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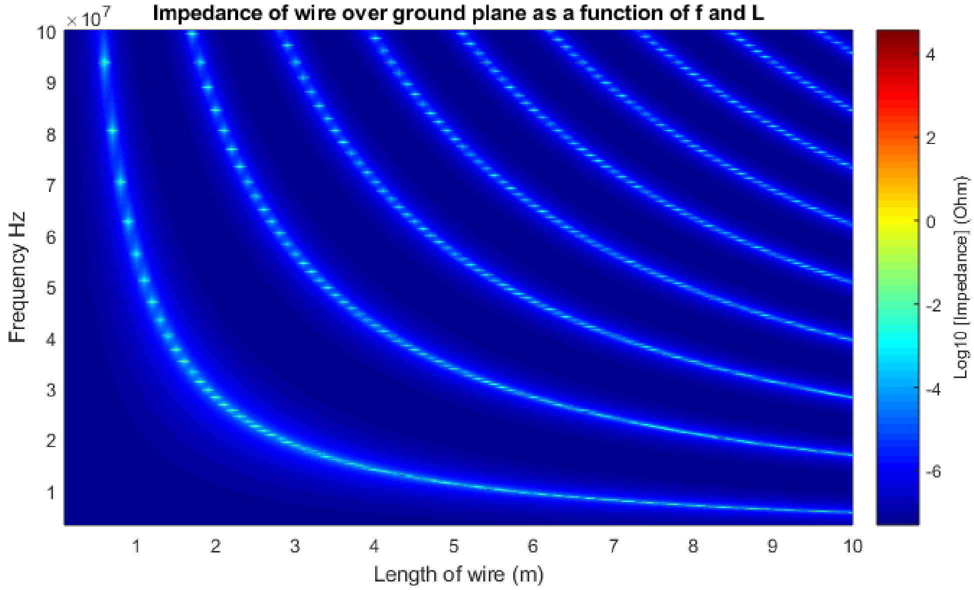

Method development for resonance characteristics

Comparament of portable measuring methods designed to examine the frequency behaviour for cables and decoupling networks whinin the automotive industry.

Master's thesis in Applied Physics (MPAPP)

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Department of Electrical Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

MASTER'S THESIS 2019:NN

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Cover: Impedance characteristics of a cable over a ground plane as a function of frequency and length.

Typeset in LaTeX
Gothenburg, Sweden 2017

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Abstract

This report aims to find the best suitable method for finding and analyzing resonance behaviour in ground cables and decoupling networks for automotive application. It starts by giving an introduction to the physics and mechanics behind cables and capacitors. The different methods tested and studied are presented witch make use of network analyzers, oscilloscopes, various probes and equipment. The conclusion being that some work better in particular situations, but a common factor is the use of a network analyzer and in some the use of good current transformers. It's concluded that further work need to be conduced in order to find the optimal setup and measurment method.

Keywords: resonance, ground cables, electrical engineering, Network analyzer, decoupling network, two-port network.

Acknowledgements

Even though I am the only author of this thesis I surly couldn't have done it by my own. There are many people that have helped me along the way during this project. Firstly I want to thank my suppervisor and mentor Bo Elm for helping me along the project and for teaching me more about practical electrical engineering. Secondly want to thank Xin Hu, Björn Starmark and Jonas Rinman for helping me with their expertise. I also want to thank Jonas Wålström for being a great manager and for giving me access to the spaces and equipment I needed. Some side test where carried out at Jan Linders EMS-laboratorium and of this I am gratefull, so a thanks to Jan Linders and his staff for letting us use his lab for some tests. Latstly I want to give a special thanks to my examiner at Chalmers Jian Yang for taking his time and letting me do this project.

Fredrik Wennermark, Gothenburg, June 2019

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List of Symbols and Abbreviation

The next list describes several symbols that will be later used within the body of the document

Ω	Ohm (Unit of Resistance and Impedance)
ω	Angular Frequency
C	Capacitance
c	Speed of light in a vacuum inertial frame
DUT	Device under test
ECU	Electric Control Unit
EMI	Electro Magnetic Interference
F	Farad (Unit of Capacitance)
f	Frequency
f_0	Resonance Frequency
H	Henry (Unit of Inductance)
j	Imaginary number
L	Inductance
NF	Near Field
R	Resistance
S	Scattering Parameter
Z	Impedance
Z_0	Characteristic Impedance

1
Introduction

1.1 Bakground

The cars of today look nothing like the first cars except for the four wheels. The numbers of features in cars have grown immensely and most of them have some electronic components and hence the costs of the electronic systems as a fraction of the total production cost of the car have grown from 1% in 1950 to 35% in 2010 and are expected to reach 50% in 2030 [1]. With more electronics comes the need for more cables and communications between the electronics. The electronic features are often connected to a Electronic Control Unit(ECU) that takes care of the electronics and distributes the signals to other places in the car. The number of such ECUs have also grown lately, with numbers up to 150 individual ECUs in the same car [2].

With this growth in electronic parts come problems. All components are designed to run at specific voltages and currents, if these parameters are compromised the component can behave badly or in worst case be destroyed. There are a lot of ways where the cables can experience unwanted change in signal, for example it can pick up Electromagnetic(EM) signals from surrounding components that leak these or it can be indirectly connected to some component through common ground that leaks current to the main component. How well a signal travels through a cable is partly dependent on its impedance as from Ohm Law. And this impedance is dependent on frequency, hence it would be good to know how this frequency behaviour looks [3].

1.2 Aim

The main outcome of the project is to develop a "in car" test method to measure resonance characteristics in the internal electronics on the CEVT platform. The method will mainly cover the resonances in the ground cables and at the decoupling capacitor clusters in ECUs.

Another outcome is to try to simulate these resonances for a simplified system of the car platform, and again looking at the ground cables and decoupling capacitors.

1.3 Limitations

In this report some limitations are present. Firstly I will stress the time frame. This work was carried out over roughly six month, and therefore somethings had to be ignored in the scope of this project. For example, this report will not focus on finding the actual impedance value of the resonance peaks and anti-peaks, instead the main focus will be to find the frequencies where these resonance behaviours are located.
Since the work was carried out on the company CEVT AB the methods that where developed where developed with CEVT at hand, i.e all the methods that where developed and tested can be used with the equipment that CEVT possesses. With this I also what to point out that with more equipment and time there could surly be a more effective method for this scope.

2

Theory

2.1 Introduction

This section will provide the knowledge and understanding that is needed to replicate and understand the result that is presented later in the thesis. It will cover the basics of how signals travels cables, why resonances occur and the problems with that. It will also touch on the relevance of resonances in capacitors and how one can measure the impedance of a system.

2.2 Cables

The wave nature of electromagnetism states that there will be conditions such that EM-waves will create standing waves and resonate. A cable is a perfect medium for a standing wave, since the inside and outside have vastly different refraction indices the wave will be trapped and create a standing wave. This happens at different frequencies dependent on the length of the cable and are also dependent on if the ends of the cable is connected or not. It is also dependent on how fast the wave can propagate through the wire. As known a EM signal propagates at light speed in vacuum but at other media it will be slowed down in some way. This property is described by the velocity factor(v_f), i.e a fraction of light speed. A normal coaxial cable has a velocity factor around 0.6-0.8. In equation 2.1 below the resonance frequency is calculated as a function of v_f, n (Harmonics number) and L (Length of the cable).

$$f_0 = \frac{c * v_f * n}{2 * L} \tag{2.1}$$

In fig 2.1 the resonance frequency is plotted as a function of the length of the cable for the first four harmonics.

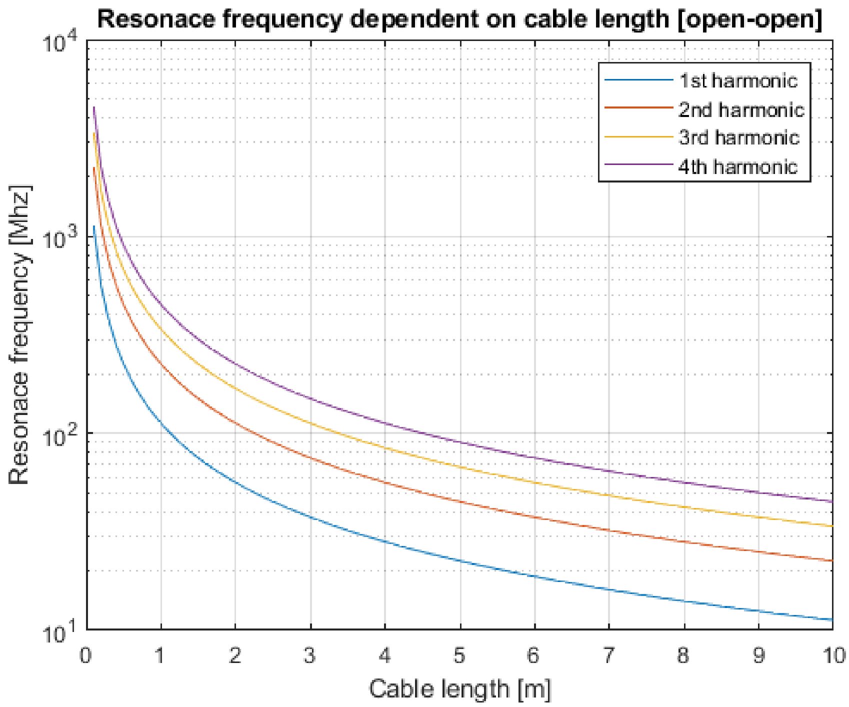


Figure 2.1: Resonance frequency as function of cable length [Both sides "open" or "closed"]

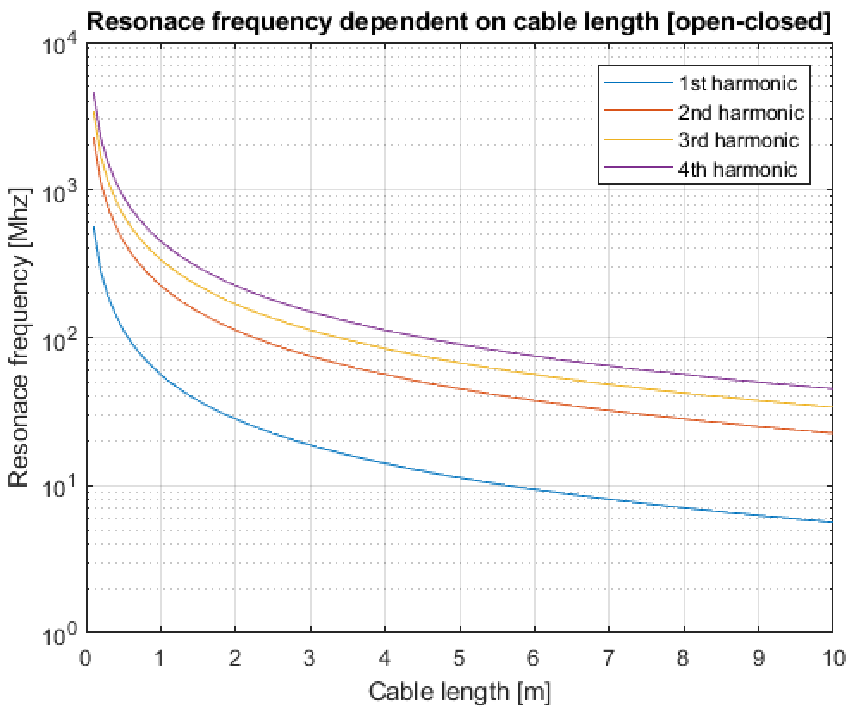


Figure 2.2: Resonance frequency as function of cable length [one end "open" one "closed"]

2.2.1 Ground wire

For a return wire running over a ground plane as in the case on many locations in the car, the ground cables can have EMI problems dependent on the design and operation. One treats the system as a transmission line and can therefor take use of the knowledge from transmission theory. The equivalent circuit can be drawn as below, see figure 2.3[4].

