Memo

HOLLANDER RESEARCH
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Topic: High frequency oscillations measured with high bandwidth current sensors at low current

Tested: Pearson 2878 and SDN-414 shunts with different resistance values

Date: 2014 April 11th

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1 Summary

1.1 Introduction

A comparison was made between the responses of two types of current sensors when used in a fast switching commutation circuit.
The wide bandwidth current transformer (type Pearson 2878) benefits from the fact that it does not galvanically connect the power circuit to the oscilloscope, but it adds considerable leakage inductance because of its geometry and its iron core.
The shunt (type T&M Research, SDN-414-50, 50 mΩ) benefits from a very low added leakage inductance, but it galvanically connects the power circuit to the oscilloscope.
A simple patch test setup was made to compare the response of both sensor types. A commutation circuit was made operating at low voltage for ease of experimenting. Not much attention was paid to its construction to minimize parasitic elements since the patch test circuit was intended to make a 1-to-1 comparison of both current sensor types. So possible oscillations resulting from the test setup would be measured by both sensors.

The waveform as measured by the 50 mΩ shunt showed a high frequency oscillation that was not observed on the waveform as measured by the wide bandwidth current transformer.

1.2 Experiments

A number of experiments were performed to investigate if the oscillation was due to actual current present in the circuit and running through the sensors. Or if the observed oscillation was due to other effects in the measurement setup for which the shunt is more sensitive than the current transformer.

1.3 Conclusion

The conclusion from the experiments described in this memo is that the high frequency signal as initially observed was mainly due to the radiated EMI-field generated by the load coil and its connecting wires and to a minor extend due to other parts in the circuit. The immunity of the shunt, in the way it was used in the patch test setup, for this external EMI-field was not as good as for the current transformer that was less sensitive for this external EMI-field.

After some relative simple improvements to the EMI performance of the patch test setup, both sensor types showed similar good performance for fast switching current signals at low amplitude (relative to the maximum current rating of the sensors).

2 Measurement setup

The measurement setup is shown in Figure 2.1, which is a commutation circuit. The IGBT and diode are rated for 1700 V, but operated only at a DC-bus voltage of only 30 V for ease of experimenting without safety concerns. Currents are up to 5 A, devices are rated for 10 A.

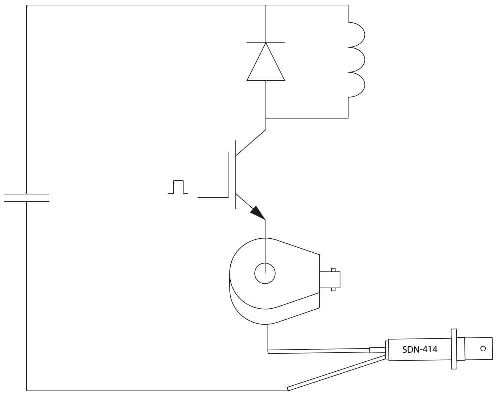


Figure 2.1 Measurement setup for testing Pearson 2878 and 50 mΩ shunt at low currents.

Both current sensor types are put in series as shown in Figure 2.2. No effort was made to minimize the parasitic capacitance in parallel to the diode and the leakage inductance in series with the IGBT. The gate driver is a ±15 V IGBT gate driver with optical signal input.

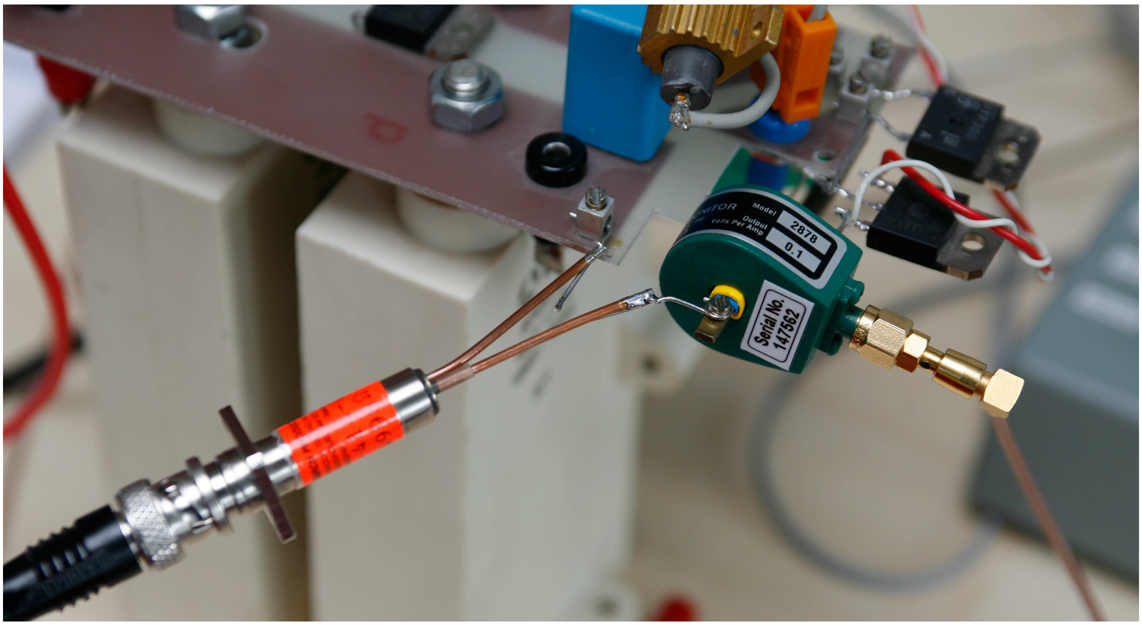
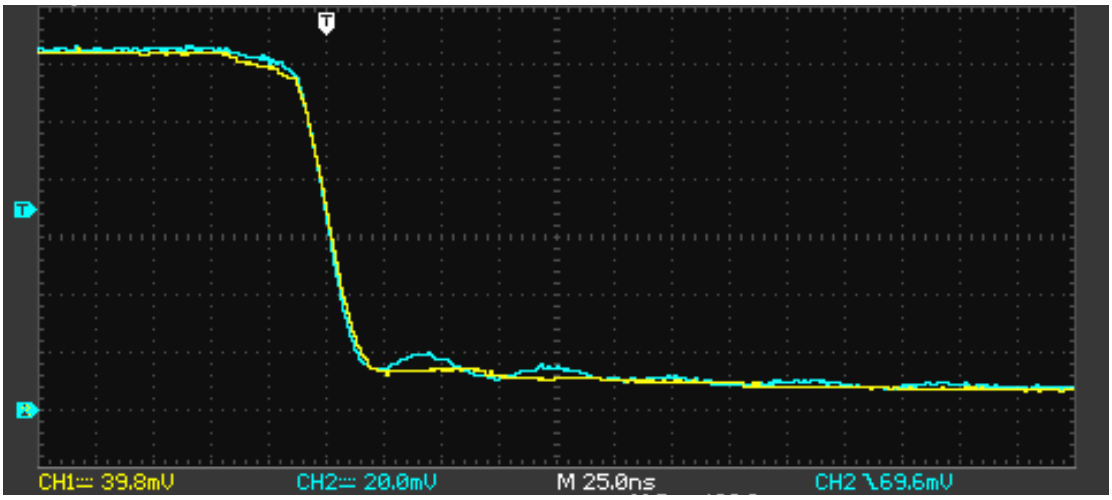


Figure 2.2 Measurement setup for testing Pearson 2878 and 50 mΩ shunt at low currents.

3 Initial result leading to question statements

The initial result of the current waveforms is shown in Figure 3.1. The switched current is 2.4 A, fall time about 30 ns.



yellow	Pearson 2878	(400 mA/div)
cyan	SDN-414-50mΩ	(400 mA/div)

Figure 3.1 Initial result of current waveforms for Pearson 2878 and 50 mΩ shunt.

The shunt shows an oscillation with a frequency of about 20 MHz on the tail current after the switching. This oscillation is not present on the response of the Pearson 2878.

The 20 MHz oscillation is within the specified measurement bandwidth of the Pearson 2878 which has the -3dB point at 70 MHz. The attenuation at 20 MHz is A = 0.95 for a single order 70 MHz system.

