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Physik
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A Ground Loop Detector

- Report-

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Contents

1 Introduction

The aim of our project in the electronics lab course was to build and test a simple system to detect ground loops in experimental setups. Therefore we used two circuits described in the article “Simple system for locating ground loops” by P. M. Bellan[1]. After a short introduction to the problem of ground loops (what is a ground loop? - why do you want to avoid them? - how could one find them?), we want to explain the concept of the ground loop detection system in the article by P. M. Bellan and describe several small modifications we had to do in the circuits to make them work. Finally we did some small tests and we want to show our results in this report.

2 The Problem

Ground loops are a common problem in many experimental setups. A ground loop is an unwanted closed loop of cables in the setup, most often through the ground system. An example can be seen in fig. 1. In this example, two devices are connected by different cables. Both devices are connected to the electricity network and both have a metallic case which is grounded through the power cord for security reasons. One or more signals are transferred between those two devices using shielded (e.g. coax) cables, where the cable shield is usually connected to the case of each device. Now we have a closed ground loop in our setup: from the case of device 1 through the signal cable(s) to device 2, from there through its power cord into the lab’s electricity network, where also device 1 is connected to. Because usually the ground connectors of all sockets are connected in a lab’s electricity network, a closed loop exists.

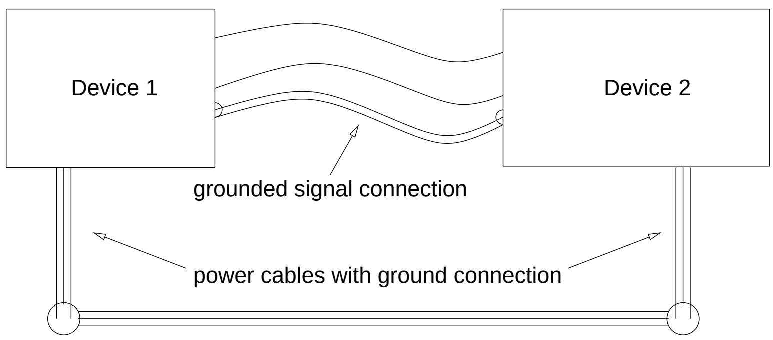

Figure 1: simple example for a ground loop in an experimental setup

This loop now works as a large coil and AC current can be induced according to the induction law for a shortcut single loop with resistance R that encloses an area A:

$$I(t) = -\frac{1}{R} \int_A \dot{\vec{B}} \cdot \mathrm{d}\vec{A} \tag{1}$$

when there are changing magnetic fields inside the loop. One source for such fields is the 50 Hz AC voltage.

Especially sensitive setups are often effected by ground loops which might in extreme cases not only influence measurement results but even harm equipment. Therefore it is important to avoid such loops. But in complex setups they might not be easy to find.

The usual way to find ground loops is to disconnect cable by cable and see if the 50 Hz-signal disappears. This method brings some problems. First, disconnecting cables can usually not be done during normal operation but the experiment has to be stopped for this. Second, it can take a very long time when there are many cables in the setup where it is also likely to have ground loops in more than one cable. And as a third point, it is possible that loops stay completely undiscovered because they do not produce a typical signal but still influence the measurement. So it would be good to have a different method to detect ground loops and one was built and tested in this course.

When you have found a loop, there are some ways to remove them or to reduce their influence. To avoid closing the loop through the electricity network, one can probably use batteries for power supply of the effected devices. If this is not possible, e.g. because the device needs 230 V AC power, a dangerous but sometimes applied solution can be to cut through the ground wire in the device's power cord. A way to reduce the influence of a ground loop that can't be removed is to minimize the area the loop encloses. As one can see in equation 1, the induced current is the integral of $\dot{\vec{B}}$ over the area enclosed by the loop and therefore minimizing this area will minimize the induced current. This can be accomplished by bringing all cables between two devices as close together as possible. Best is to twist cables, because in the ideal case where time-dependent magnetic fields are in good approximation constant in space, all induced voltages will then compensate. But this method has also its disadvantage because it can lead to stronger cross-talk between different signal cables, especially if those are not properly shielded.

3 Solution

3.1 General functionality of the system

The idea behind the ground loop detection system is to generate a 100 kHz test signal and induce this signal into the ground system. If there is a closed loop in the ground system, the test signal will cause rather high AC current of this frequency in the loop, as the loop has only very small resistance of approximately 1 Ω. AC current will of course emit oscillating electro-magnetic fields which can then be picked up by a coil wrapped around any cable that is part of the loop.

So the system will consist of four different parts:

- the exciter: a circuit that generates the 100 kHz test signal
- some kind of clip connected to the exciter that can be attached to a cable and will induce the test signal into that cable
- a coil to wrap around your signal cables, we will use a *Rogowski coil* for that
- the detector: a circuit that takes the signal from the coil and displays the level of the test signal in it

The complete system is shown in fig. 2 as a schematic drawing.