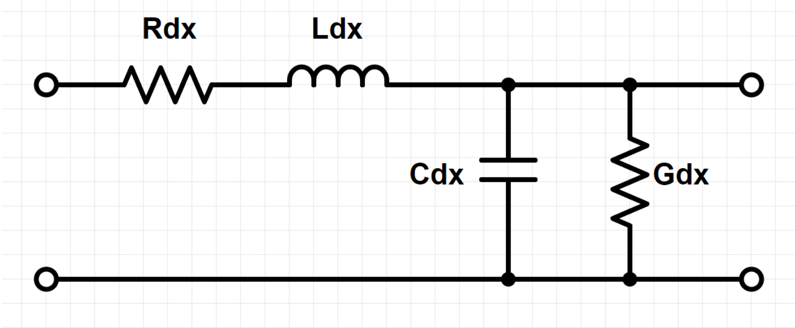


Figure 2.3: Cable schematic

and the characteristic impedance of the system can be calculated as equation 2.2

$$Z_0 = \sqrt{\frac{R + jwL}{G + jwC}} \tag{2.2}$$

Where R and 1/G is in $\Omega/Length$, L in $H/Length$ and C in $F/Length$. If the system is treated as lossless, equation 2.2 reduces to

$$Z_0 = \sqrt{\frac{L}{C}} \tag{2.3}$$

The crucial impedance of the system is not Z_0 but the impedance looking into the wire of finite length l. This impedance is denoted Z_{in} and for a loss less transmission wire is derived as.

$$Z_{in} = Z_0 \frac{Z_L + j * Z_0 tan(\beta l)}{Z_0 + j * Z_L tan(\beta l)} \tag{2.4}$$

where $\beta = \frac{2\pi}{\lambda}$. An ideal grounding setup looks something like figure 2.4 below. For a grounding connector connecting to a ground plane there is ideally no loss and hence no impedance and therefore $Z_L = 0$. The Z_{in} is then reduced to

$$Z_{in} = Z_0 * j * tan(\beta l) \tag{2.5}$$

As seen from the equation above the impedance for the ideal case is purely imaginary and therefor reactive rather than resistive.

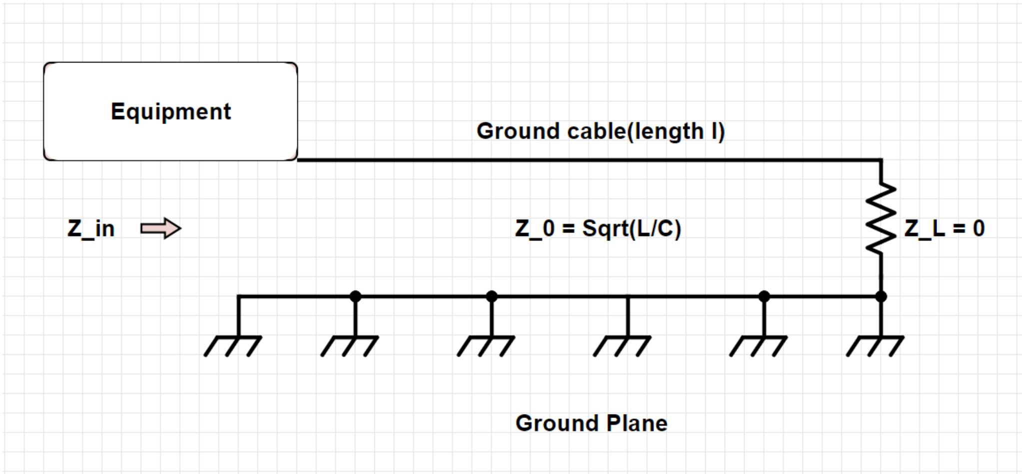


Figure 2.4: Cable over ground plane schematic

A plot for Z_{in} with a fixed cable length of $2m$ is shown in fig 2.5 below. As can be seen there are some clear resonance peaks at different frequencies and the spacing between the peaks decreases as the frequency increases. In this purely loss less case these peeks will be infinitely high, but in real life no system is truly loss less and hence the peaks will be finitely bound.

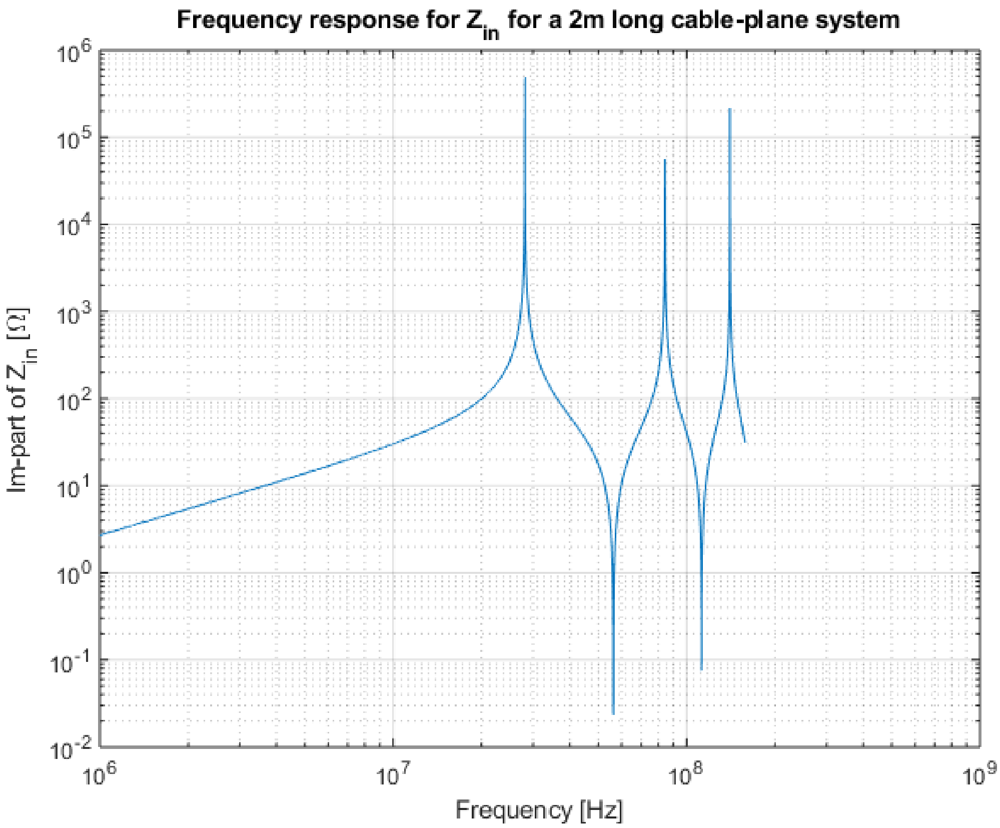


Figure 2.5: Impedance characteristic for 2m long cable over ground plane.

For a cable with a different length there will be a different response. For a longer cable there will fit more peaks in the same frequency spectrum and they will also be shifted left in to lower frequencies. In fig 2.6, Z_{in} is plotted with respect to both frequency and cable length. It also shows which parts of the landscape that's negative/positive. This is crucial to know since a positive imaginary Z_{in} corresponds to a phase shift of $\pi/2$ and a negative imaginary corresponds to $-\pi/2$ in phase shift.

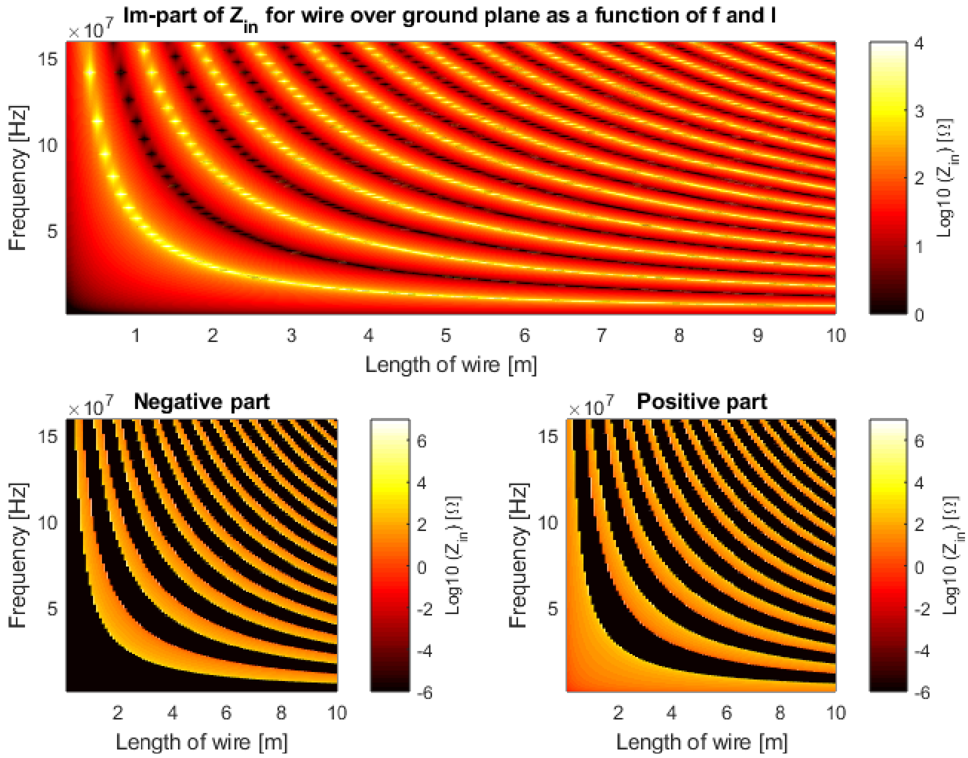


Figure 2.6: Impedance as function of frequency and length for cable over ground plan

2.2.1.1 Real life

As shown above it's quite easy to simulate the resonate characteristics of one wire-plane setup. But in real life in the car there are lots of things that makes it enormously complex. Below is a list of some issues that make the model in previous section not accurate.

- Lots of cables run parallel with each other down to the same ground plane.
- Parallel cables can be twisted around each other which will make the distance down to ground plane longer and hence affect the capacitance down to the plane lower.
- A wire can change direction along the way to the plane, thus not being parallel with the plane.
- The ground plane itself is usually so large that there will be a potential difference of some millivolts across it.

2.2.2 Attenuator

All that is needed to know for this thesis is that an attenuator is an electronic device that passively reduces the amplitude of any given signal. This can be done by different kinds of circuits, but the most common is a Pi-pad and a T-pad (see figure 2.7). The amplitude is reduced trough voltage dividers with purely resistive resistors. The use of attenuator in this project is mainly to reduce noise and to better match impedances between different components.

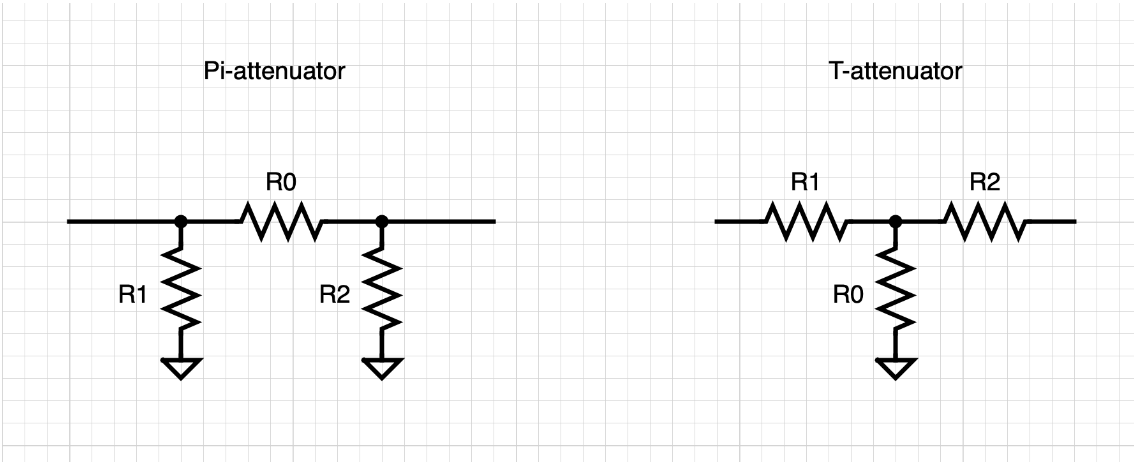


Figure 2.7: Diagram over a Pi-attenuatro(left) and a T-attenuator(right).