Question statements:

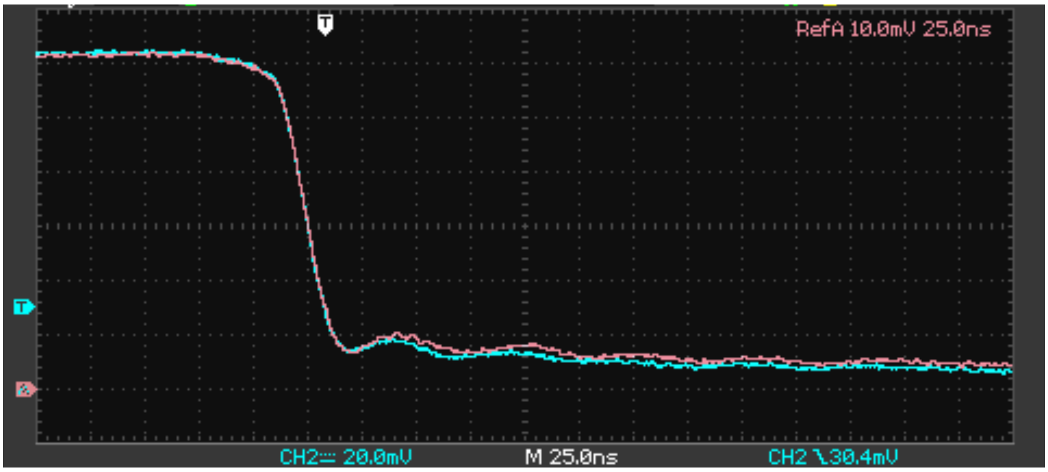
- ⇨ Do the recorded waveforms represent the actual current in the circuit?
- ⇨ Why do the responses of both sensor types differ from each other?

4 Measurements to investigate hypotheses

4.1 Connection between sensor and oscilloscope

Hypothesis: oscillation is due to common mode current, ground loops, impedance mismatch to oscilloscope.
Test approach: simplify setup by measurement on shunt only; eliminate possible common mode currents and ground loops; verify impedance matching shunt to oscilloscope.

The current at turn-off the IGBT has been measured with the SDN-414-50 shunt (Pearson removed from system). Only measurement signal to the oscilloscope is from the shunt, other inputs to the oscilloscope (LeCroy WaveAce 2024) are unused. Input impedance oscilloscope at 50 Ω.
Figure 4.1.1 compares two measurements, one at 1.2 A (10 mV/div) and the other at 2.4 A (20 mV/div) with comparable results.

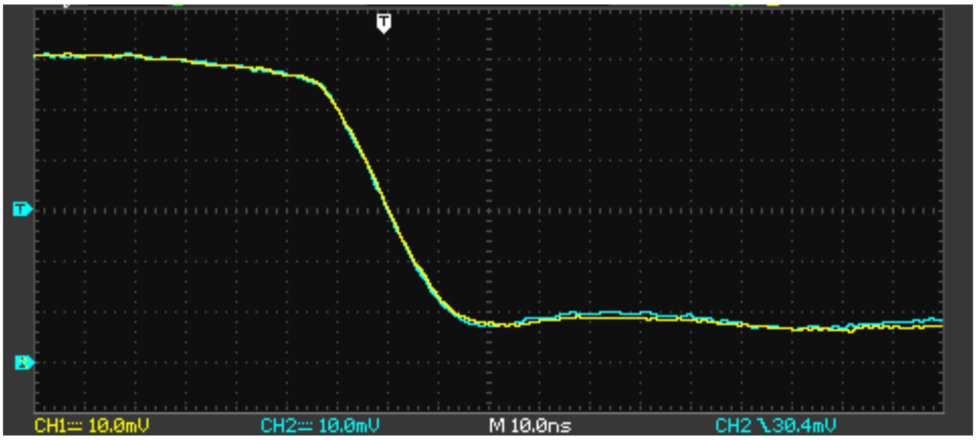


pink SDN-414-50mΩ at 10 mV/div
cyan SDN-414-50mΩ at 20 mV/div

Figure 4.1.1 Shunt signal at 10 mV/div and at double signal amplitude (recorded at 20 mV/div).

The oscilloscope is connected to the mains by a mains cable with a ferrite core, forming a common mode filter. Another experiment with a complete disconnect of the DC-power supply feeding the DC-bus capacitor during the pulse shows the same result.

Figure 4.1.2 shows identical oscillation for two BNC-cables to two channels of the oscilloscope. The shunt is connected to a BNC T-split with two channels measuring the same shunt signal with two different BNC-cables to the oscilloscope.

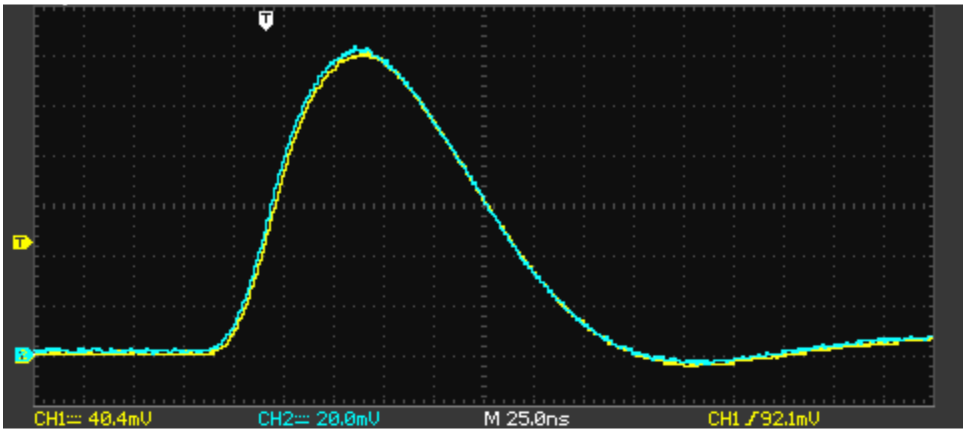


yellow	SDN-414-50mΩ at 10 mV/div
cyan	SDN-414-50mΩ at 10 mV/div

Figure 4.1.2 Identical response for same shunt connected with two BNC-cables to the oscilloscope.

In a simplified setup the current of the Pearson 2878 and the 50 mΩ shunt is compared. An isolated IGBT gate driver with optic input acts as an isolated current source. Uout = ±15 V, Rg = 4.7 Ω into capacitor Cge of 10 nF. The resulting current to charge Cge is measured with the Pearson 2878 and the shunt (type SDN-414-50).

Figure 4.1.3 shows the recoded waveforms of the Pearson and the shunt for the charge current of Cge. The frequency of this signal is somewhat lower than the frequency of the turn-off current waveform measured in Figure 3.1.



yellow	Pearson 2878	(400 mA/div)
cyan	SDN-414-50mΩ	(400 mA/div)

Figure 4.1.3 Identical responses for Pearson 2878 and shunt SDN-414-50 for output current of IGBT gate driver.

Conclusion:

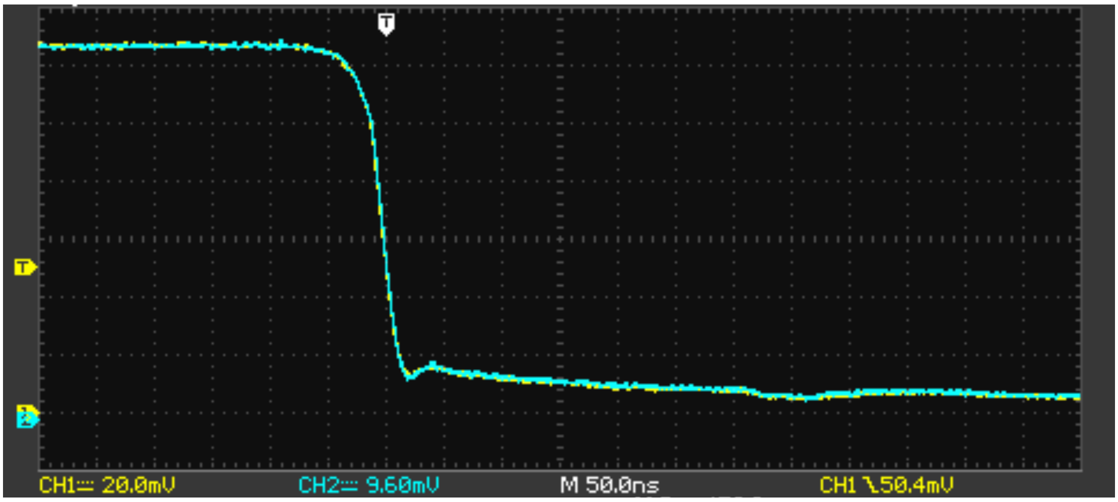
- No trivial explanation found for oscillation based on measurements related to connection with oscilloscope.
- Result of Figure 4.1.3 with floating gate driver proves that observed response difference (oscillation) between current transformer and shunt is not present in a more simplified measurement setup.

4.2 Switching with resistive load

Hypothesis: current oscillation is due to high frequency current slope
Test approach: simplify setup by measuring on resistive load at short fall time.