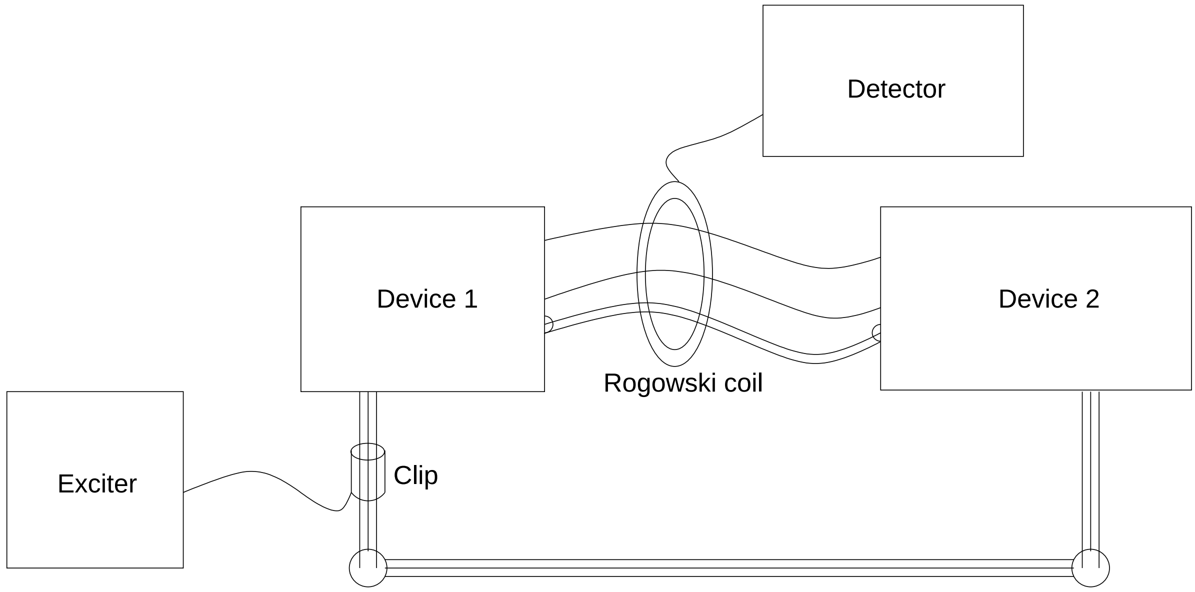

Figure 2: the complete ground loop detection system

3.2 The exciter circuit

The circuit as described in RevSciInstr[1] is shown in fig. 3. An IC555 is used to generate an 100 kHz rectangular signal. As the IC can only output quite low power, a transistor is used to amplify the output signal. The exciter coil can then be connected in series with the transistor. To be able to see if everything works, an LED was added in series with the coil connector so that it will only light up, if the coil is connected properly.

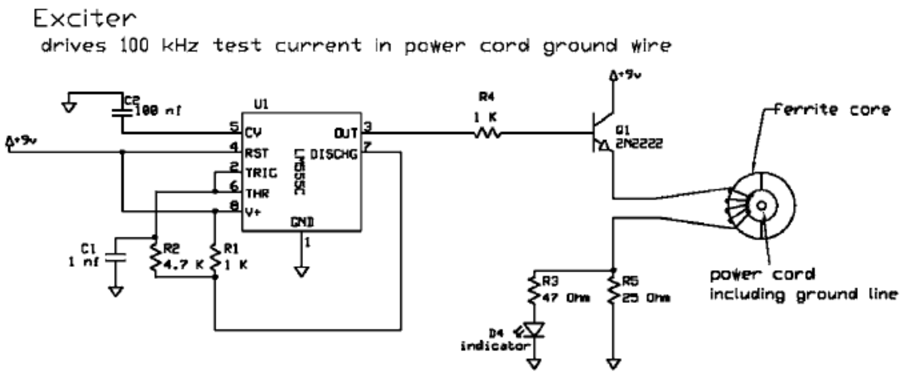

Figure 3: the original exciter circuit (from [1])

3.3 The inductor clip

To induce the test signal into the ground system, a small ferrite core clip is used. These are usually clipped around signal cables to filter out high frequency noise. Here about ten turns of coil wire were wound around the ferrite core. Now this clip can be attached to a power cord of a device that should be tested for being part of a ground loop. Fig. 4 shows photos of our clip.