2.3 Capacitors

2.3.1 Introduction

An ideal capacitor's impedance is frequency dependent as through eq

$$Z_{Ideal} = \frac{1}{i\omega C} \tag{2.6}$$

Where $\omega = 2\pi * f$. But no capacitor is purely capacitive but also resistive and inductive and can best be described by

$$Z_{cap} = R_{cap} + j\omega L_{cap} + \frac{1}{j\omega C} \tag{2.7}$$

If the absolute value of 2.7 plotted for some typical values on R, L and C following frequency response is obtained

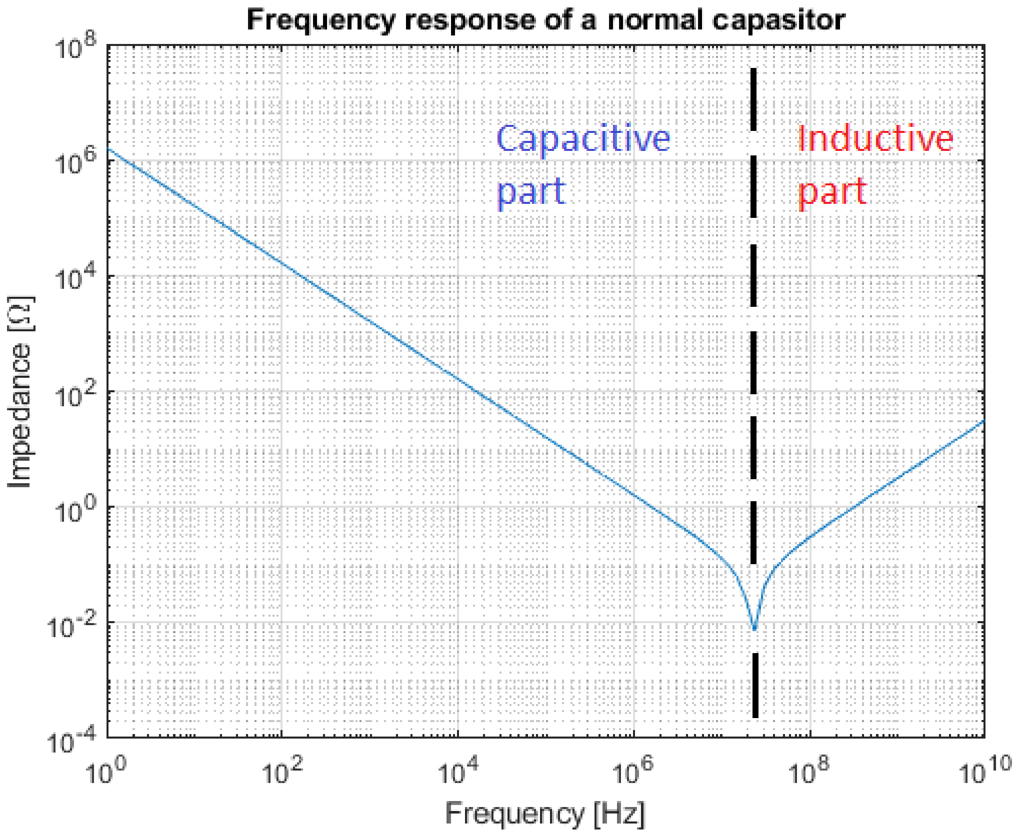


Figure 2.8: Frequency response for a real capacitors

At the resonate frequency the impedance is at it's lowest and can be derived as

$$\frac{d|Z_{cap}|}{d\omega} = L_{cap} - \frac{1}{\omega^2 C} = 0 \tag{2.8}$$

which leads to

$$\omega^2 = \frac{1}{LC} \longrightarrow \omega = \frac{1}{\sqrt{LC}} \tag{2.9}$$

And since $\omega = 2\pi f$ equation 2.10 shows the resonance frequency of the capacitor

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{2.10}$$

Below this frequency the capacitor acts as it should, i.e like a capacitor but above this point the capacitor starts to work more like an inductor. Depending on the values of L and C this anti-peak will move left or right. The value of the internal resistance moves the anti-peak up or down.

2.3.2 Decoupling capacitors

To reduce noise and transients to harm any equipment a decoupling capacitor is commonly used. A decoupling capacitor shunts the noise down to ground before reaching the sensitive equipment. Since a capacitor has one specific resonance frequency where it's impedance has the lowest value, one needs different types of capacitors to cover a broad range of frequencies. In figure 2.9 is a typical setup for a decoupling network.

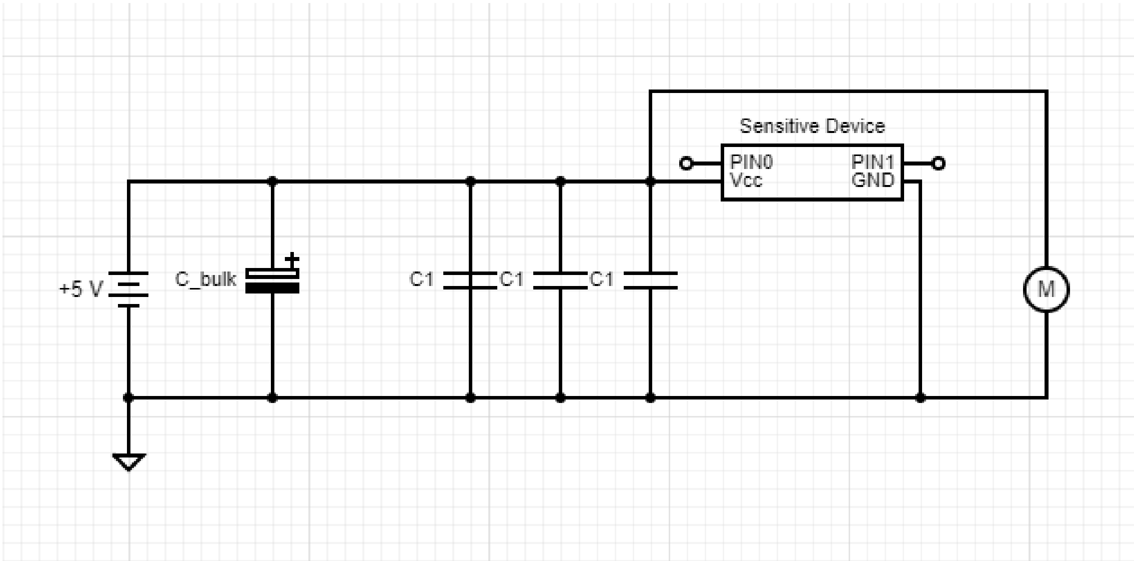


Figure 2.9: Schematic for typical decoupling network

This would be all fine if the capacitor resonances just added together but when different capacitors is combined like this in parallel one has to calculate with the inverse impedance instead and this will give rise to bad anti-resonances. In figure 2.10 there are two different capacitors of different values. Their individual frequency response is plotted as the dashed lines. But when put in parallel they gives rise to a spike that has very high impedance compared to the normal behaviour. As seen from the plot the impedance can differ of a factor 500 for just a small change in frequency. This means that the decoupling network would be able to pull 500 times less of the harmful current from reaching the sensitive device and hence at this anti-resonances the decoupling network would not work and could damage other components or cause harmful EMC issues like conducted emissions or conducted susceptibility issues.

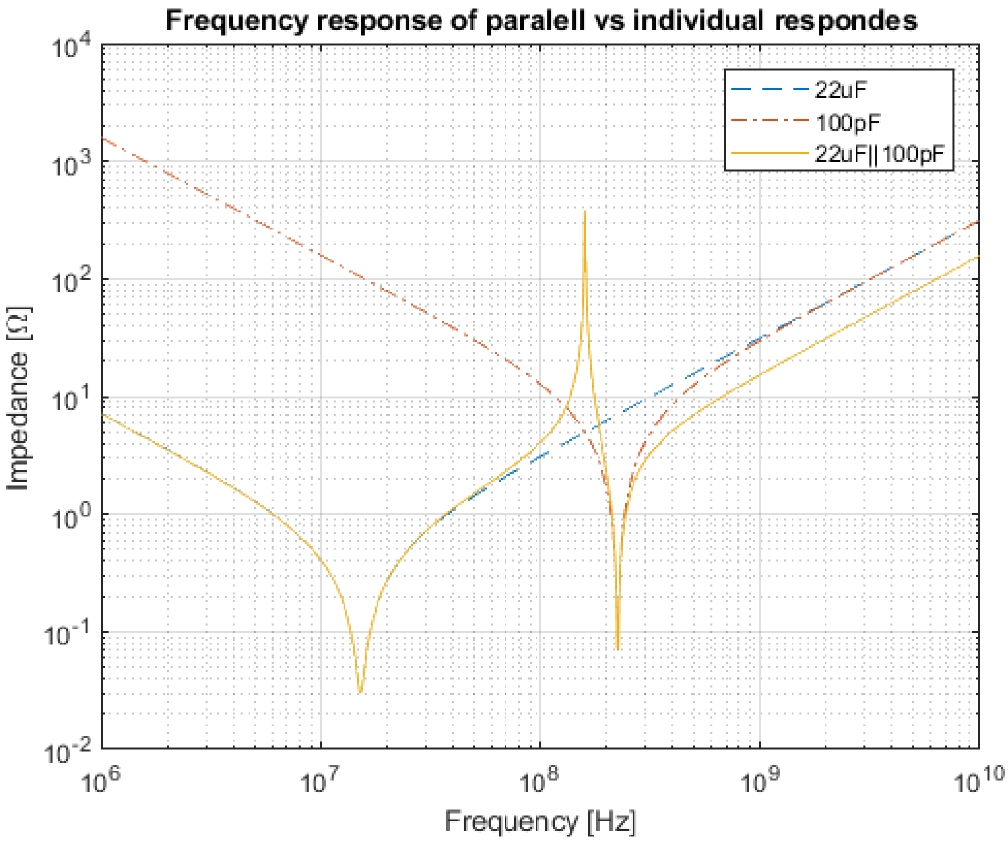


Figure 2.10: Capacitor resonances for two arbitrary capacitors

2.4 Two-port network

Since it's extremely difficult to simulate all components in an effective way it would be better to have an measuring method that you could apply to the car. All the above results are presented in the Z-parameter i.e impedance, but in most measuring devices it's more suitable to measure in the S-parameters (scattering parameter) which is showing how big relative part of the signal power is reflected(S_{22}) or scatter(S_{21}) as a ratio of the generated wave. The S-parameters for a two-port system are defined as equation 2.11 below with notation as figure 2.11

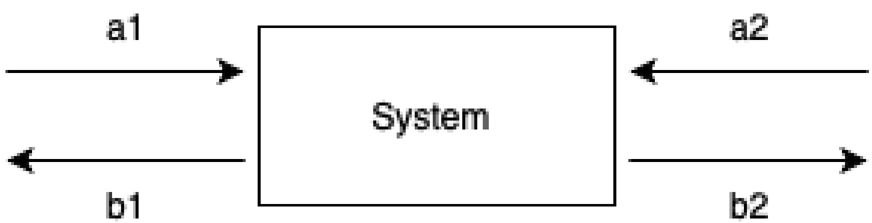


Figure 2.11: Two-port network

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \times \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \tag{2.11}$$

or

$$b_1 = a_1 * S_{11} + a_2 * S_{12}$$
$$b_2 = a_1 * S_{21} + a_2 * S_{22}$$

To be able to compare with simulation results and also be able to see where the resonate peaks is located it would be good to be able to convert between S- and Z-parameter. This can be done trough the $ABCD-parameters$. They work similar to the $S-parameter$ but are easier to work with. The $ABCD-parameters$ is defined as

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \tag{2.12}$$

Where

$$A = \left.\frac{V_1}{V_2}\right|_{I_2=0}, B = \left.\frac{V_1}{I_2}\right|_{V_2=0}, C = \left.\frac{I_1}{V_2}\right|_{I_2=0}, D = \left.\frac{I_1}{I_2}\right|_{V_2=0} \tag{2.13}$$