The 50 mΩ shunt was connected with the 1m Radiall RG223 double screened cable, length 1 m (R284C0351012), to the oscilloscope with input impedance set to 50 Ω by external 50 Ω termination on BNC T-split.

Figure 4.2.1. shows the measured response for the Pearson and the 50 mΩ shunt for a resistive switching load. With the fine gain adjustment of the oscilloscope, the waveform of the shunt is scaled to visually fit the waveform of the current transformer.



yellow	Pearson 2878	(200 mA/div)
cyan	SDN-414-50mΩ	(200 mA/div)

Figure 4.2.1. Identical response for Pearson 2878 and shunt SDN-414-50 for switching a resistive load.

Conclusion:

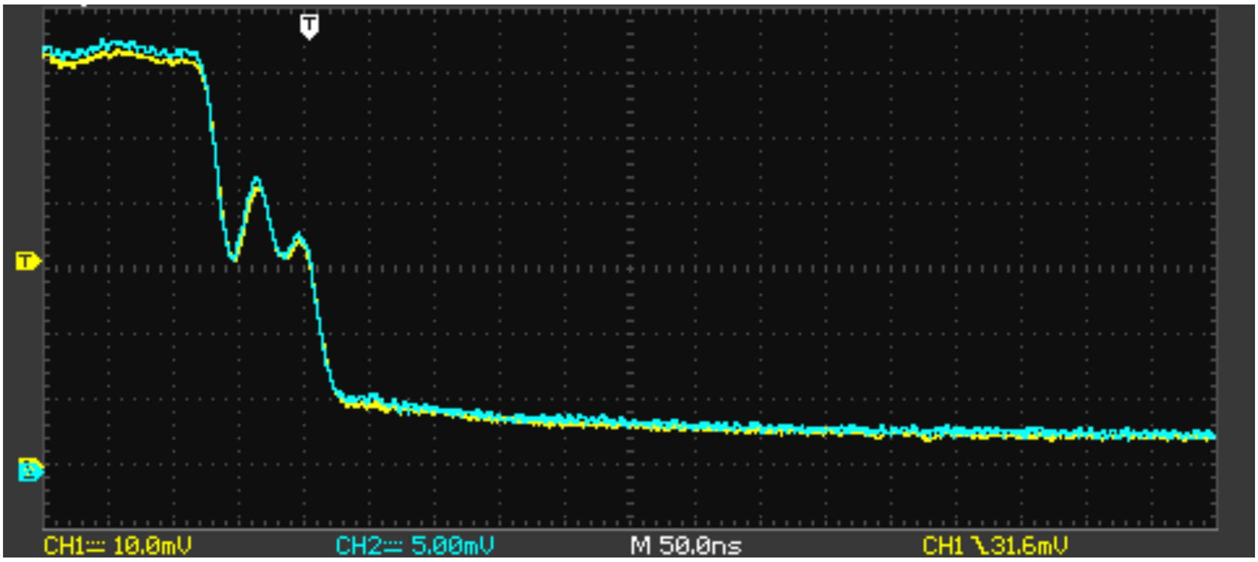
- Oscillation observed in Figure 3.1 is not due to the high frequency current slope.
- Oscillation is not present in circuit with resistive load.

4.3 Provoke oscillation by increasing parasitic C and L

Hypothesis: current oscillation is real signal, but is not measured by Pearson
Test approach: provoke real oscillating signals by adding parasitic capacitance and inductance

By removing the clamp capacitor on the DC-bus and adding an inductive loop in series with the emitter of the IGBT and adding a capacitor in parallel to the diode, a high frequency oscillation is provoked which should be recorded by the current sensors.

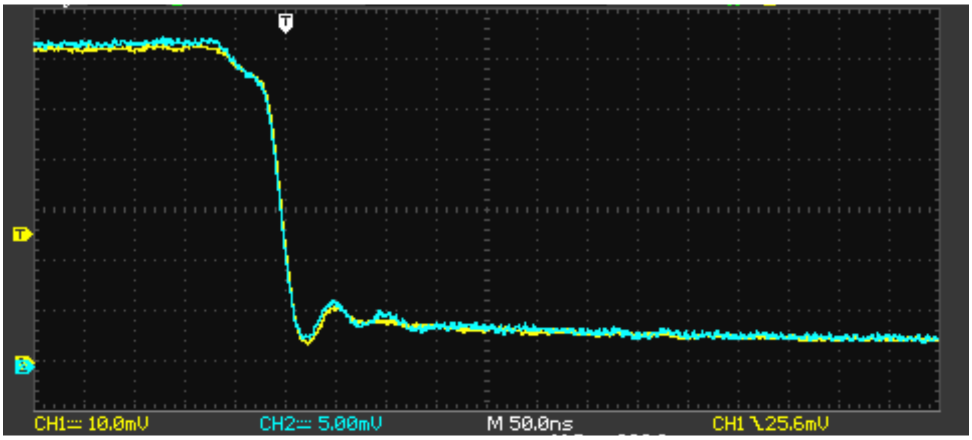
Figure 4.3 shows a resonance with a frequency of about 31 MHz during the slope. This resonance is due to a 470 pF capacitor that is placed in parallel to the diode and additional leakage inductance.



yellow	Pearson 2878	(100 mA/div)
cyan	SDN-414-50mΩ	(100 mA/div)

Figure 4.3.1 Identical responses for Pearson 2878 and shunt SDN-414-50 for high frequency oscillation during the slope.

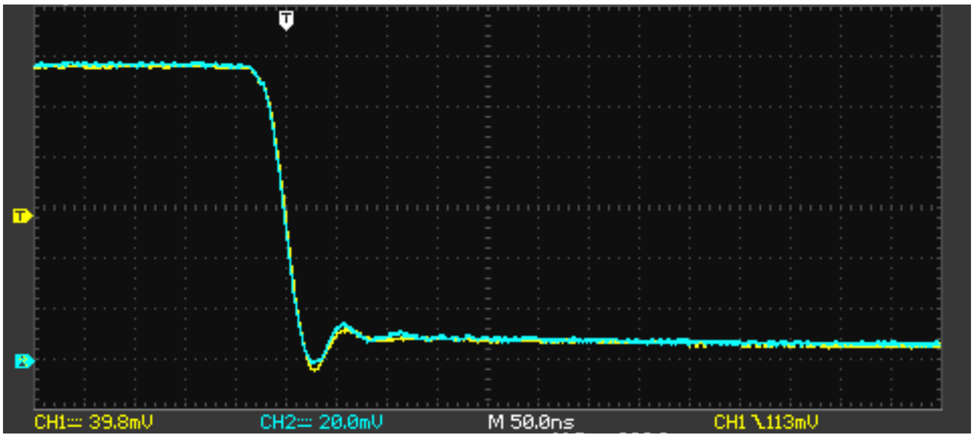
Even more inductance is added by introducing a round loop with a diameter of about 5 cm between the emitter of the IGBT and the current sensors. Figure 4.3.2 shows the response of the Pearson and the shunt with this increased inductance (without the parallel capacitance to the diode). The resonance frequency is about 20 MHz.



yellow	Pearson 2878	(100 mA/div)
cyan	SDN-414-50mΩ	(100 mA/div)

Figure 4.3.2 Identical responses for Pearson 2878 and shunt SDN-414-50 for oscillation after the slope provoked by additional leakage inductance. I_{top} = 620 mA

Figure 4.3.3 shows the same signals at same conditions at higher current. I_{top} = 2.3 A, t_{fall} = 31 ns.



yellow	Pearson 2878	(400 mA/div)
cyan	SDN-414-50mΩ	(400 mA/div)

Figure 4.3.3 Same conditions as Figure 4.3.2 but at I_{top} = 2.3 A

Conclusion:

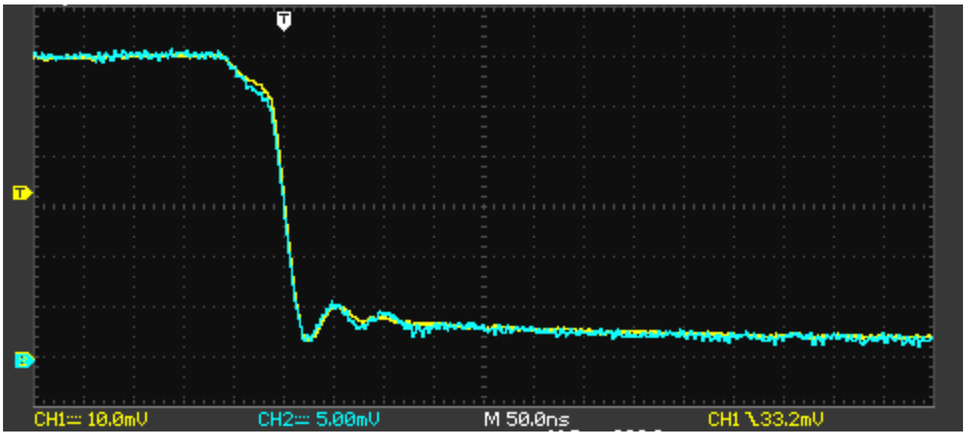
- The Pearson and shunt show identical responses for the provoked high frequency oscillation during and after the slope.
- The lower frequency oscillation shown about 100 ns after the slope in Figure 4.3.2 does not significantly scale in amplitude when increasing the turn-off current a factor 4 in this test setup with additional leakage inductance.