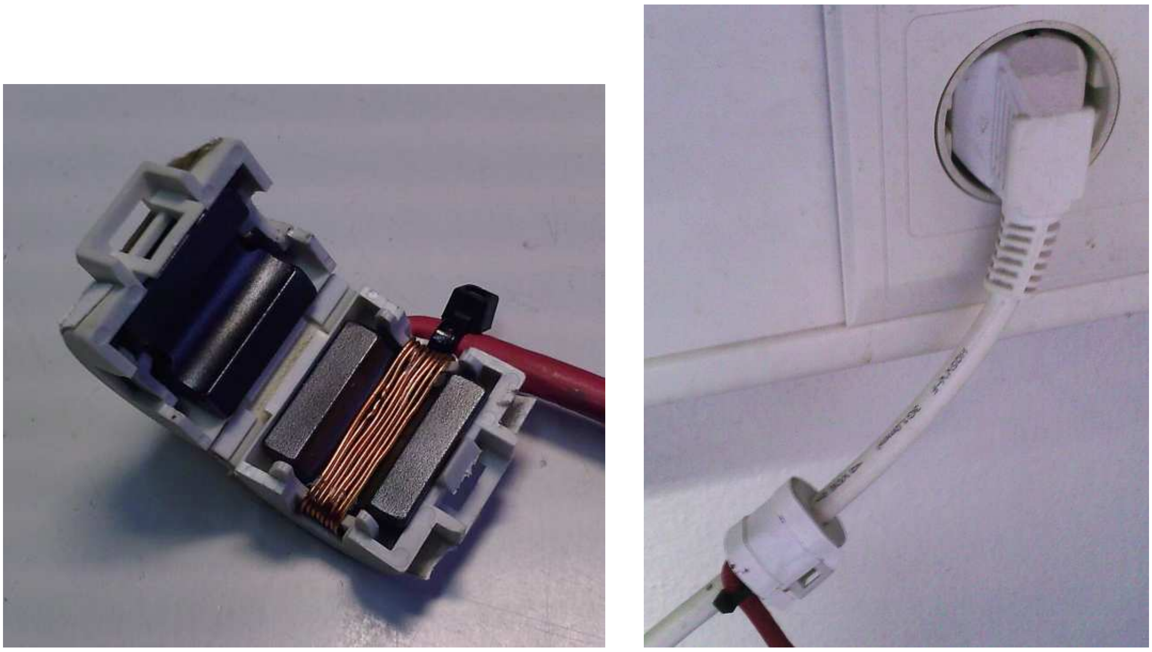

Figure 4: our ferrite clip

3.4 The Rogowski coil

A Rogowski coil is a device for measuring alternating current (AC) or high speed current pulses. It consists of a helical coil of wire with the lead from one end returning through the center of the coil to the other end, so that both terminals are at the same end of the coil. The whole assembly is then wrapped around the straight conductor whose current is to be measured. The voltage that is induced in the coil is proportional to the rate of change of current in the straight conductor. One advantage of a Rogowski coil over other types of current transformers is that it can be made open-ended and flexible, allowing it to be wrapped around a live conductor without disturbing it. Since a Rogowski coil has an air core rather than an iron core, it has a low inductance and can respond to fast-changing currents as we have here. Also, because it has no iron core to saturate, it is highly linear in its output. Fig. 5 shows a photo of our Rogowski coil.

3.5 The detector circuit

Now we need a detector circuit that can filter for our 100 kHz test signal and display its level.

The detector circuit as described in the article uses three amplifier ICs of type OP27. The first of them (U20) is mainly used as a filter. The amplification level of amplifier ICs is controlled by the value of the resistor that connects negative input and output pin (R_o) in relation to the value at positive (R_+) and negative (R_-) input (see fig. 6). The amplification level is then given by

$$\nu = -\frac{R_o}{R_-}$$

This means: the higher R_o the stronger the amplification.

With that we can explain the functionality of the filter stage. Instead of a resistor a coil and a

Figure 5: our Rogowski coil

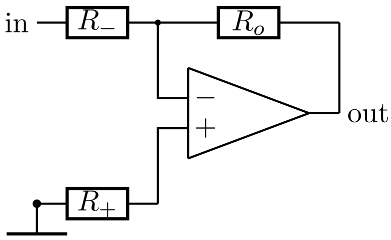

Figure 6: basic inverting amplifier layout

capacitor in parallel are used to connect negative input and output. The impedance of an ideal capacitor is $-\mathrm{i}/\omega C$, the impedance of an ideal coil is $\mathrm{i}L\omega$. So the total impedance of the parallel connection is:

$$Z_{\text{tot}} = \frac{1}{\frac{1}{Z_C} + \frac{1}{Z_L}} = i\frac{1}{-\omega C + \frac{1}{\omega L}}$$

which goes to zero for $\omega \to 0$ and $\omega \to \infty$ and diverges at $\omega_0 = \sqrt{1/LC}$.

This means: very high and very low frequencies are suppressed by U1 while frequencies near ω_0 are strongly amplified.

But the output signal amplitude is still not large enough to drive an LED which typically needs about 1 V to light up. Therefore we need a second amplification stage U21. The signal is now filtered for frequencies around 100 kHz and amplified to an amplitude bigger than 1 V for a closed loop.

To have a more detailed output to the user than just an LED that lights up or not, a small display should be added. For this a standard digital panel voltmeter is used. So the output of U1 has to be transferred to a DC voltage. Normally one would just use a bridge rectifier for that, but here with signals typically lower than 1 V the ≈ 0.7 V voltage drop of diodes becomes a problem. To compensate that, another amplifier IC is used. Amplifier always bring voltage at input and output to the same level. So one use a chain of the same resistor as the one in front of the input and a diode and the same chain again with a diode in opposite direction in parallel as feedback between input and negative input. The amplifier will then raise up every output signal by the value of the voltage drop of a diode.