With notation as figure2.12

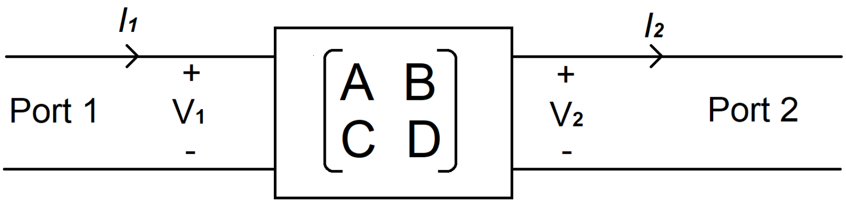


Figure 2.12: ABCD description of two-port network

The ABCD is very easy to work with since if a system can be divided in to n subsystem then the total system responce is just the matrix product of those subsystem i.e

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{Tot} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_1 \begin{bmatrix} A & B \\ C & D \end{bmatrix}_2 \cdots \begin{bmatrix} A & B \\ C & D \end{bmatrix}_n \tag{2.14}$$

Another benefit with these parameters is that if you know what one of your subsystems consists of you can find tabulated results for that system. Per example, if you know a part of the system can be described as a series impedance then you know that

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{S-Imp} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \tag{2.15}$$

where Z is the impedance of that sub system. More conversions can be found in Appendix.. And since most instruments measure in $S-parameter$ it would be nice to convert between the S- and $ABCD-parameter$ as well. This can be done and is presented in eq

$$A = \frac{(Z_{01}^{*} + S_{11}Z_{01})(1 - S_{22}) + S_{12}S_{21}Z_{01}}{2 * S_{21}\sqrt{R_{01}R_{02}}} \tag{2.16}$$

$$B = \frac{(Z_{01}^{*} + S_{11}Z_{01})(Z_{02}^{*} + S_{22}Z_{02}) - S_{12}S_{21}Z_{01}Z_{02}}{2 * S_{21}\sqrt{R_{01}R_{02}}} \tag{2.17}$$

$$C = \frac{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}}{2 * S_{21}\sqrt{R_{01}R_{02}}} \tag{2.18}$$

$$A = \frac{(1 - S_{11})(Z_{02}^{*} + S_{22}Z_{02}) + S_{12}S_{21}Z_{02}}{2 * S_{21}\sqrt{R_{01}R_{02}}} \tag{2.19}$$

where Z^{*} is the coplex conjugate of Z. Or equvialently

$$S_{11} = \frac{A + B/Z_0 - CZ_0 - D}{A + B/Z_0 + CZ_0 + D} \tag{2.20}$$

$$S_{12} = \frac{2(AD - BC)}{A + B/Z_0 + CZ_0 + D} \tag{2.21}$$

$$S_{21} = \frac{2}{A + B/Z_0 + CZ_0 + D} \tag{2.22}$$

$$S_{22} = \frac{-A + B/Z_0 - CZ_0 + D}{A + B/Z_0 + CZ_0 + D} \tag{2.23}$$

When measurements on a symmetric system is made it can be assumed that $S_{11} = S_{22}$ and that $S_{12} = S_{21}$ which yields $Z_{11/22}$ and $Z_{12/21}$. And also $Z_{11/22}$ is the same as $Z_{in/out}$.

3

Results

3.1 Cables

This section will address the methods of finding resonance behaviours in cables.

3.1.1 Vector network analyzer

When using a network analyzer there are lots of different ways to use it. There are direct measurements, where the ports are directly connected to the DUT, which has the advantage of not needing any extra test probes that can interfere with the test setup. On the contrary one has to be careful not to damage the DUT, since you have a direct contact and thus send the test current directly in to the DUT.

First some tests were carried out to see which type of probes and setup to use for a normal non impedance measurement.

3.1.1.1 Probes

A test was then done to see if two different methods of picking up the signal gives the same result and to investigate if one is better than the other. The two different methods tested where

- Current probes on both in and out ports

- Current probe on the generation port and a magnetic NF probe on the pickup port.

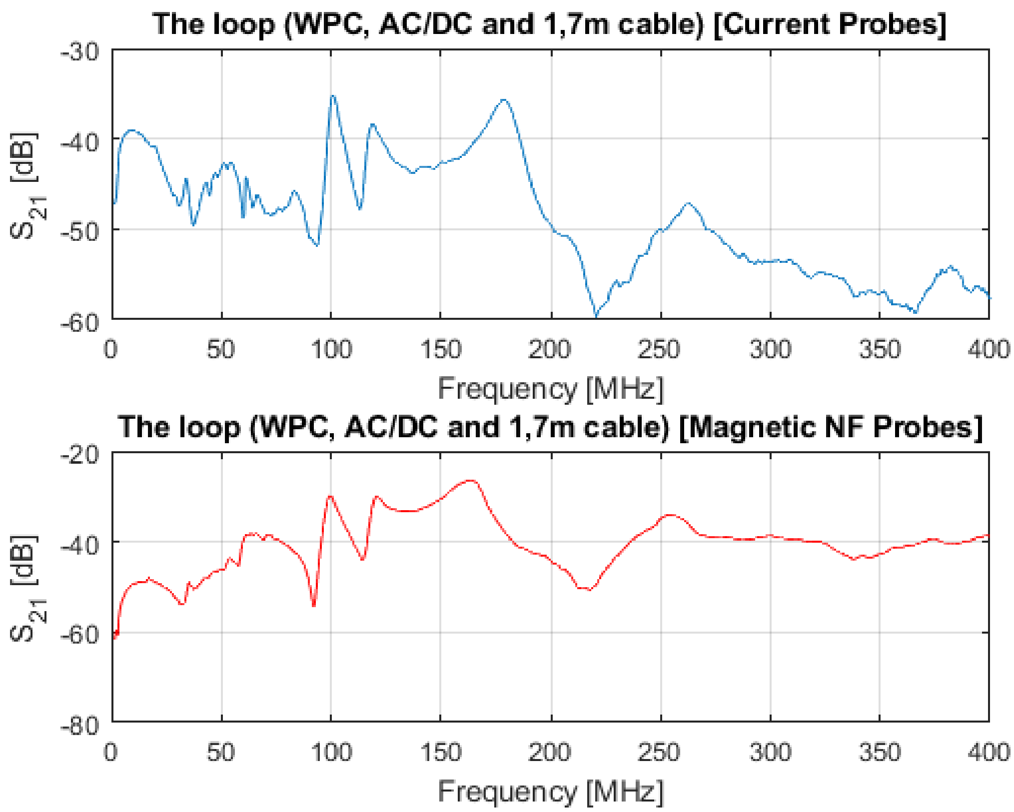
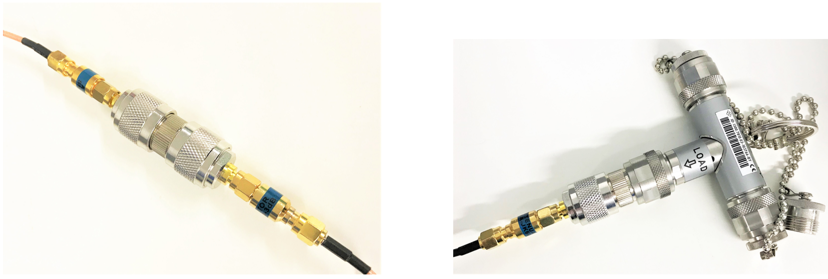


Figure 3.1: Comparison between magnetic and current probes

As can be seen from figure 3.1 they both looks quite similar, at least the peaks show up at the same place. This comparison has been done for different DUTs and they all show the same pattern. The one with both the current probes shows a bit more clearly where the peaks are and seems a bit more accurate. Furthermore the current probes is much easier to handle and place at the right position and angle, as for the NF magnetic probe one needs to hold it in place during the measuring process. There are some difference in portability as well. The current probes where passive with no power supply from the instrument, as for the magnetic NF probe which needs an external amplifier connected to a power supply. Portability is listed as a key factor in the requirements which makes current probes more favourable. With this test it can be concluded that current probes on both port is more favorable than a magnetic NF probe on the pickup port.

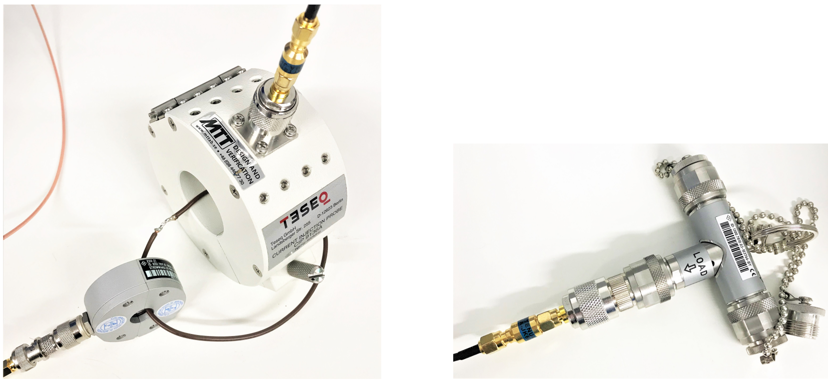
3.1.1.2 Calibration

In order to get accurate result the Spec has to be calibrated, this can be done in different ways. There is a calibration kit provided by the manufacture with load, short and open ports. A S12 calibration consist of a "Through" calibration and a "Load" calibration. The easiest ways to calibrate is to attached the cables that will be used to the current probes and then calibrate with those attached. The problem with this method of calibration is that the effects of the current probes won't be eliminated. Another calibration method could be to have a small cable loop through both of the probes and then calibrate the "Through" and the calibrate the "Load" as the same way as the easy calibration. The benefits of this method is that the effects of the probes are eliminated but at the same time you suppress the response of the small cable loop. See figure 3.2 and 3.3 for calibration setup.



(a) "Through" connection **(b)** "Load" connection

Figure 3.2: Calibration setup of method 1



(a) "Through" connection **(b)** "Load" connection

Figure 3.3: Calibration setup of method 2

In order to see if this method of measuring is accurate a test was made on a cable with known length and estimated velocity factor. The resonance frequency of that cable can easily be calculated or be extrapolated from 2.1. The experimental result is shown in figure...

3.1.1.3 Probe position

Since the probes is manually placed along the cables, they can be positioned a lot of different ways. A test is needed to see if this position is affecting the result. A one meter cable was placed straight on a table top and measured with the probes that was concluded to be the best suited by section 3.1.1.1. Some different positions was tested. In figure 3.4 the setup is shown.