4.4 Different shunt values

Hypothesis: behavior of oscillation is related to damping by shunt resistance
Test approach: test response for shunts with different resistance

The circuit of Figure 2.1 with an additional inductive loop between the emitter of the IGBT and the current sensors is used to test the response at low current for the Pearson 2878 and SDN-414 shunts with different resistance values. Udc = 30 V, Itop = 612 mA, Rg,driver = 0 Ω, tfall = 38 ns.

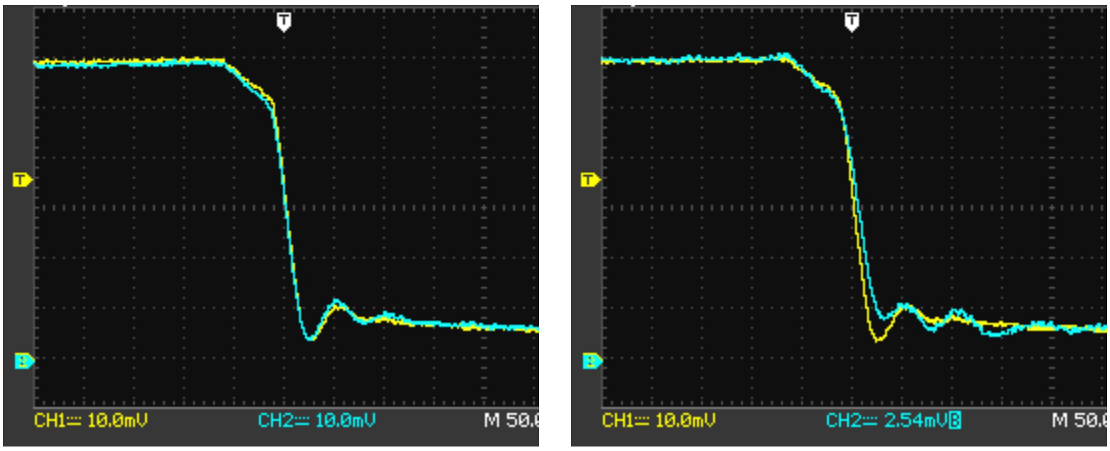
Figure 4.4.1 shows the response of the Pearson and the 50 mΩ shunt. The oscillation directly after the slope has a frequency of about 18.5 MHz.



yellow Pearson 2878 (100 mA/div)
cyan SDN-414-50mΩ (100 mA/div)

Figure 4.4.1 Responses for Pearson 2878 and shunt SDN-414-50 at 0.6 A.

Figure 4.4.2 shows the responses for the 100 mΩ shunt (left) and the 25 mΩ shunt (right).

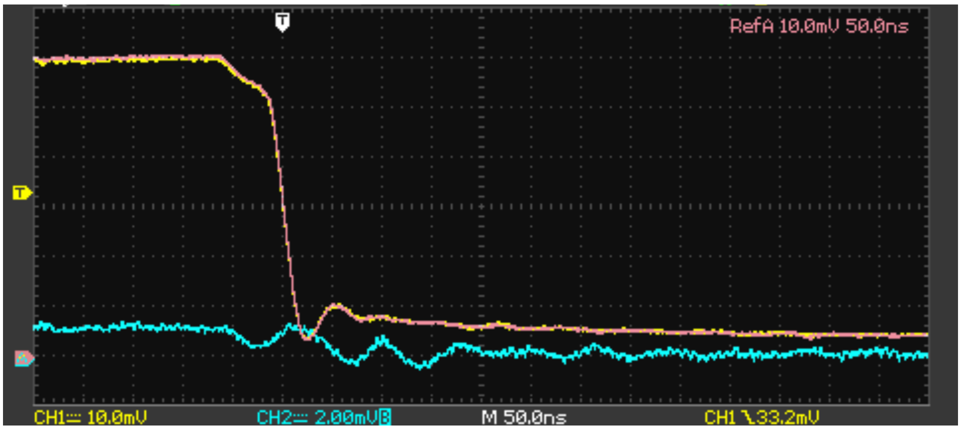


yellow Pearson 2878 (100 mA/div)
cyan SDN-414-100mΩ (100 mA/div)

yellow Pearson 2878 (100 mA/div)
cyan SDN-414-25mΩ (100 mA/div)

Figure 4.4.2 Responses for Pearson 2878 and 100 mΩ shunt (left) and 25 mΩ shunt (right)

Figure 4.4.3 shows the response of the Pearson and the 1.84 mΩ shunt. The low shunt resistance in combination with low current levels results in low voltage signal levels to be measured.



yellow Pearson 2878 (100 mA/div)
cyan SDN-414-1.84mΩ (1.08 A/div)
{pink 100 mΩ shunt – memory previous recording (100 mA/div)}

Figure 4.4.3 Responses for Pearson 2878 and 1.84 mΩ shunt at 0.6 A.

Figure 4.4.4 and 4.4.5 show the responses of the Pearson 2878 compared to SDN-414 shunts with different resistance values for the test setup with additional leakage inductance loop at a turn-off current of 0.6 A. Figure 4.4.4 shows the waveforms as recorded by the oscilloscope in Volts. Figure 4.4.5 shows the measured current, which is determined by same voltage waveforms divided by the sensor sensitivity.

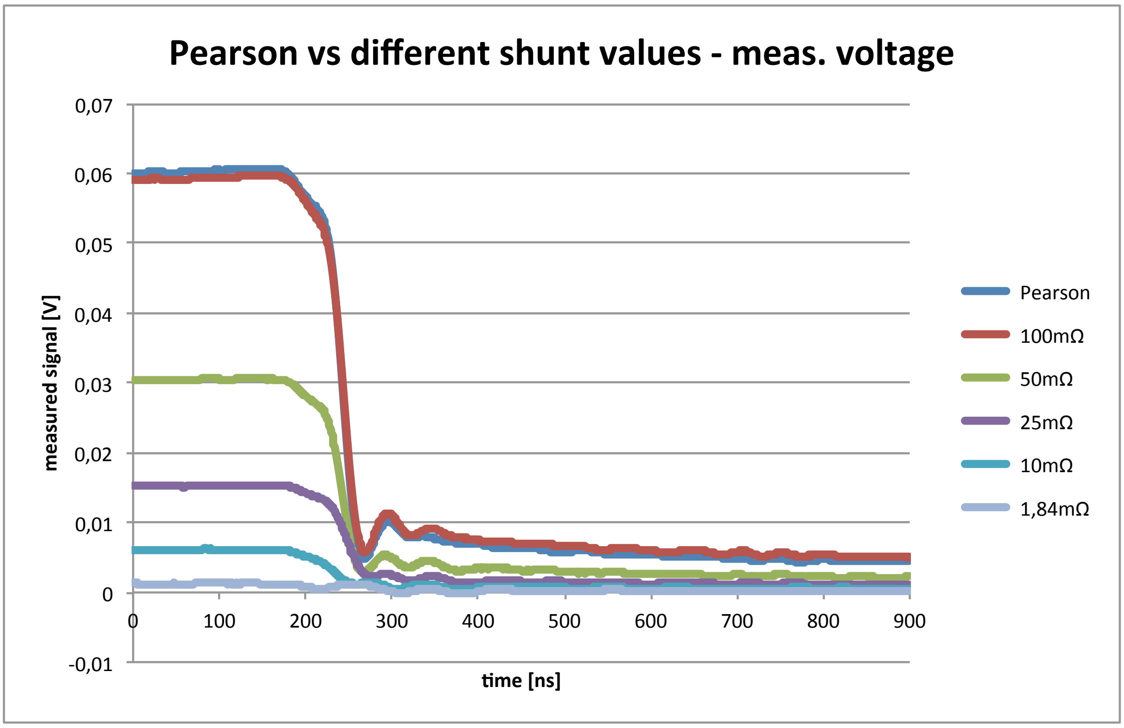


Figure 4.4.4 Recorded voltage by oscilloscope for Pearson 2878 different SDN-414 shunts at 0.6 A.