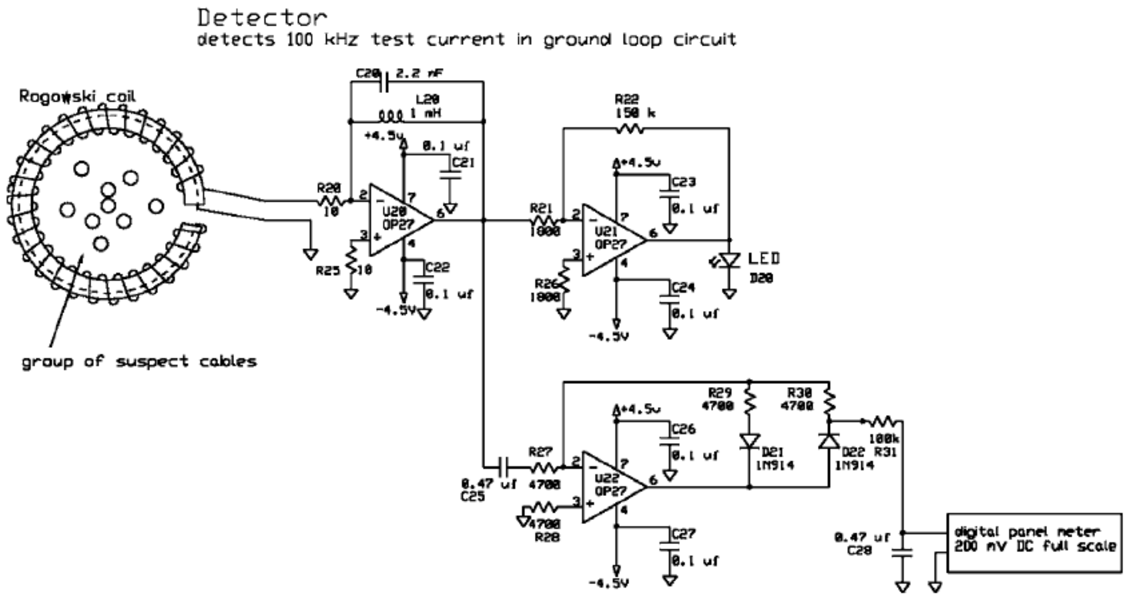

Figure 7: the original detector circuit

4 Realization and tests

4.1 Modifications in the circuits

4.1.1 Modifications in the exciter

Compared to the circuit described in the article we had to do some small modifications in the exciter circuit layout.

The npn-transistor Q1 type 2N2222 burned through within 10 s when we realized the described circuit. Therefore we replaced it by an pnp-transistor type MJE2955T. This type can stand a much higher collector-emitter-current (10 A instead of 800 mA) and has the possibility to attach an additional heat-sink. The difference between pnp and npn does not matter to us, because this will just invert the output signal but will not change form or frequency. Differences in output voltage/current can be compensated by regulating the current at the B-port of the transistor. During the short test-operation of the original circuit we measured a current of approx. 160 mA flowing through our coil. Now we replaced resistor R4 (1 kΩ) by a chain of a 220 Ω-resistor and an 1 kΩ-potentiometer. By bringing the potentiometer into the correct position, we were able to reconstruct a current of 160 mA through the coil.

We also saw that our output frequency was not exactly 100 kHz as described in the paper by P. M. Bellan but roughly 130 kHz. We found out, that the frequency can be controlled by the value of the two resistors R1 and R2. Because R1 had less effect on the frequency, we chose to modify this one, as this allows finer tuning. To be a bit flexible again, we used a potentiometer again thus allowing us to tune our exciter circuit to the resonance frequency of the detector later. Higher resistance at R1 gives lower frequency, therefore we used a chain of an 1 kΩ resistor and a 5 kΩ potentiometer instead of R1. This lets us choose the output frequency between approx. 85 and 130 kHz.

Our final layout can be seen in fig. 8, photos of our exciter device are shown in fig. 9.