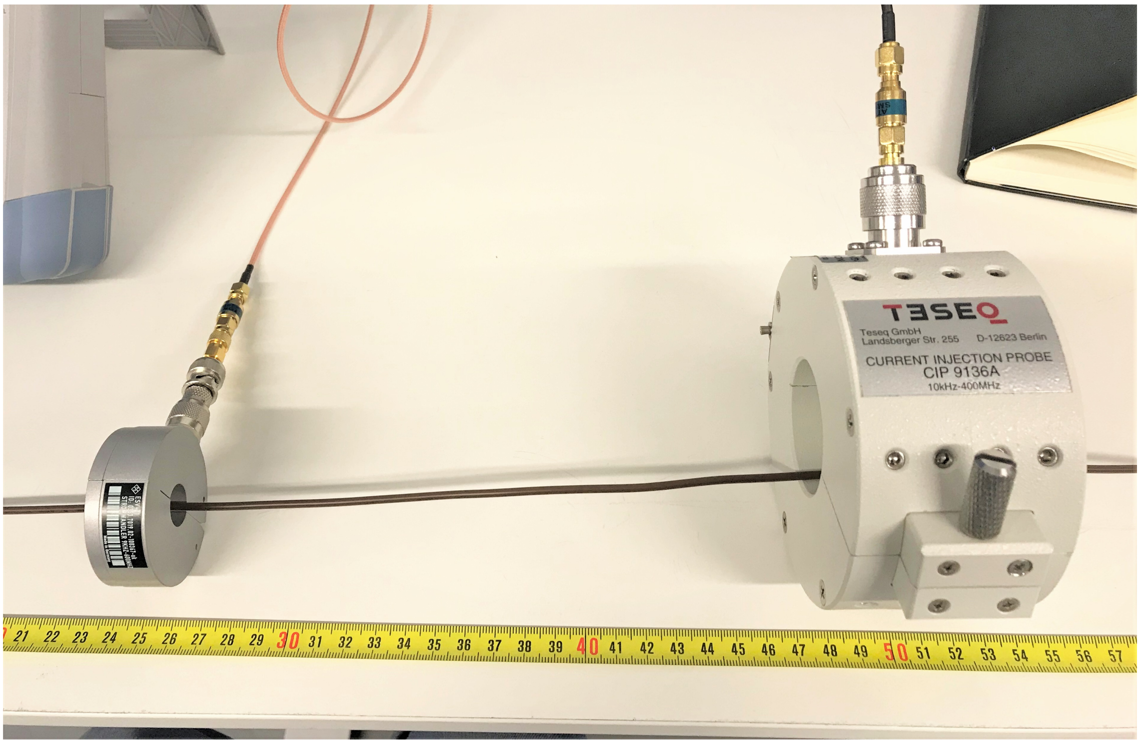


Figure 3.4: Test setup for P2 = 50cm ad P1 = 25cm

In figure 3.5 below the results of some of the positions tested are shown. They all looks quite different except that they all get the first harmonic peak of 112MHz right. From this results one can conclude that a standardized placement of the probes need to be determinate. Looking at the result both the first and 4th curve looks to noisy. The best one is the 2nd one since it gets the dip at the 2nd harmonic at 225MHz best and even the 3d harmonic in almost in the right place.

The conclusion is that the test that will be executed by this method will use the positions of the probes as follows.

Position injection probe (P2)	at 25% of cable length
Position pick up probe (P1)	at 50% of cable length

Table 3.1: Experimentally found optimal probe position

3.1.1.4 Dampers

Sometimes there are multiple reflections in the test setup that effects the test result, then attenuators can reduce the effect from the multiple reflections. There are most probably some dampers inside the VNA side of things, but the probes does not have any dampers and could therefor be good to have. A test to see if dampers is necessary can be shown in figure 3.6, here the measurements was made on a standard 100cm cable with open ends.

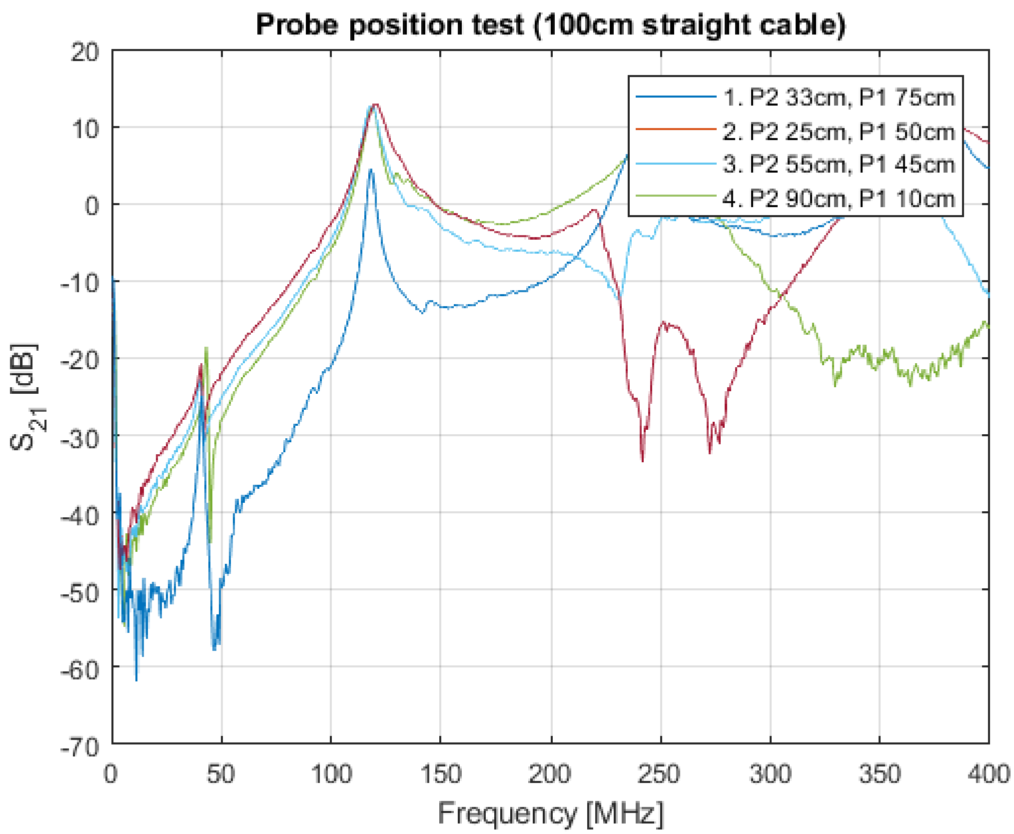


Figure 3.5: Four different probe positions. P2 = Injection port, P1 = Pickup port

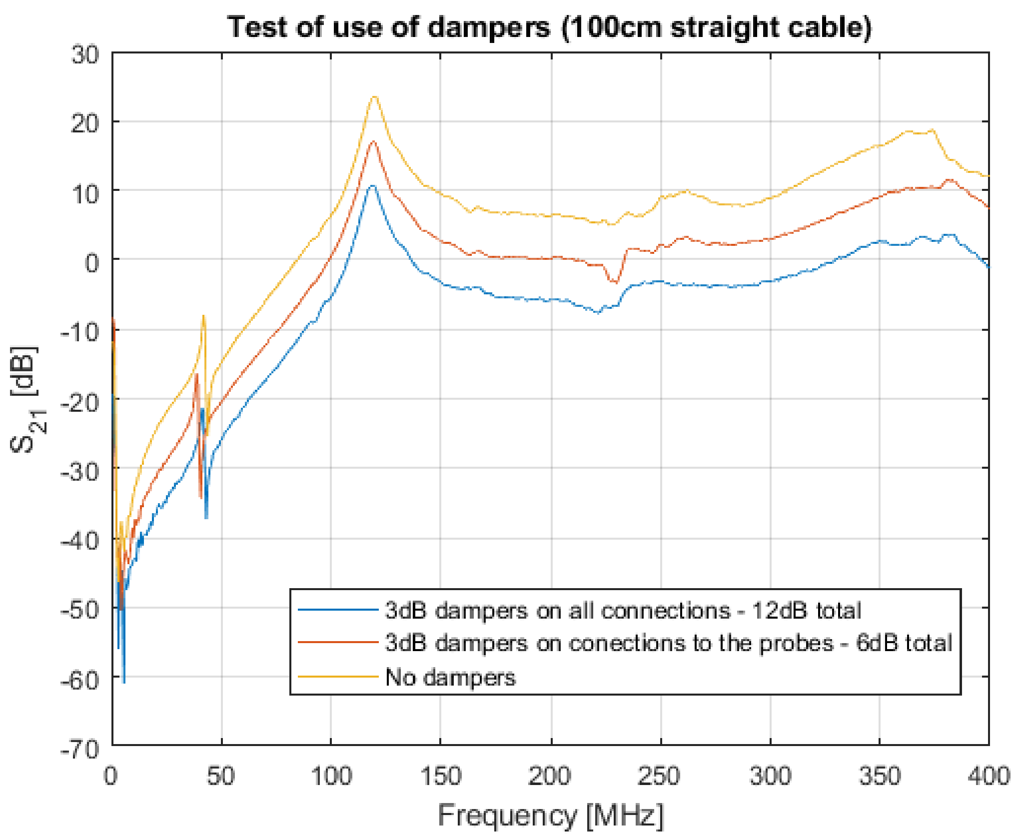


Figure 3.6: Damper test

The curves in fig 3.6 looks very similar except for the offset in amplitude that corresponds to the total damper value. This concludes that for this particular case dampers does not help the results, but for systems with more components connected like a ECU there maybe be a use for it.

3.1.1.5 A method with current transformers

The point of all these measurements is to develop a method for consistent and easy measurements. In the tests some different types of instruments have been used to test consistency and suitability. Using a network analyzer is a very good choice to get fast and easy frequency responses. To have a portable instrument is very important, the RS network analyzer I have tried suits this task perfect. Regarding the probes I would recommend to use current probes instead of magnetic near field probes since the current probes have a more stable response depending on how you place the instrument and they are easier to set up and deal with. It would be good if both probes can operate from some hundreds of kHz up to 400MHz. The instrument used have N-connections on it's port and so does most of the current probes but i would recommend that one uses adapters and use SMA-cables instead since they are smaller and therefore easier to move around. Smaller cables unfortunately have a worse performance at higher frequencies but at the range that is interesting in this case it still has good performance.

3.1.2 LCR-meter

A simple way to roughly check the impedance characteristics could be through an impedance measuring LCR-meter. The downside to this is that a simple LCR-meter only have a few different predifined sampling frequencies and thus it's hard to find any resonance behaviour with such a instrument. The upside if the instrument would have a lot of sampling frequencies is that no math would be needed to obtain the impedance.

3.1.3 Oscilloscope and signal generator

Another way to check the frequency response of a cable would be with a Oscilloscope and a signal generator. This is a technique that only show the resistance of the cable and not the full impedance and hence would not give a totally accurate picture but at least a check roughly where the cable behaves unwantedly. The ideal setup for such a measurement is described in figure 3.7

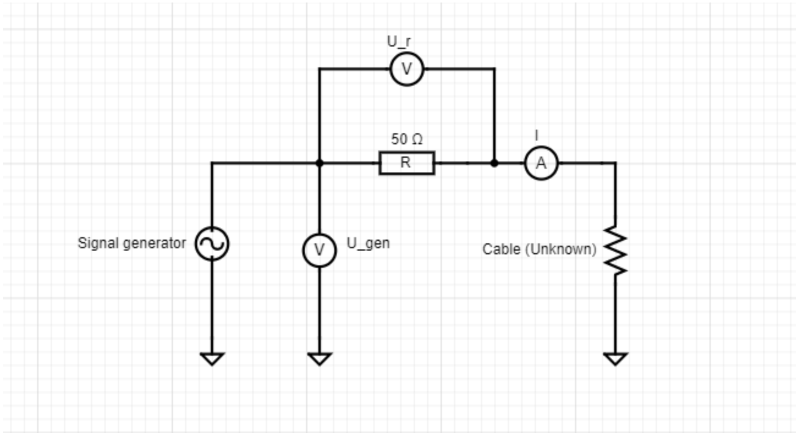


Figure 3.7: Schematics of ideal setup for cable resistance measurements

The corresponding equations for this system follow from equations 3.1 bellow.

$$\begin{aligned} U_c &= U_{gen} - U_r \\ I &= U_r/R \\ Z &= U_c/I \end{aligned} \tag{3.1}$$

Where U_c is the voltage over the cable and Z is the resistance over said cable.
But as usual no system is ideal and in this case the signal generator can not be modeled this simplistically, it will to have a internal resistance. In many cases as in this, that resistance is known and is 50Ω. The new schematic for the real case is shown in figure