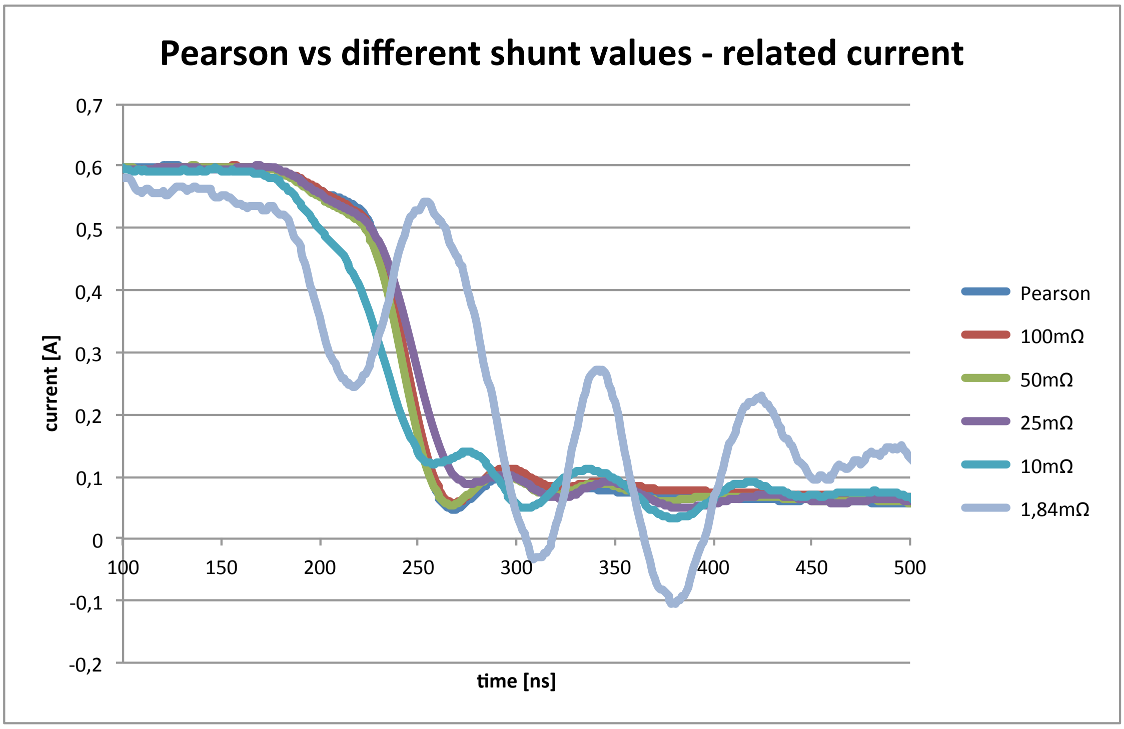


Figure 4.4.5 Measured current by Pearson 2878 different SDN-414 shunts at 0.6 A.

Conclusion:

- The resistance of the shunt does not significantly affect the behavior of the oscillation.
- Signal fidelity is best at higher resistance values because the signal level has higher amplitude at higher shunt resistance values.

4.5 Electro-magnetic coupling with load

Hypothesis: the oscillation is caused by electro-magnetic coupling with the load
Test approach: measure EM-field in the system

The setup is in its original configuration without the additional inductive loop and without additional parasitic capacitance. The Pearson 2878 is part of the setup, but the shunt is removed from the circuit and replaced by a short-circuit.
Then, only the midpoint of the shunt is connected to the circuit as indicated in Figure 4.5.1.

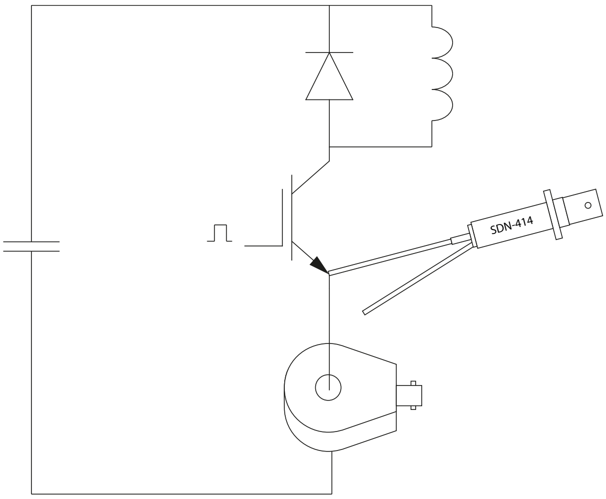
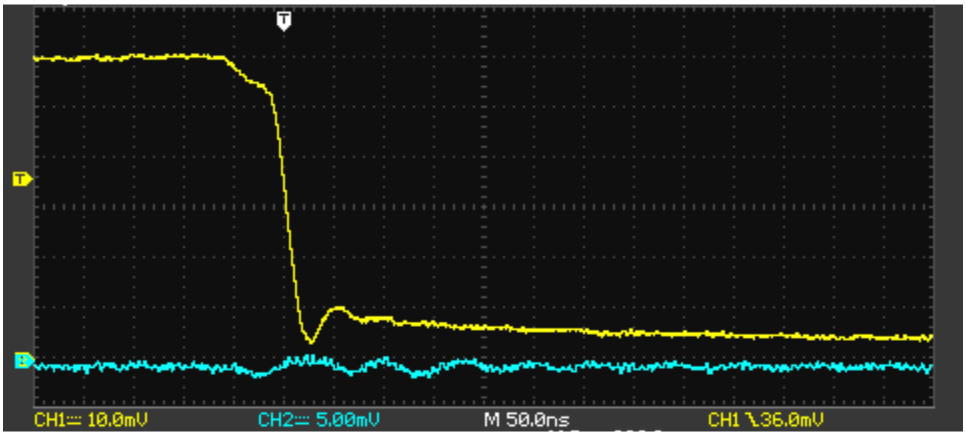


Figure 4.5.1 Test setup for measuring disturbance with shunt only connected with one lead to the circuit.

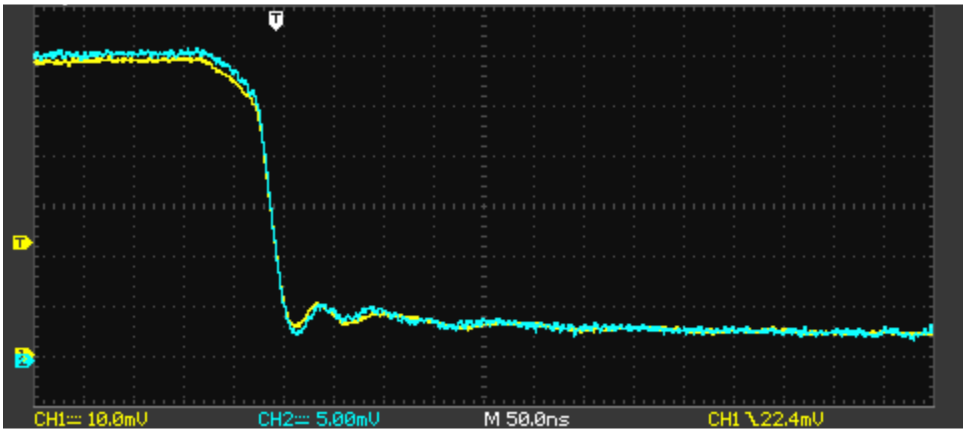
Figure 4.5.2 shows the measured signals of the Pearson and the 25 mΩ shunt for the setup shown above in Figure 4.5.1.



yellow Pearson 2878 (100 mA/div)
cyan SDN-414-25 mΩ (200 mA/div)

Figure 4.5.2 Responses for Pearson 2878 and 25 mΩ shunt connected with one lead only.