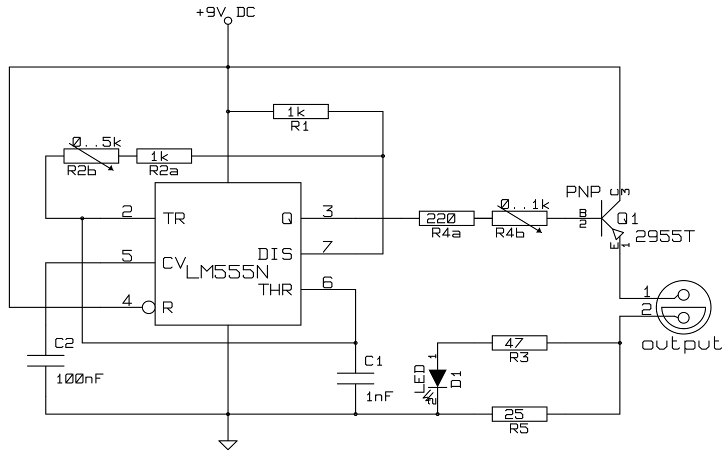

Figure 8: our exciter circuit

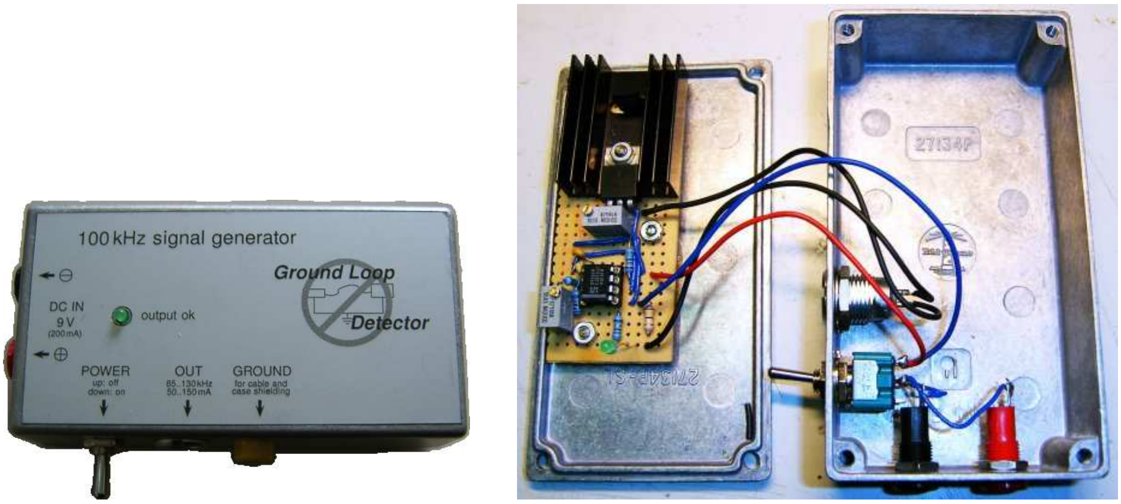

Figure 9: photos of our exciter

4.1.2 Modifications in the detector

The detector circuit needed some modifications compared to the circuit described in the article, too.

The first problem was that the exact values of capacitor and coil for amplifier feedback were not available, so we tried slightly different ones and tried to get the resonance frequency as near as possible to 100 kHz. For this we connected a frequency generator to the input and gave amplifier output to an oscilloscope. In the end 2.2 mH and 470 pF turned out to be the best combination.

In the second amplifier stage (U21 in the original layout) we lowered the amplification factor a bit by using a smaller resistor for feedback and added a potentiometer in series to that resistor thus one can modify the signal level at which the LED lights up.

The rectifier stage did not work as good as expected, because the display did not work very well with the rather noisy DC signal we got from the described circuit. Therefore we connected a normal bridge rectifier to the amplifier output. Because the voltmeter we used has a maximum input voltage of 200 mV but our signal went up to 800 mV during our tests, we decided to split the voltage 1:10.

Our final circuit layout is shown in fig. 10, photos of our detector device are shown in fig. 11.

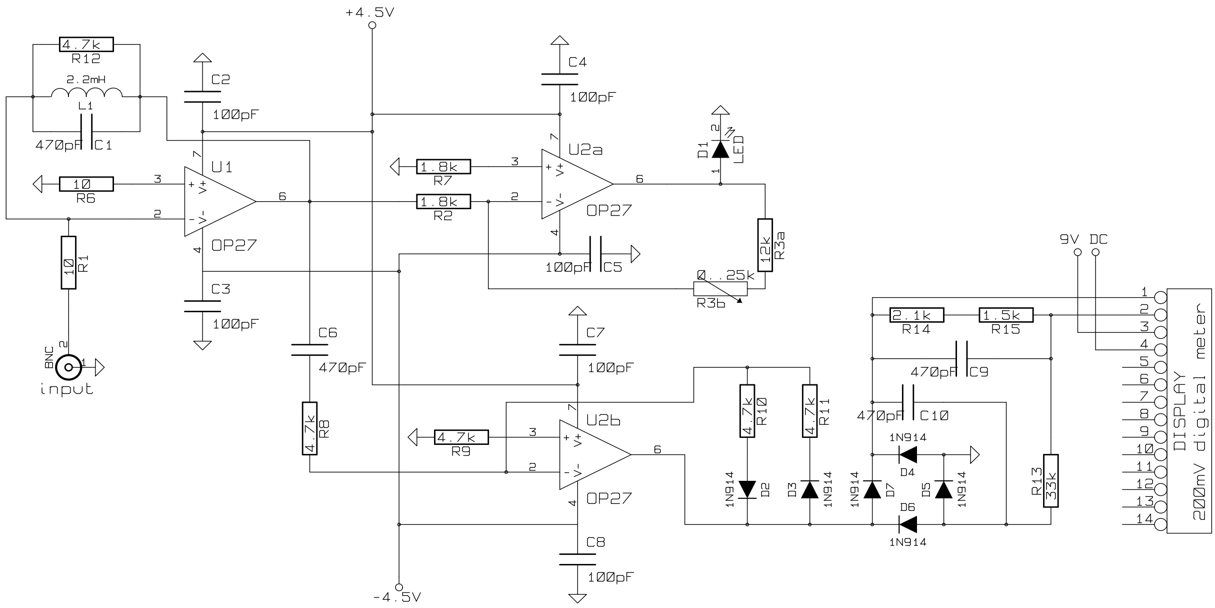

Figure 10: our detector circuit

Because the circuit would need three power supplies (±4.5 V for the amplifiers and 9 V for the display where display and circuit power supply must be separate) we added two 5 V → ±5 V DC-DC converters, so only one power supply is needed.