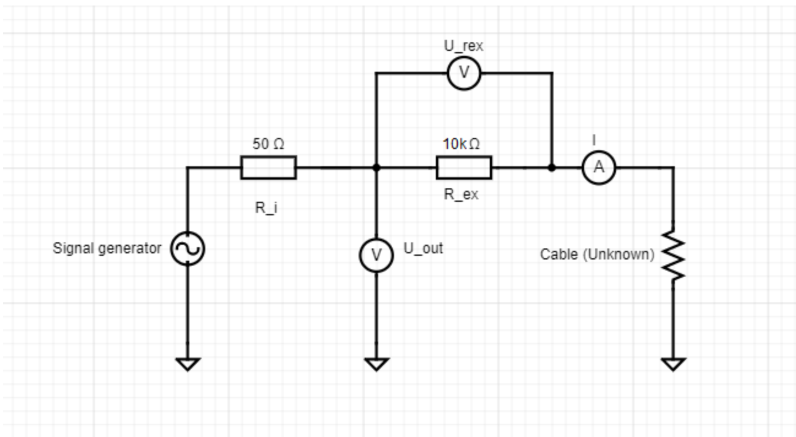


Figure 3.8: Schematics of realistic setup for cable resistance measurements

The equations in this case gets a bit more complicated but still quite trivial and is listed in 3.2 below

$$\begin{aligned} R_{tot} &= R_i + R_{ex} \\ U_{Ri} &= U_{Rex} * (R_i/R_{ex}) \\ U_{Rtot} &= U_{Rex} + U_{Ri} \\ U_{gen} &= U_{out} + U_{Ri} \\ U_c &= U_{gen} - U_{Rtot} \\ I &= U_{Rtot}/R_{tot} \\ Z &= U_c/I \end{aligned} \tag{3.2}$$

where Z is the desired impedance of the cable. The way it works is by connecting voltage probes as in figure 3.8 to the oscilloscope and optionally a current probe to be sure. The signal generator produces a sine-waveform with adjustable frequency. Pick a start frequency and then take average peak-to-peak measurements for the different probes then increase frequency with desired step and repeat until final frequency is reached. The setup from one of the measurements on a $1mm^2$ $1m$ cable is shown in figure 3.9

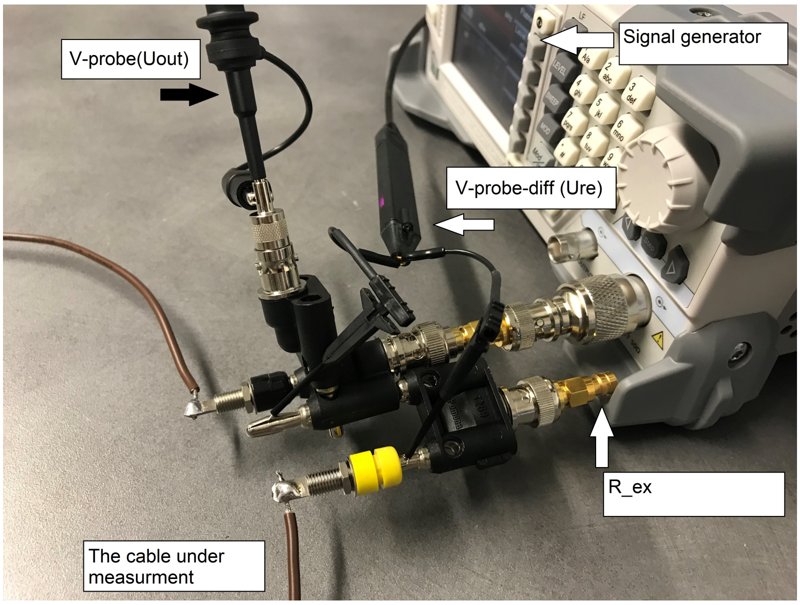


Figure 3.9: Setup of oscilloscope measurement

The results from such a measurement could be seen in figure 3.10. Examining the plot one can notice the three distinctive peaks roughly equidistant and in fact the 2nd peak is roughly at double the frequency as the 1st peak and the 3rd peak three times that frequency. This is exactly what is expected as it most probably is the 1st harmonics and its two first overtones.
One thing noting is the dip in the beginning and the end where the impedance is below zero which is nonphysical, This could either be caused by the phase which is not considered in this case, or it could be some other interference.

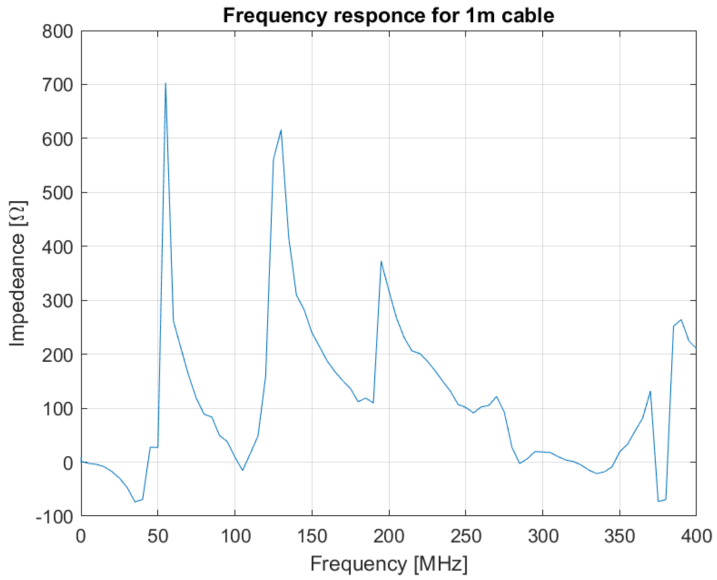


Figure 3.10: Frequency dependent impedance on a 1m cable measured with a oscilloscope and a signal generator

Another measurement was done on a 4m cable and is seen in figure 3.11. Here it is not as clear as the previous measurement. Since the cable is longer in this case the harmonics of the cable should be located lower in frequency. For a cable four times as long the 1st harmonic will be at a quarter of the frequency. Since the 1m cable had the 1st harmonic at roughly 55MHz the 4m one should have the same harmonic at ca 14MHz. A small fisrt peak can be observed near 14Mhz, but it's not as prominent as predicted.

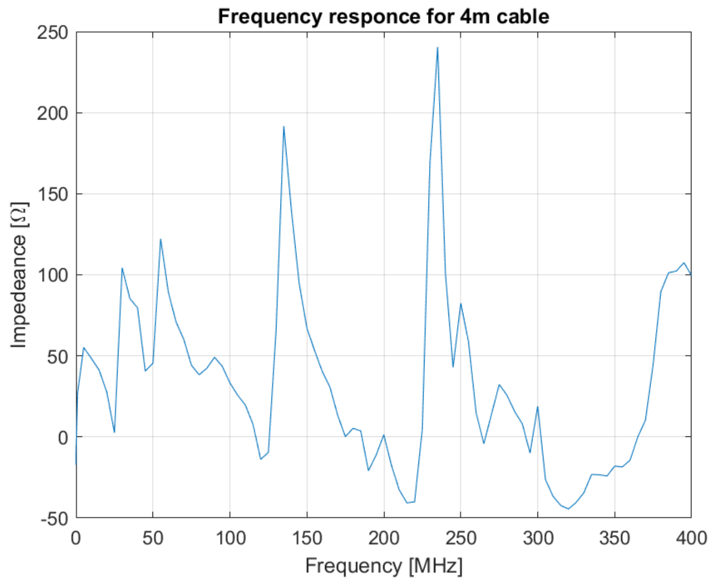


Figure 3.11: Frequency dependent impedance on a 4m cable measured with a oscilloscope and a signal generator

3.1.4 Shunt-through

Another fairly simple way to measure is with the so called Shunt-through method. This is also done with the VNA that has been used before. In this method you have your DUT placed to ground as shown in 3.12. One advanatge with the coming methods is that we can quite accurately find the impedance values. This is done with the math introduced in the Two-port theory in section 2.4. If we use 2.22 with the fact that in a shunt setup the ABCD matrix reduces to:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{Shunt} = \begin{bmatrix} 1 & 0 \\ Y & 1 \end{bmatrix} \tag{3.3}$$

Plugging 3.3 into 2.22 one yields

$$Z = \frac{1}{Y} = \frac{50}{2}\frac{S_{21}}{1 - S_{21}} \tag{3.4}$$

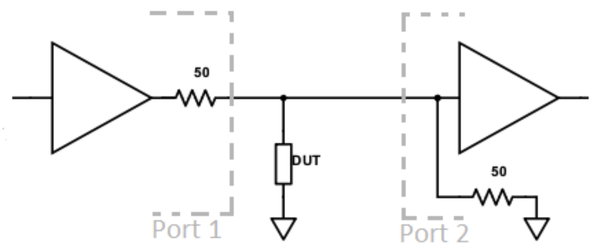


Figure 3.12: Shunt-through schematic

3.1.4.1 Validation

The test started by scrapping the old setup which consisted of a SMA connector soldered on a small Cu-board(see picture). The new setup was just the Cu-board. A 46 Ω Surface mounted resister was soldered parallel over the gap, see figure. 3.13. The first test showed some oscillation around 46 Ohm which is though to originate from miss-match from the setup so attenuators was added to dampen these mismatches. The result is shown in figure 3.14 below. As can be seen the use attenuators does help but it also brings the signal strength down and hence the more noisy signal. But there is still some miss-match in the setup but when attenuators is used the deviation is +-10% at most frequencies. It could be the resistor that is unstable or that the board is mismatched.

Figure 3.13: Shunt-through setup

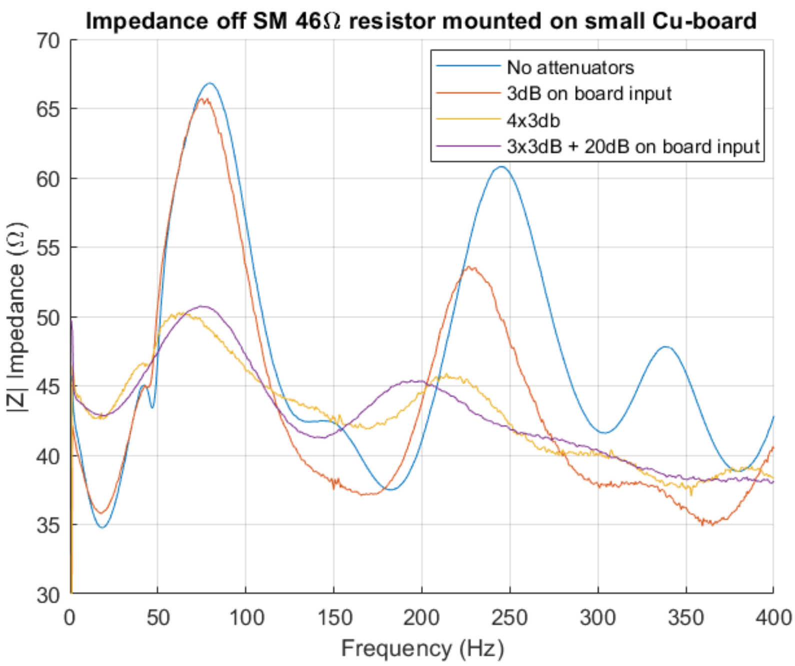


Figure 3.14: Validation Shunt-through

3.1.5 Series-trough

Instead of having the DUT in parallel and terminated to ground one can put the DUT in series and in-line with the ports. This setup is shown in figure 3.15 below. One of the advantages of this method is that one does not need to ground the DUT. The math is fairly similar. Instead of the the reduction to 3.3 the ABCD-matrix reduces to

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{Series} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \quad (3.5)$$

Plugging this equation into 2.22 one obtains

$$Z = \frac{2 * 50(1 - S_{21})}{S_{21}} \quad (3.6)$$

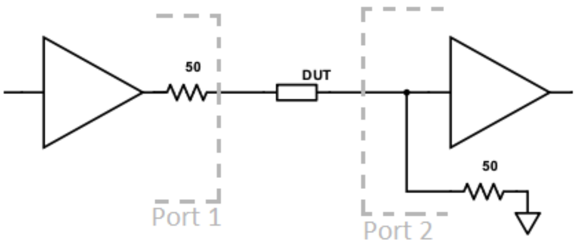


Figure 3.15: Series-through schematics

3.1.5.1 Validation

The next setup that is validated is the series-through method mentioned in section 3.1.5. The setup for these tests looked alot like the one in figure 3.13 except the resistor was positioned in series with the positive terminals. In this first case a 10kΩ long legged resistor was used and after using the formulas in equation 3.6, 3.5 the impedance of the resistor was calculated and shown in figure 3.16 below.