With the original setup as in Figure 2.1, the response of the Pearson and the 50 mΩ shunt was measured while positioning a coil close to the Pearson and the shunt. This coil is formed by 11 turns with a diameter of about 5 cm of the output leads of the midpoint to the coil. In Figure 4.5.3 it can be seen that both the response of the Pearson and the shunt show a lower frequency oscillation on top of the tail current of the IGBT. The connecting leads to the shunt with a length of about 4.5 cm are spread apart and form a triangle shape with approximate distance at the end of the leads of about 2.5 cm.



yellow	Pearson 2878	(100 mA/div)
cyan	SDN-414-50 mΩ	(200 mA/div)

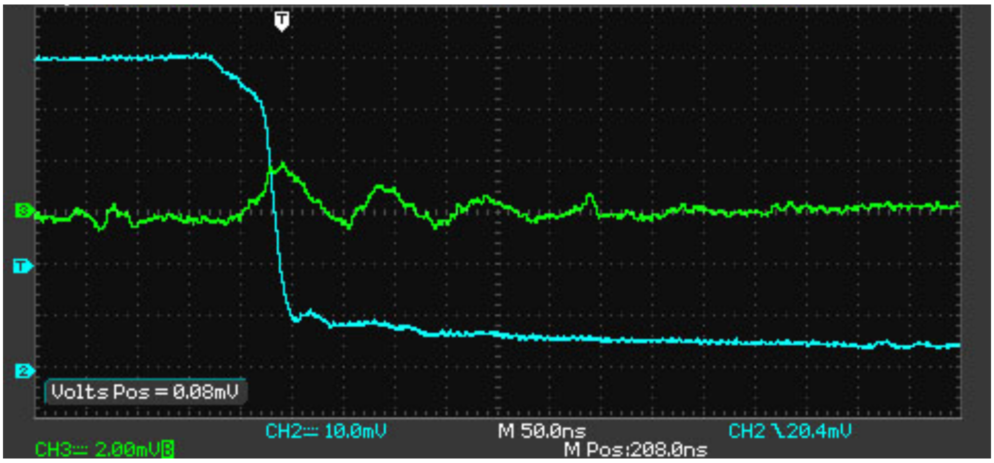
Figure 4.5.3 Responses for Pearson 2878 and 50 mΩ shunt close to an air coil carrying load current.

With the original setup without the air coil, different experiments were done with near field probes (H and E probes) of different sizes at various locations in the setup. Figure 4.5.4 shows the response of the 50 mΩ shunt, the output voltage of the commutation cell and the signal of a big (10 cm) H-probe close to the commutation cell. The response of the H-probe was found to be relative clean at the power supply and coil. The output voltage is measured by a voltage probe that is connected to the collector of the IGBT with the reference lead connected to the ground (flange) of the shunt.

Cyan	SDN-414-50 mΩ	(200 mA/div)
Red	Output voltage	(10 V/div)
Green	H-field probe signal	(100 mV/div)

Figure 4.5.4 Responses for 50 mΩ shunt, output voltage and H-field probe close to commutation cell.

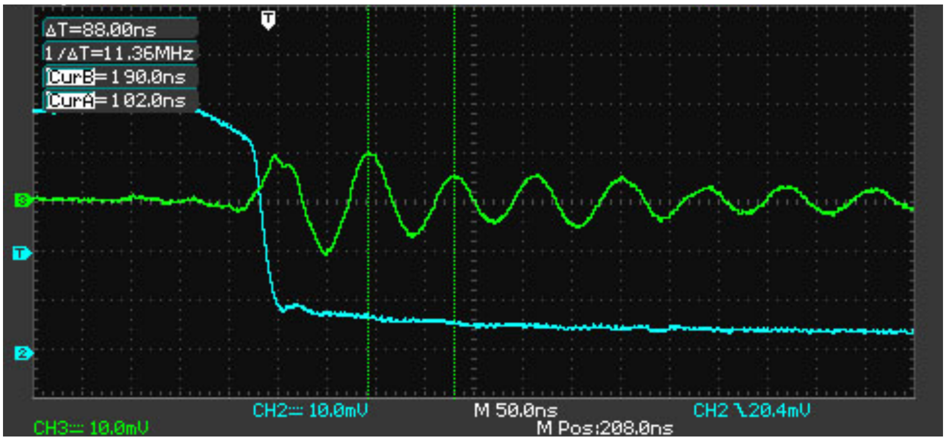
Figure 4.5.5 shows the measured signals of the 50 mΩ shunt and the E-probe near the shunt leads. The measured frequency of the E-field is approximately 9.6 MHz.



cyan	SDN-414-50 mΩ	(200 mA/div)
green	E-field probe signal	(2 mV/div)

Figure 4.5.5 Responses of 50 mΩ shunt and response of E-probe near shunt leads.

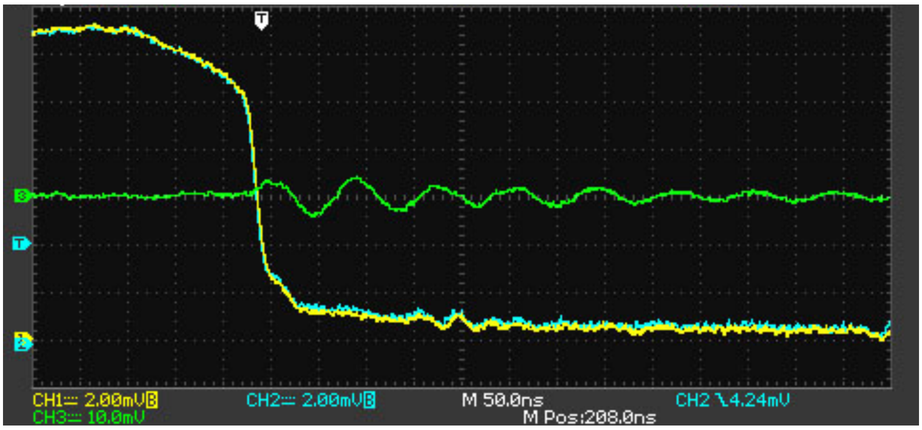
Similar frequencies were found with the E-probe at the leads from the DC-bus capacitor to the power supply and near the core of the load coil, see Figure 4.5.6 and Figure 4.5.7 respectively.



cyan	SDN-414-50 mΩ	(200 mA/div)
green	E-field probe signal	(10 mV/div)

Figure 4.5.6 Responses of 50 mΩ shunt and response of E-probe near leads from DC-bus capacitor to power supply.

Figure 4.5.7 is at turn off current of 132 mA only.



yellow	Pearson 2878	(20 mA/div)
cyan	SDN-414-100 mΩ	(20 mA/div)
green	mini field probe signal	(10 mV/div)

Figure 4.5.7 Responses of 50 mΩ shunt and response of E-probe near core of load coil.

<u>Conclusion:</u>

- The EM-field close to the commutation cell has a frequency in the range of 20 – 25 MHz. This frequency correlates with the oscillation recorded by the Pearson 2878 at the end of the slope as seen for example in Figure 4.5.2. (yellow waveform).
- At the load coil the E-field has a frequency of about 10 MHz, this frequency is also seen at the location of the shunt and at the leads connecting the DC-bus capacitors to the power supply. The Pearson 2878 is less sensitive for this field than the SDN-414 shunts (in the setup used), as can be seen in Figure 4.5.2 where the shunt signal shows this lower frequency oscillation while no current is routed through its leads as indicated in the circuit in Figure 4.5.1.

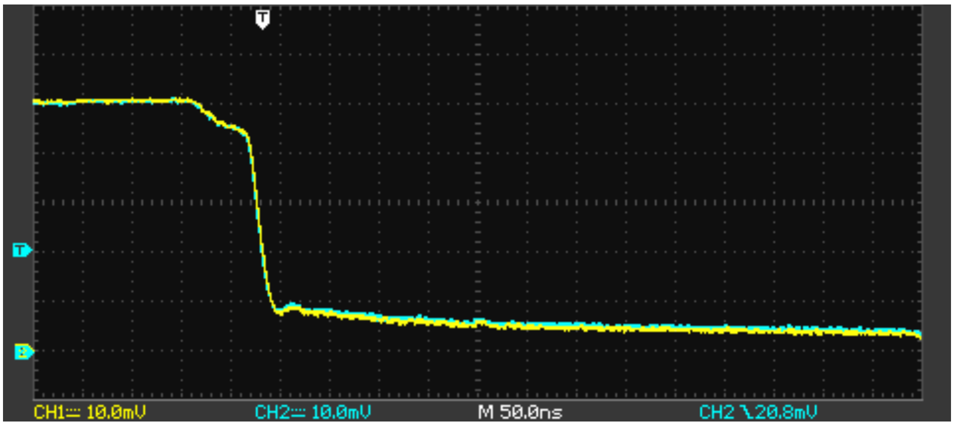
5 Measurements with EMI improved setup

5.1 Changes to measurement setup

Only some small modifications were made to the patch test setup described in Chapter 2. The main changes are: The connection leads of the load coil were re-routed and the position of the coil was changed, so generated field is less and distance between disturbance and receiver (commutation cell with current sensors) is increased. All cables entering and leaving the commutation cell were filtered with ferrite common mode filters. No effort was made to minimize parasitic elements in the test setup.