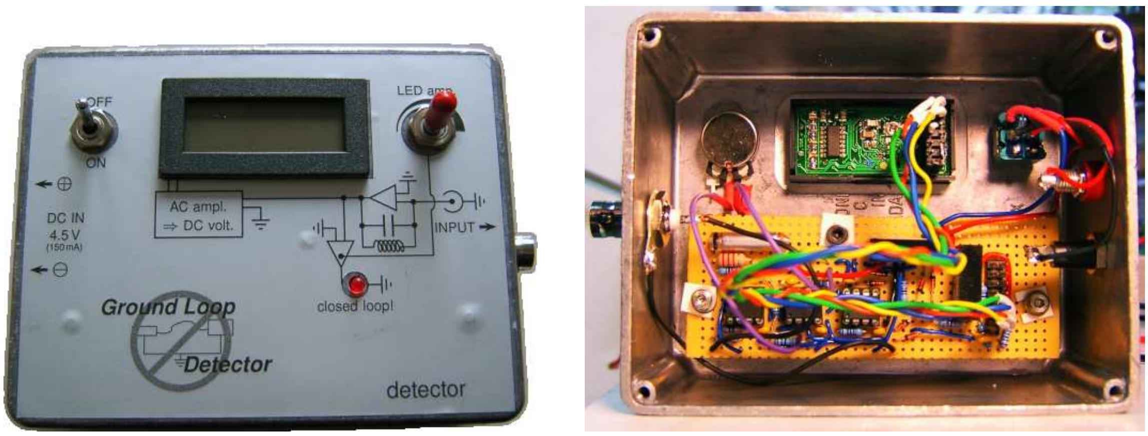

Figure 11: photos of our detector

4.2 Tests

After building the exciter and the detector our next aims were to test if they are working well and to analyze their characteristics. How to use the ground loop detector will be explained in the instructions following this report. In fact we were interested in the shape of the signal produced by the exciter and, what is more important, how the signal will look like in the subsequent stages, like the cable we induct the signal into or at the input of our detector. We used an oscilloscope to record the shape of the signal at these interesting points under different conditions e.g. different cable lengths.

Fig. 12 shows the measurement of a set-up consisting of the exciter with the Rogowski coil which is wrapped around a 1.8 m long coaxial cable arranged in a (closed) loop. The signal is picked up by the Rogowski coil.

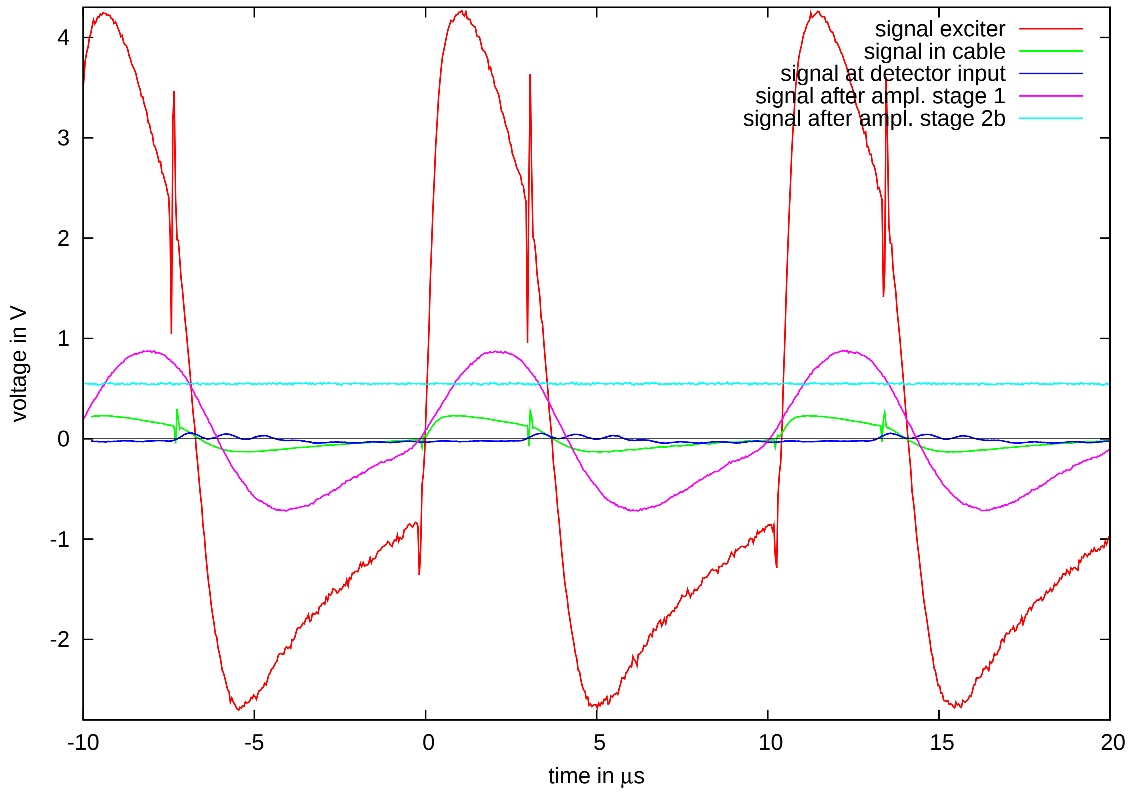

Figure 12: short cable

Different colors of the lines mean different stages where the signal was recorded.

The first one in the order is the red curve; it is the direct output signal of the exciter, with rather high amplitude. High output amplitude was our main goal at the improvement of the exciter circuits. The characteristics are dominated by the transistor, especially the peak at the sloping edge.

The next step is the signal induced in the tested coaxial cable, it is the green signal. Its amplitude is about ten times smaller than the one of the exciter (red). That's the reason why we improved the output power of our exciter. We measured the voltage in the loop of the coaxial cable by inserting a small resistance ($< 1\,\Omega$).

Because we use a second coil, the Rogowski coil, to pick up the signal form the cable, signal characteristics will change further. This is the dark blue line, which is also the input of the detector. Amplitude decreases a second time to the lowest level of about 0.06 V, and some oscillation with a higher frequency occurs. A reason for that could be higher harmonics of the

Rogowski coil.