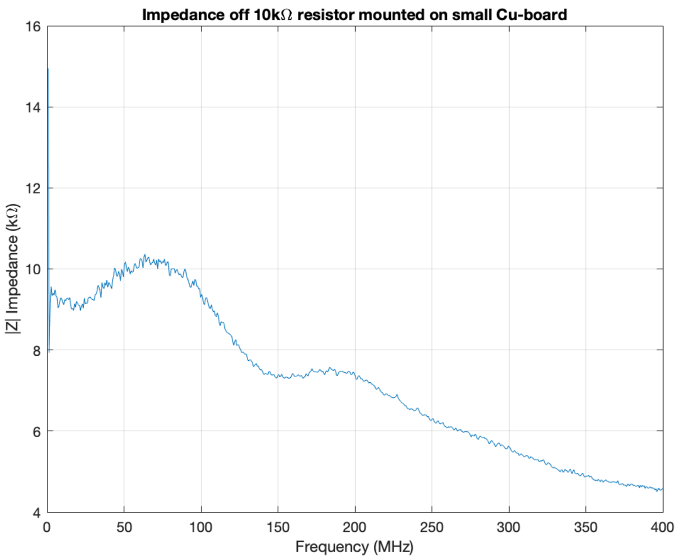


Figure 3.16: Validation series-through 10Ω

As can be seen in the figure the curve isn't straight at 10kΩ which could mean that the method isn't the best or that the resistor or setup isn't exactly 10kΩ. But one can see that at least the value is close to 10kΩ at the lower frequencies and that it actually follows the same behaviour as for the SM 46Ω shunt-through setup in figure 3.14. From observation one can guess that this behavior is more likely caused by the setup than the individual resistors.

Another test with a smaller test board and a 20kΩ resistor was conducted. In this case the resistor was surface mounted on the small board. The result after calculations from the test can be seen in figure 3.17 below.

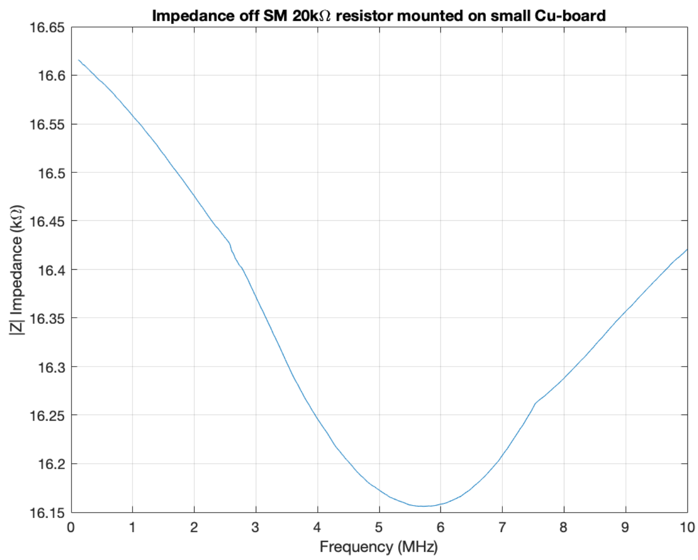


Figure 3.17: Validation series-through 20Ω

The result from this test clearly shows a value that's more equal but the value seems to be a bit off. But as had been said earlier the point of these validations is not to find the exact impedance but to check that it is in the right ball park and that it deviate to much at certain frequencies.

3.1.6 Reflection

Measurements can be done through a reflection method as well. In this method you send in a signal that then reflects when arriving at a DUT. This method is often called S_{11}. A general schematics for this method is depicted in 3.18

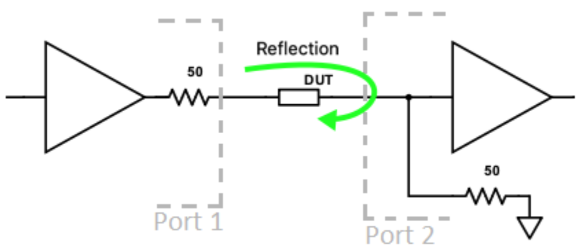


Figure 3.18: Schematics of a reflection measurement

This measurements can then be transferred in to Impedance trough 3.7

$$Z_{11} = 50 * \frac{(1 + S_{11})}{(1 - S_{11})} \tag{3.7}$$

S_{11} in this case is complex i.e both the magnitude and the phase has to be considered. Such a measurement was tested on a 4m cable in the lab environment, and transferred to impedance and can be seen in figure 3.19. There are some very clear peaks and troughs in the lower frequencies .

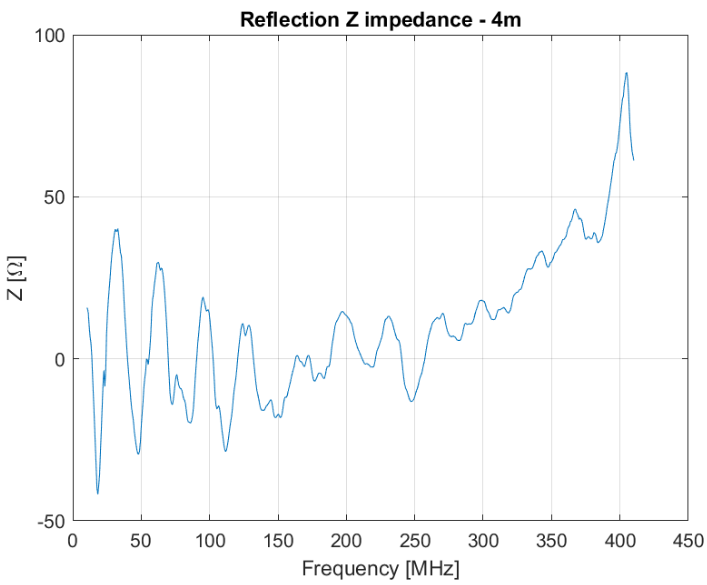


Figure 3.19: Reflection measurement on 4m cable

This measurement can be compared to a measurement done with the normal current transformer method on the same cable. The two probes in this case is placed in the end of the cable close to each other. This measurement is shown in figure 3.20 below.

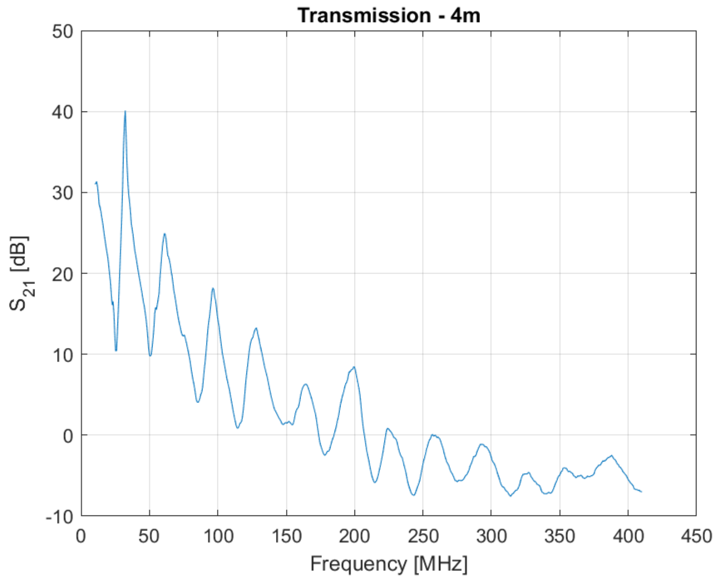


Figure 3.20: S21 measurment on 4m cable

In this figure the value has been flipped to more represent resistance more than transmission. If compared with figure 3.19 one can see that the peaks and troughs is situated at the same frequencies at least at the fist half of the frequency spectra. They both show clearly where the resonances are and therefore easy to use. This justify to investigate both methods further.

3.2 Capacitors

The second part of the thesis is regarding a test method for measuring resonances in decoupling clusters. Decoupling capacitors is covered in section 2.3.2 Making measurements on capacitors in mainly done with the same equipment as has been already used in previous sections. Many of the same principals also apply for capacitors as for ground cables so this part will not be as thorough, instead the point is to try to use the same methods as for the cables and show that they can be applicable for capacitors as well. With that said it will be some new methods in this section as well.

Some initial tests on single capacitors was carried out in order to test which type off measurements is the best way to go. Reflection, Shunt-through and Series-through was tested for the same capacitors. After converting the amplitude and phase into a complex number and running it through the corresponding impedance equations the result was obtained. In figure 3.21 below is a comparison between the shunt-through and the reflection method for the same setup and same capacitor. It seems like the shunt-through gives a more clear peak but instead has ripples in the higher frequency range. They both show the resonance at 12MHz with roughly 0.1Ω. Since the objective is to find where the peaks is located it seems like the shunt-through is the best.

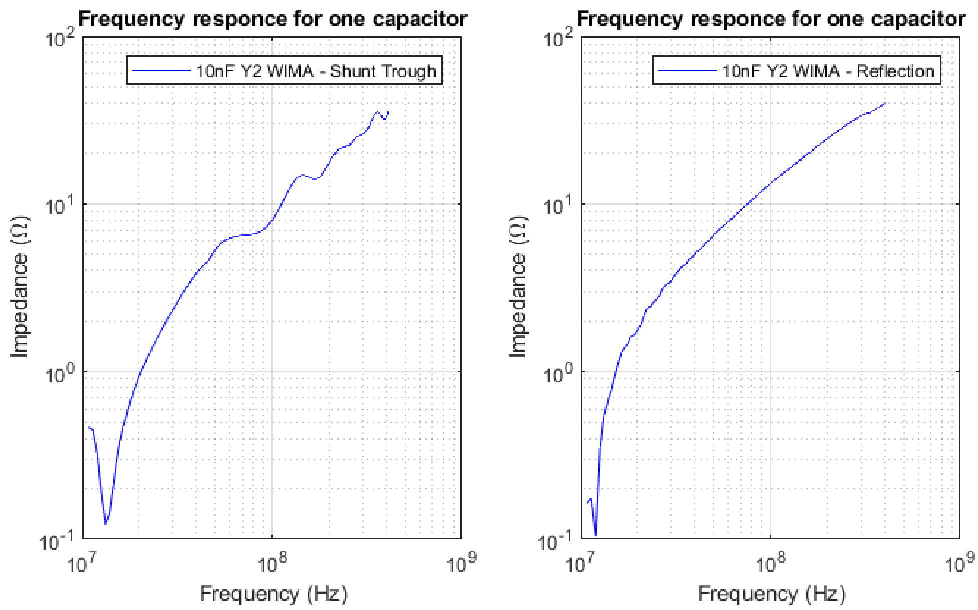


Figure 3.21: Comparison between shunt-through and reflection methods.

In order to get rid of the ripples at the higher frequencies which is most likely a result of standing waves in the cables, the cables was shorted as much as possible. The results of this is presented in figure 3.22.

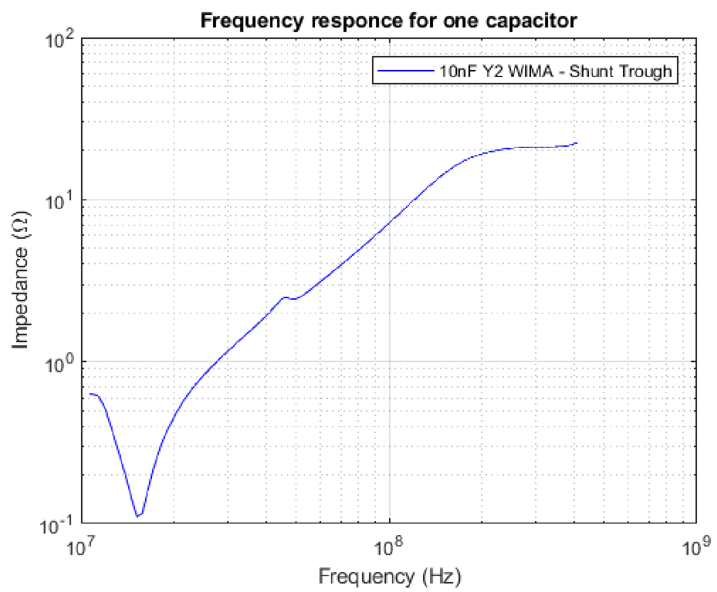


Figure 3.22: Capacitor measurement shunt-through with short cables

In this case the dip is much clearer and the ripples at the higher frequencies is much smaller. But it seems to stagnate at the higher frequencies which is not expected.