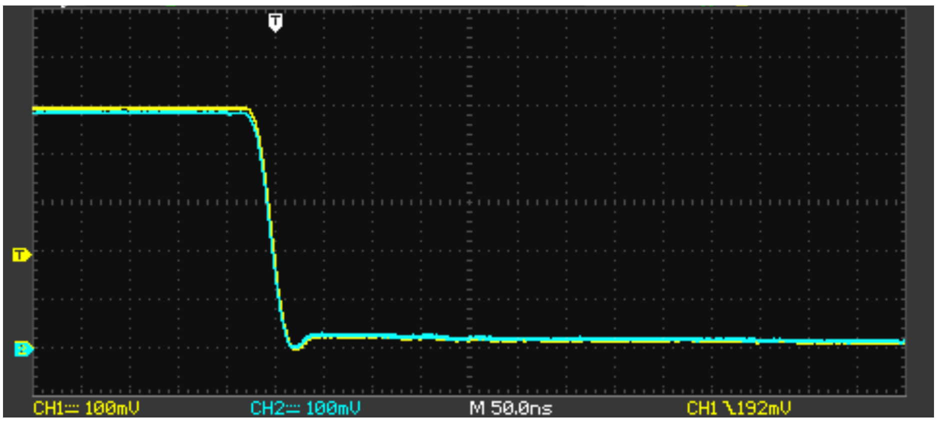
5.2 Measurement results with improved setup

Figure 5.2.1 and 5.2.2 show the turn-off current of the IGBT at Itop = 500 mA and 5 A respectively as measured with the Pearson 2878 and the shunt SDN-414-100mΩ with the improved setup regarding EMI. The oscillation after the pulse is not visible anymore on the shunt signal. The coaxial cable to connect the shunt to the oscilloscope with input impedance 50 Ω is a RG223 double screened cable from Radiall, length 1 m (R284C0351012) but other cables gave same results.



yellow	Pearson 2878	(100 mA/div)
cyan	SDN-414-100 mΩ	(100 mA/div)

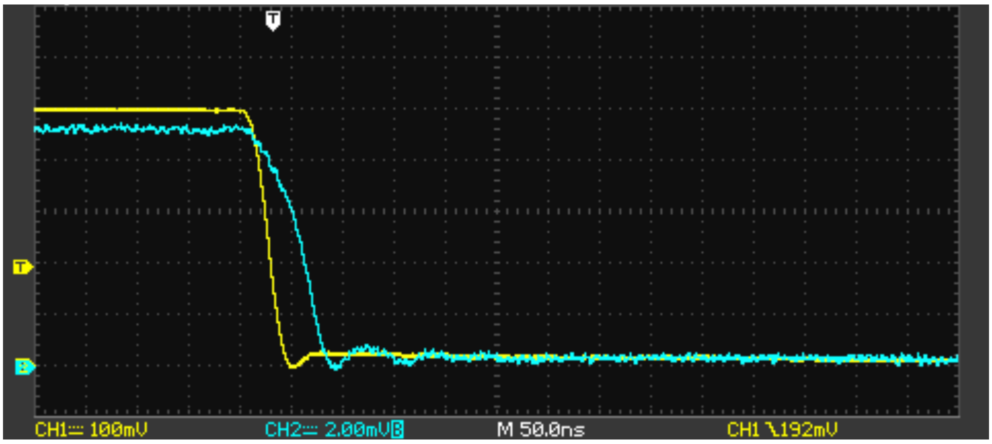
Figure 5.2.1 Responses of Pearson 2878 and 100 mΩ shunt at 500 mA in the EMI improved setup.



yellow	Pearson 2878	(1 A/div)
cyan	SDN-414-100 mΩ	(1 A/div)

Figure 5.2.2 Responses of Pearson 2878 and 100 mΩ shunt at 5 A in the EMI improved setup.

Figure 5.2.3 shows the response of the Pearson 2878 and the 1.84 mΩ shunt. This low resistive shunt has limited bandwidth. The Pearson 2878 as well as the shunts with higher resistance have sufficient bandwidth to measure the fast turn-off current waveform with tfall = 26 ns. The low resistance shunt signal shows some remaining 18 MHz oscillation since the generated EMI field is relative high at 5 A and the measurement signal is relative low (2 mV/div).



yellow	Pearson 2878	(1 A/div)
cyan	SDN-414-1.84mΩ	(1.086 A/div)

Figure 5.2.3 Responses of Pearson 2878 and the low resistance 1.84mΩ shunt at 5 A in the EMI improved setup.

Figure 5.2.4 and 5.2.5 show the responses of the Pearson 2878 compared to SDN-414 shunts with different resistance values for the test setup with improved EMI at a turn-off current of 0.5 A. Figure 5.2.4 shows the waveforms as recorded by the oscilloscope in Volts. Figure 5.2.5 shows the measured current, which is determined by same voltage waveforms divided by the sensor sensitivity.

Figure 5.2.6 and 5.2.7 show similar waveforms at a turn-off current of 5 A.

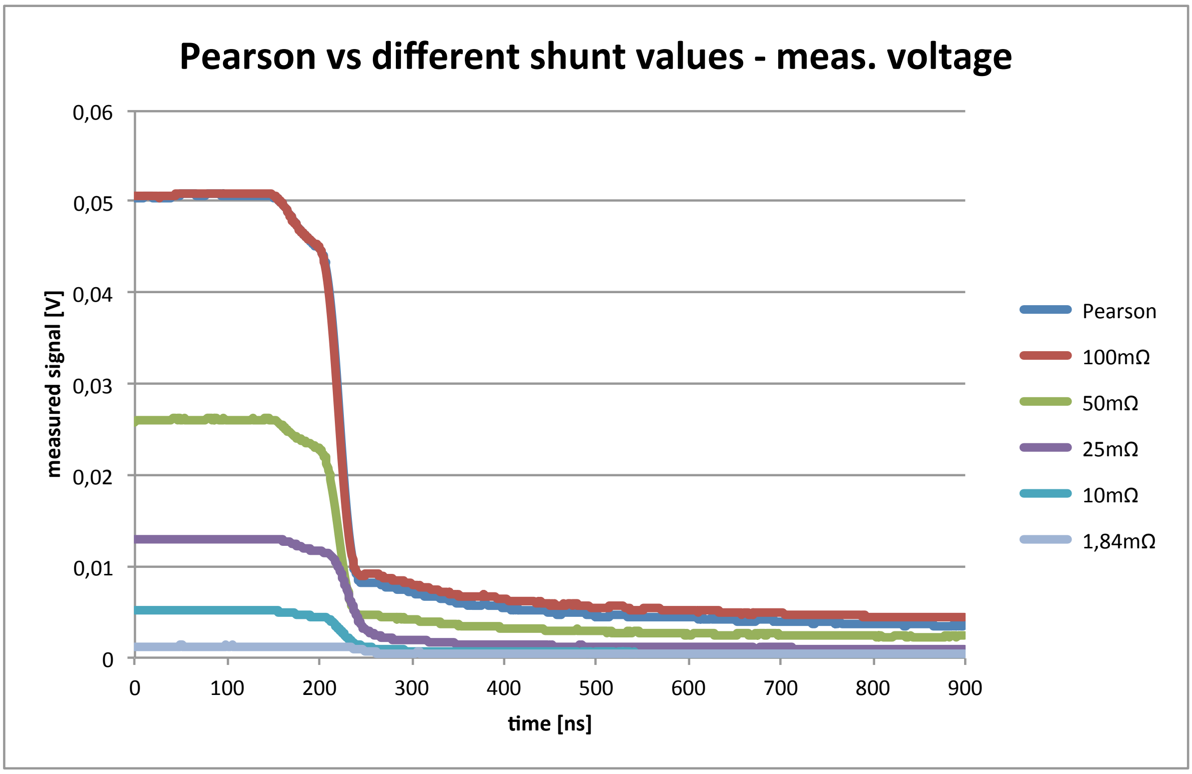


Figure 5.2.4 Recorded voltage by oscilloscope for Pearson 2878 different SDN-414 shunts at 0.5 A.