As you know from above the input signal is filtered for the exciter frequency (about 100 kHz) and amplified in the first stage of our detector, we get a fairly clean sine-like function with an amplitude of almost 1 V. So in the first stage the input signal is amplified by a factor of about 15.

The last plotted signal is a constant light blue line. It is the output signal of the rectifier bridge and respectively the input for the built-in voltmeter.

In a second assembly we replaced the short coaxial cable with a 10 meter one, see fig. 13. As expected, all amplitudes except the exciter output decreased by a factor of about five. We also get some higher harmonics in the signal measured in the loop of the 10 m cable. In the end, the signal after the first amplification stage is quite clean sine-like.

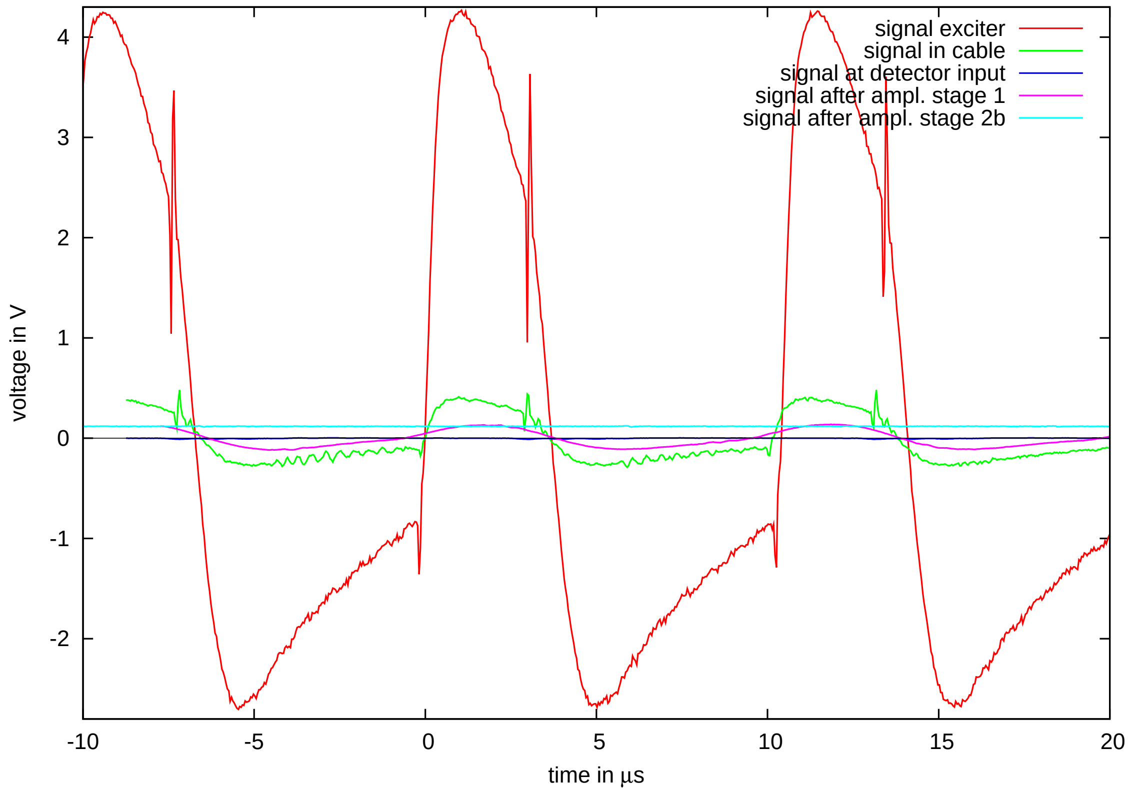

Figure 13: long cable

What to do if the cable length extends further?

The signal will decrease more and more until it's not separable from the background. More power to the exciter output will require a stronger power supply and new components and circuits. Likewise a stronger signal induced in the tested system could probably harm sensitive equipment.

A quite simple solution lies in the design of the Rogowski coil. It consists of a copper wire warped around a flexible plastic tube. Its flexibility and length allows us not only to wrap it just one time around the cable, but to make an additional winding. So, two windings of the Rogowski coil mean a double flux of the magnetic field through it. Accordingly this leads to an increase of the amplitudes. This is what Maxwell told us in his equations:

$$\vec{\nabla} \times \vec{B} = \mu_0 \left(\vec{j} + \epsilon_0 \frac{\mathrm{d}\vec{E}}{\mathrm{d}t} \right)$$

$$\vec{\nabla} \times \vec{E} = -\frac{\mathrm{d}\vec{B}}{\mathrm{d}t}$$

In figure 14 the advantages of wrapping the Rogowski coil two times around the tested cable is directly visible. The red and the green lines are the signals at the detector input resp. output of the Rogowski coil.

