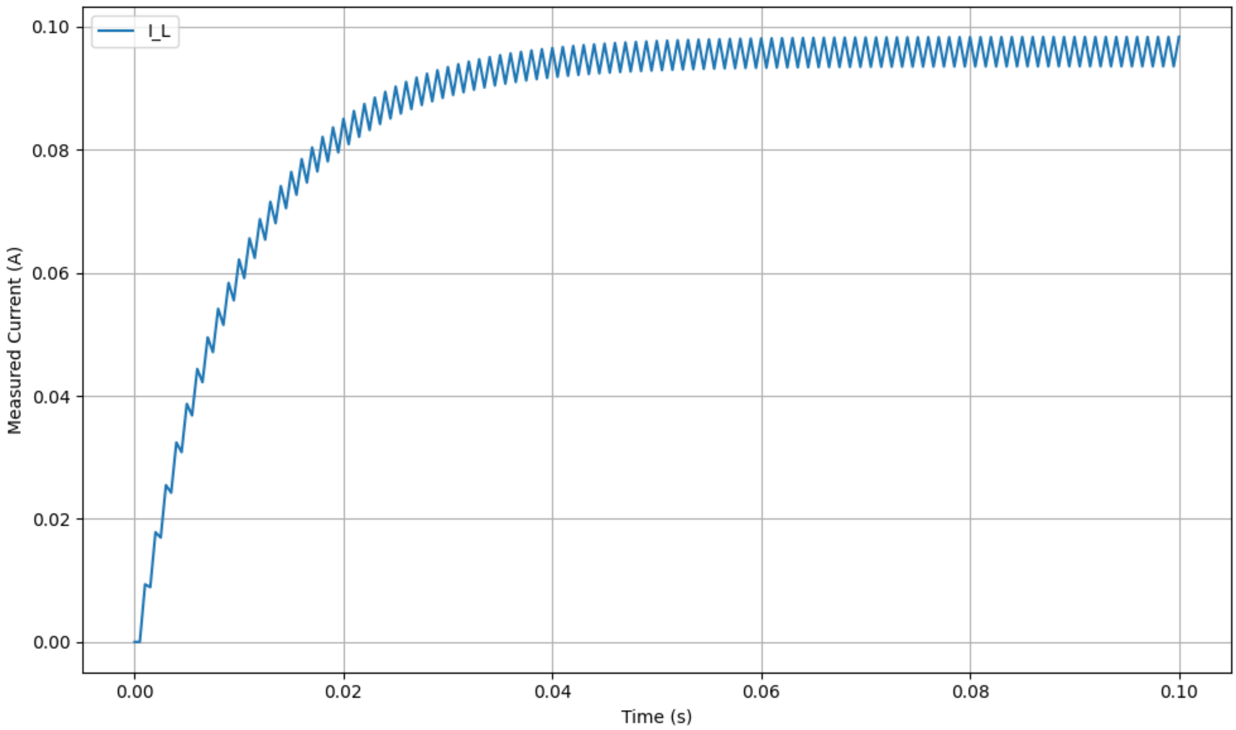

Figure 8 Inductor Current Waveform in 25% Load

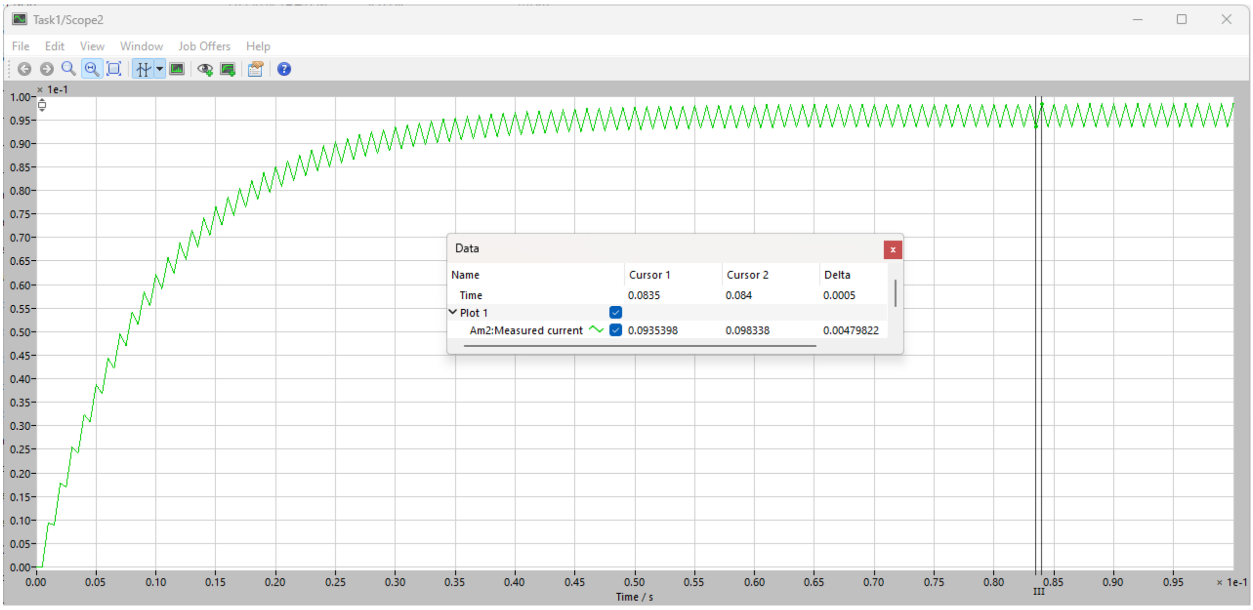

Figure 9 Ripple Current of Inductor in 25% Load