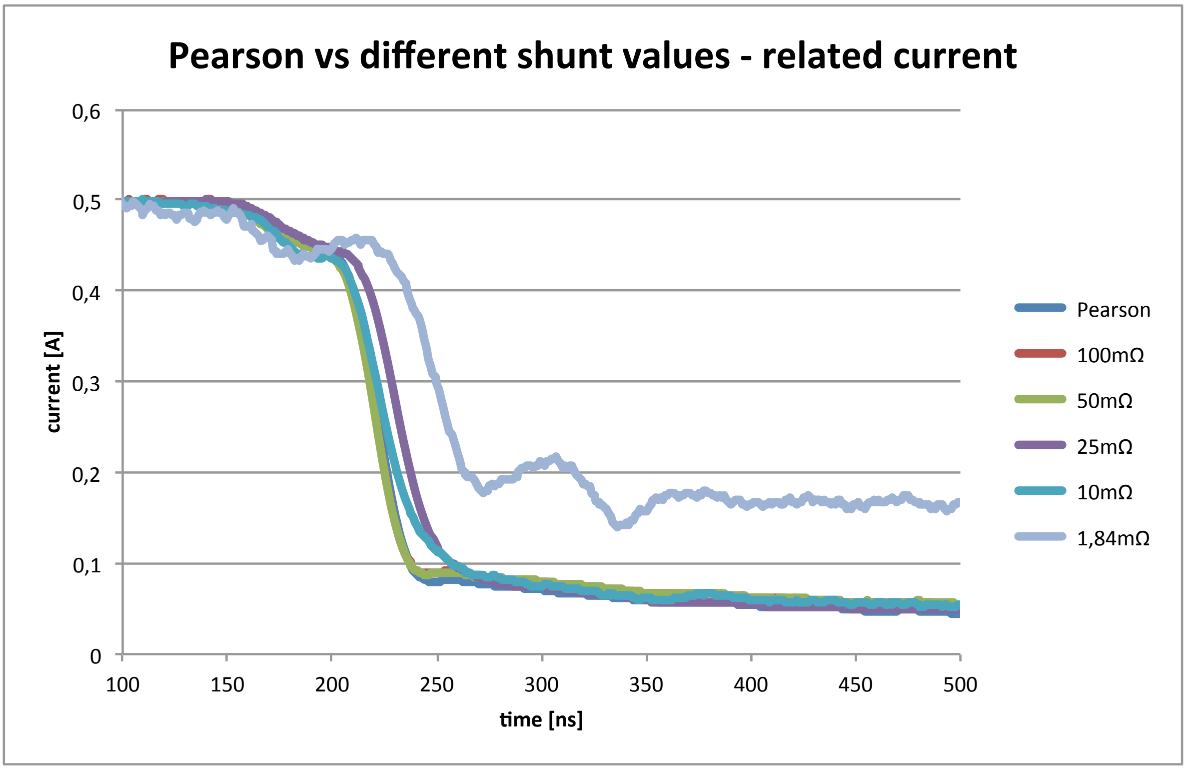


Figure 5.2.5 Measured current by Pearson 2878 different SDN-414 shunts at 0.5 A.

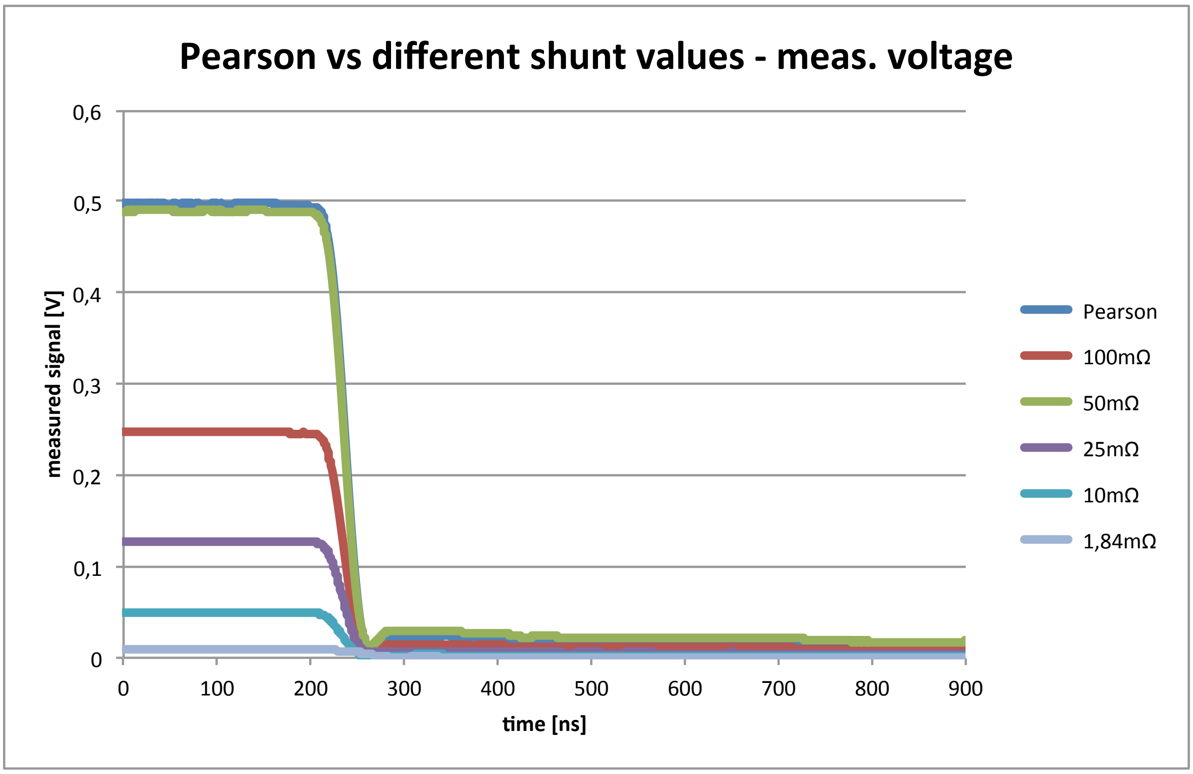


Figure 5.2.6 Recorded voltage by oscilloscope for Pearson 2878 different SDN-414 shunts at 5 A.

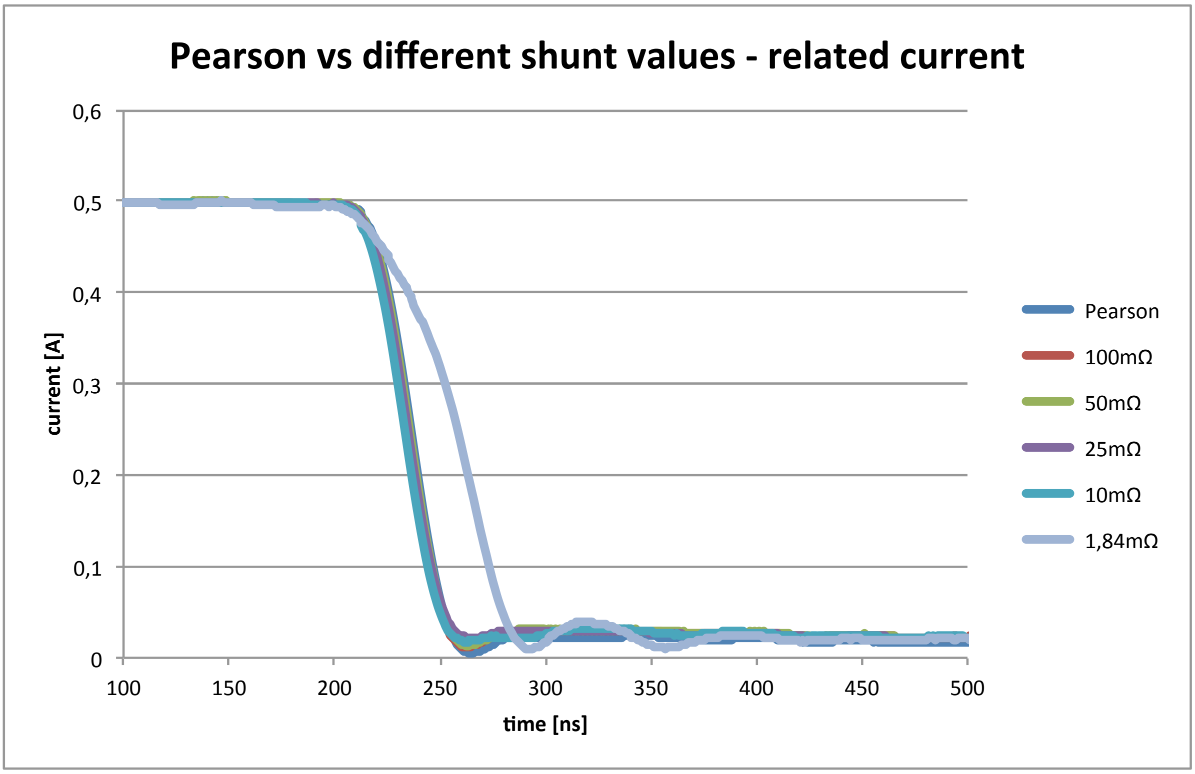


Figure 5.2.7 Measured current by Pearson 2878 different SDN-414 shunts at 5 A.