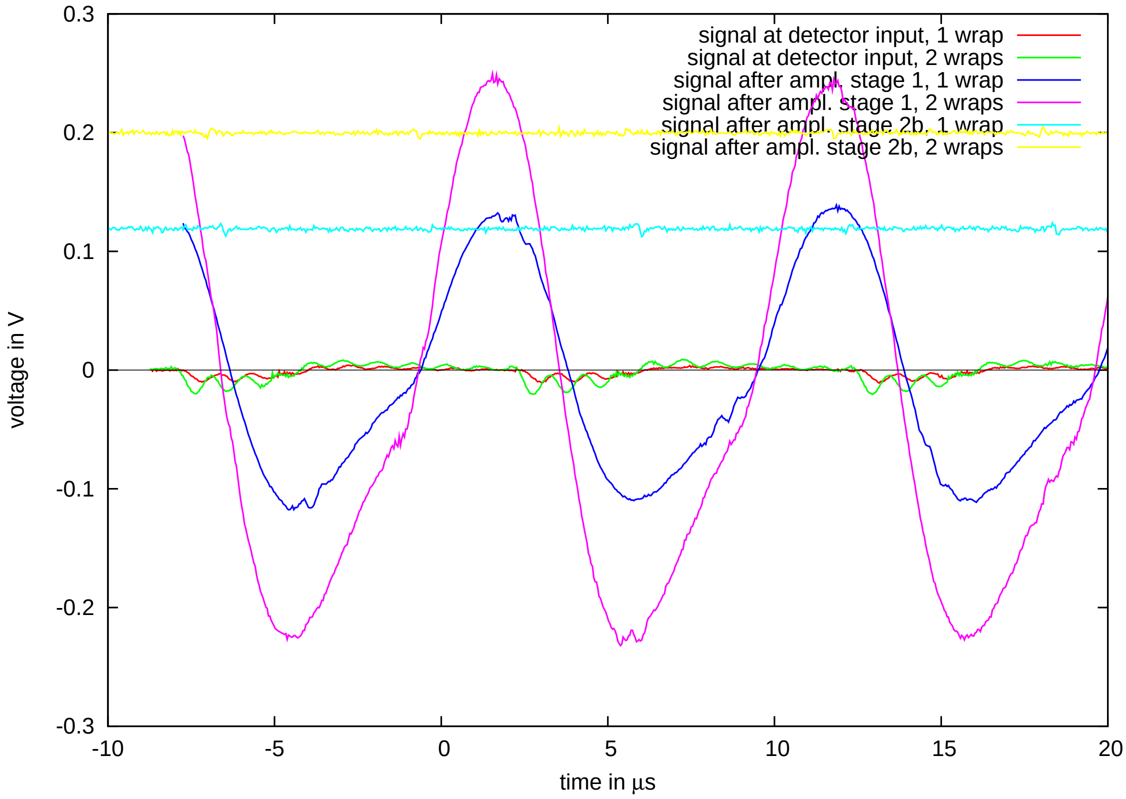

Figure 14: 1 vs. 2 wraps of the Rogowski coil

Amplitude of this input signal with two wraps is about two times higher than using just one warp. This factor two is present in all following stages, so Maxwell seems to be right.

5 Conclusions

The maximum of windings we can achieve with our hand-made Rogowski coil is three, so there is still some back-up to test longer cables. Form these values you can expect that the setup is working at least up to 25 meters of cable, which would hopefully be enough for a typical small laboratory assembly.

Important for a clear identification of the induced signal is also a significant difference between a closed loop of cable and just a cable with unconnected endings, because our aim is to search for ground *loops*. With the built-in voltmeter we were able to compare the signal received at a closed loop and an unclosed one. Using the 10 meter coaxial cable a closed loop produces a DC signal of $\sim$120 mV, by opening the connection the signals drops to a value < 10 mV. So it is indeed possible to make a diversification, whether the loop is closed or not.

It is clear that the LED driven by the 2a amplification stage is just a relative weak indicator compared to the built-in voltmeter. A LED needs a certain voltage to run, so we assembled a potentiometer to adjust the sensitivity of the LED indication. Due to the amplification circuits it is not possible to cover a wide range with the LED indication. For short cables (< 5 m) the LED works well, if the tested cables are longer, one should refer to the voltmeter.

References

[1] P. M. Bellan
Simple system for locating ground loops
Review of Scientific Instruments 78, 065104 (2007)

A Acknowledgments

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B Instructions – How to use the ground loop detector

Let's consider we'd like to test a system consisting of an instrument #1 connected in some way with an instrument #2 as shown in fig. 1. Both instruments are linked to the ground by their power cord.

First step is to place the exciters ferrite split core around the power cable of the instrument one likes to test, let's say instrument #1. By switching on the exciter, the 100 kHz test current is induced into the power cord, consisting of the two wires conducting the AC voltage and the ground wire. Instrument #1 got certain signal out- and inputs, which could be shielded or not.

Next step is to wrap the Rogowski coil around all of them. If it is necessary (due to long cables) or possible (not too many or too thick cables) one should warp it more than just one time around to get a stronger signal. After switching on the detector one should try to tune the sensitivity of the LED starting form the lowest level, in that way that the LED is just running.

First indication of a ground loop could be achieved by switching off the exciter. If the LED turns off in this moment, there is a closed ground loop in the system.

A stronger indication, as mentioned above, is the value of the built-in voltmeter. A significant difference between enabled and switched-off exciter. We could not give certain values, whether higher or lower values denote a ground loop or not. But with a bit practice one could easily get a feeling. As said above, the difference is the significant value.

Now let's consider we found a ground loop in the system. The next information we need is the identity of cable(s) originating the ground loop. In some cases the number of input and output cables of an instrument could be high, so one should take subgroups of cables. If a subgroup of cables causes a ground loop, it's recommended to split the subgroup again and again until the cable or cables causing the ground loop are isolated.