3.2.0.1 Validation

Since the shunt-through seemed to be the best one a validation test was done on a capacitor where the impedance characteristics was known from the supplier. In figure 3.23 the result from this measurment is shown and in figure 3.24 the corresponding characteristic from the supplier is shown.

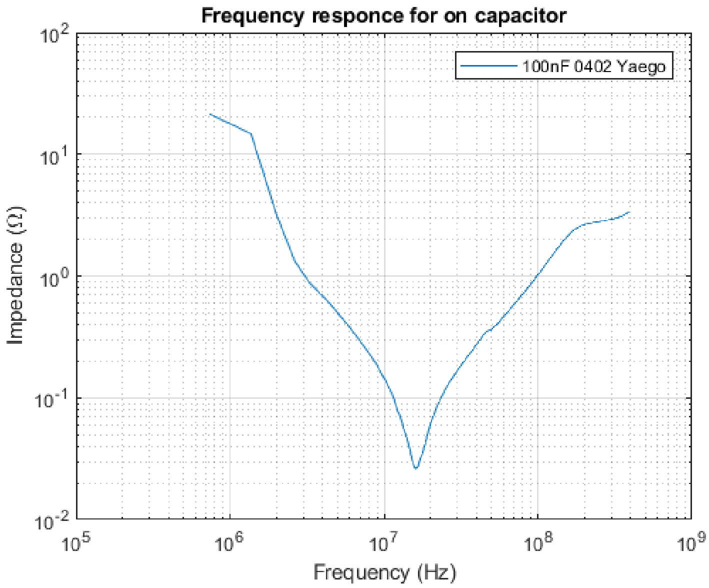


Figure 3.23: Capacitor measurement shunt-through on capacitor with known data

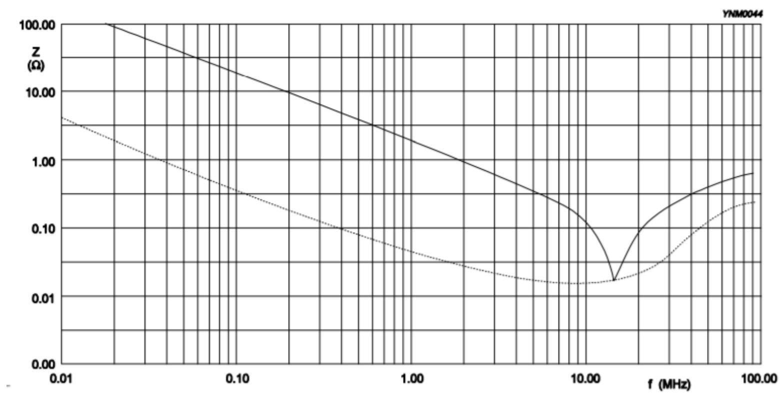


Figure 3.24: Impedance curve for the same capacitor from supplier [5]

Comparing the two curves some things can be established. The positive thing is that the resonance is located at the same frequency and at the correct value. The less positive things is that the inclination and boundary behaviour does not correlate with the provided data. This is not a big problem though since the main purpose of the method is to find where the resonance is located.

3.2.1 Loop methods

One of the new types of methods is a method including the same current transformers as in the cables methods but this will be used in a loop instead. The setup will look something like in figure 3.25

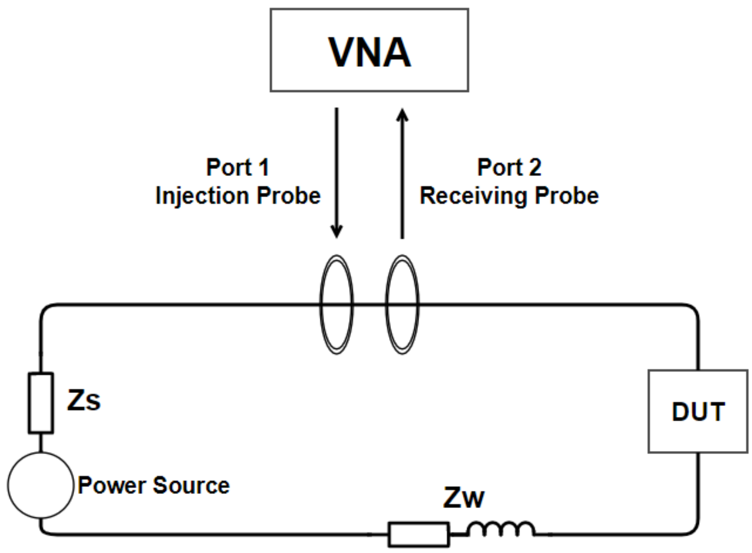


Figure 3.25: Loop measurment setup

where the impedance of the DUT(Z_x) is what is interesting. This setup can be described as

$$Z_x = K\Big(\frac{S_{11}+1}{S_{21}}\Big) - Z_{setup} \tag{3.8}$$

Where K and Z_{setup} describes the characteristics of the system such that power supply and current probes, i.e they are unknowns in the systems.
But if the DUT is replaced with two known impedance the system can be solved for Z_x. In this case a measurment with a known 50Ω resistor and a short connections was collected.

$$Z_x\Big|_{50\Omega} = K\Big(\frac{S_{11,50\Omega}+1}{S_{21,50\Omega}}\Big) - Z_{setup} \tag{3.9}$$

and

$$Z_x\Big|_{0\Omega} = K\Big(\frac{S_{11,0\Omega}+1}{S_{21,0\Omega}}\Big) - Z_{setup} \tag{3.10}$$

If we define

$$\Big(\frac{S_{11,50\Omega}+1}{S_{21,50\Omega}}\Big) = A \tag{3.11}$$

and

$$\Big(\frac{S_{11,0\Omega}+1}{S_{21,0\Omega}}\Big) = B \tag{3.12}$$

Our system is now described as

$$\begin{bmatrix} A & -1 \\ B & -1 \end{bmatrix} \begin{bmatrix} K \\ Z_{setup} \end{bmatrix} = \begin{bmatrix} 50 \\ 0 \end{bmatrix} \tag{3.13}$$

And can easily be solved to get

$$\begin{bmatrix} K \\ Z_{setup} \end{bmatrix} = \begin{bmatrix} 50/(A-B) \\ 50B/(A-B) \end{bmatrix} \tag{3.14}$$

Hence for a wanted unknown impedance Z_x we finally get

$$Z_x = \frac{50}{A-B}\left(\frac{S_{11}-1}{S_{21}} - B\right) \tag{3.15}$$

The advantage of this method is that the characteristics of the setup and redundant system doesn't need to be known since there impact will be accounted for in the equation.

3.2.1.1 Validation

To make sure the method preformed as wanted a validation test was preformed with a known resistor of 50Ω. It's important to test with another resistor than the one used when calculating K and Z_setup. The results is shown in figure 3.26 below.

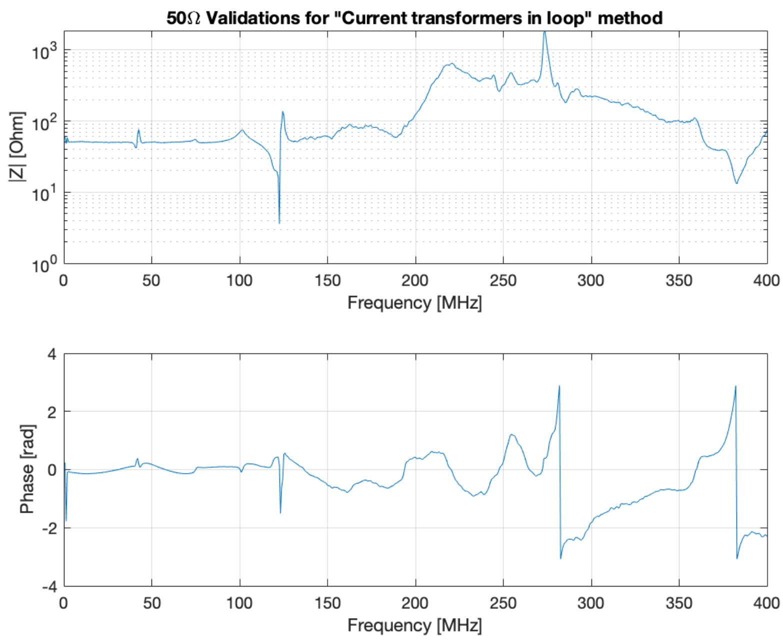


Figure 3.26: Validation of the current transformers in loop method.

What can be said from these results then? The first thing we can observe is that it shows correctly the impedance at low frequencies then both the impedance and the phase start to deviate from the expected value.

4
Conclusion

In the following chapter the conclusion of this work will be presented, starting with the methods for measuring cable resonances. A lot of different methods were tested and many of them fill the objective in some way but non of them can be said to be the go-to method for resonance measurements related to the automotive industry. But depending of what type of cables that are the test subject, different methods can be selected to fit the best.
If the cable in question is easy to access and be connected to, the best choice would be the series-through or the reflection-method since they are quite low-setup but still gives accurate results. If the cable in question is located in a tricky position and connected to a lot of different things, a simple transmission measurement with the current transformers and some attenuators would be preferable since this gives a quick and easy way to see the resonance behavior but it will not give you the actual impedance just the S21 signal between the the current tranformers, witch often is good enough to find the corresponding resonance frequency.

When it comes to the decoupling and capacitor networks it's basically the same story. The loop method with the current transformers is a good way to find the resonance behaviour from a DUT, but this could be troublesome if there is no easy way to replace the DUT with the known impedances for reference values for the calculation.

In the aim of this thesis some simulations where said to be carried out but this has been discarded except for the standalone cable ones in the beginning of the report. This since I quickly understood that the systems were to complex for simulations and that more time would have been required if this should have to be done.

4.1 Further work

There are a lot of things that can be further worked on regarding this project. For starers it would be good to really test the methods in functioning cars and see witch fare best in live-situations and the focus extra hard on the best one and really find in which regimes the method works best and refining it for the clients main usage.

Another thing that would be great is the use of different types of equipment. During the progression of the project one have found that another type of equipment would be better to use in this particular situation. To name a few, more broadband current transformers would be good to be able to measure a wider frequency spectra. A proper network analyzer with injection and pickup on both ports would be preferable when using the loop method.

Bibliography

[1] Deloitte analysis. "Semiconductors - the Next Wave". In: *Deloitte* (2019). https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/technology-media-telecommunications/deloitte-cn-tmt-semiconductors-the-next-wave-en-190422.pdf, p. 14.

[2] Ally Winning. "Number of automotive ECUs continues to rise". In: *eeNews Automotive* (2019). https://www.eenewsautomotive.com/news/number-automotive-ecus-continues-rise.

[3] Freedman Young. *University Physics with Modern physics 13th edition.* Pearson, 2012. ISBN: 978-0-321-69686-1.

[4] J. B. Calvert. "The Telegrapher's Equation". In: (2004). https://mysite.du.edu/~jcalvert/tech/cable.htm.

[5] YAEGO. "Data Sheet Surface-mounted ceramic capacitors, Class 2, X7R, 6.3V to 50V, 100uF to 22uF". In: *YAEGO* (2017). http://www.yageo.com/documents/recent/UPY-GPHC_X7R_6.3V-to-50V_18.pdf, p. 11.

A

Appendix 1

The equipment used to develop the method is mentioned briefly bellow.

- R&S FSH13 handheld spectrum/network analyzer
- Current injection probe TESEQ CIP 9136A
- Current probe Rohde Schwarz ESV-Z1
- Calibration kit RS FSH-Z28
- SMA-cables of various lengths
- N-cables
- Magnetic NF probes RS®HZ-14 Active E and H near-field probe set
- Various connection adapters and dampers.
- LCR measuring device - Keysight U1730C
- Signal generator RIGOL DSG830
- Oscilloscope Teledyne Lecroy Waverunner 8404m
- Current propes and differential voltage probes - Lecroy(ZD1500, CP031A, PP022)