

Reuse and verification of test equipment for ISO 7637

Återanvändning och verifiering av testutrustning för ISO 7637

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Abstract

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Acknowledgments

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1 Introduction

The standards ISO 7637, *Road vehicles – Electrical disturbances from conduction and coupling*, and ISO 16750, *Road vehicles – Environmental conditions and testing for electrical and electronic equipment*, are international standards that apply to equipment in road vehicles with a nominal supply voltage of 12 V or 24 V.

The standards states that the product shall withstand a sufficient amount of disturbances applied to its power supply. The reason for this being that there can be voltage surges and noise in a vehicle's power supply lines. In general, the source of disturbances and noise in a vehicle origins from inductance in other devices connected to the power line, the cables and the vehicles alternator in combination with switching of loads or the supply. [11, 9]

To test if a product comply with this standard, there is equipment that simulates different events on the power supply lines. The test events consists of voltage pulses that are applied to the DUT, device under test. The pulses of interest in this paper are denoted pulse 1, pulse 2a, pulse 3a, pulse 3b and load dump test A. The standard defines the different scenarios, raise and fall times of test pulses, repetition times etc. It also defines the functional requirements of the equipment during these tests for what is considered a passed or a failed test. [11, 9]

1.1 Motivation

The standard defines all the timing requirements that must be met, and also specifies the load conditions for which the requirements apply [11]. From time to time the standards are revised, which may alter the requirements form the previous versions of the standard. Test equipment might be constructed for the currently valid standards, and possibly older versions, but might not be compatible with newer versions. New equipment might not be affordable by smaller test labs, and can thus inhibit labs from performing tests for this standard.

An appealing alternative would be the possibility to reuse the test equipment that was used along with the older revision of the standard, as long as it is capable of performing the tests reliably. For this to be possible, the test equipment must be verified in some way so that it is possible to guarantee that the tests are performed according to the new standard.

1.2 Aim

The main goal of this work is to investigate the possibility of reusing test equipment, made for a previous version of a standard, with the current version of that standard and how to assure that the test results are reliable.

If the above goal is met, the verification process of the system is desired to be automated.

1.3 Research questions

The following questions will be answered in this paper:

TODO

1. Can test equipment made for ISO 7637-2:2004, be used for testing compliance against ISO 7637-2:2011, the newer version of the standard?
2. If it can; What considerations must be made to allow for automating the test and verification process?
3. If it can't; What causes the failure, and what possible fixes can be made to make the equipment usable for the newer standard?

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1.4 Delimitations

This paper only compares the standard ISO 7637-2:2004 to ISO 7637-2:2011 and ISO 16750-2:2012, because these are the most recent versions of the standards.

This paper only considers Pulse 1, Pulse 2a, Pulse 3a, Pulse 3b and Load dump A. The main reason being that these are the pulses that the available equipment can generate, but also that these pulses share many properties and the method of analysing them will probably be very similar.

This paper only considers the test equipment for ISO 7637-2 that was available at the company, presented in Table 1.1, for the practical tests.

Table 1.1: The test equipment available for the project

Brand	Model	Description
EMTEST	EFT 200A	Burst generator
EMTEST	MPG 200B	Micropulse generator
EMTEST	LD 200B	Load dump generator
EMTEST	CNA 200B	Coupling network

1.5 Report structure

The theory chapter presents all necessary theory to back up the methods used in the project.

The method chapter describes how the project was executed so that it can be replicated.

The result chapter is tightly coupled to the method chapter, in such a way that each header can be found in both. This allows for an easy correlation between the method and its result.

The discussion chapter reflects on the results achieved and comments on the methods used. This is also where source criticism is brought up.

The conclusion chapter reconnects the project to the original research questions. There are also some suggestions for topics that need further research related to the project.



2 Theory

This chapter introduces the theory and facts that are related to this project. It describes the necessary parts of the ISO standards, measurement theory and methods to analyse acquired data.

2.1 Previous research

No previous research directly relevant to the reuse of test equipment was found. Though research that has been made on topics relevant to project, such as measurement techniques and curve fitting, are presented in this theory chapter.

2.2 ISO standards

The ISO organisation, International Organization for Standardization, was founded in 1947 and has since published more than 22,500 International Standards. ISO standards does not only cover the electronic industry, but almost every industry. The purpose of the standards is to ensure safety, reliability and quality of products in a unified way, making international trade easier. The name ISO comes from the Greek word *isos*, which means *equal*. [3]

A standard is developed and maintained by a Technical Committee, TC. The TC consists of, amongst others, experts in the area that the standard concerns [7]. A new standard is only developed when there exists a need for this from the industry or other groups that may require it [4]. Existing standards are automatically scheduled for review five years after its last publication, but can manually be reviewed before that time by the committee [5]. During the review process it will be decided if the standard is still valid, need to be updated or if it should be removed [5].

The naming convention used for ISO standards is in the format *number-part:year*, where the *number* is the identifier to the unique ISO standard, *part* denotes the part of the standard if it is divided into several parts and *year* is the publishing year. For example; the name *ISO 7637-2:2011* refers to part 2 of the ISO 7637 standard published in 2011, whilst *ISO 7637-2:2004* would refer to an earlier version of the exact same document published in 2004.

To get hold of a copy of a standard, one need to buy it from ISO store or from a national ISO member. [6]

2.3 ISO 7637 and ISO 16750

The ISO 7637 standard, *Road vehicles — Electrical disturbances from conduction and coupling*, concerns the electrical environment in road vehicles. The standard consists of four parts, as of August 2019.

Part 1, *Definitions and general considerations*, defines some abbreviations and technical terms that are used throughout the standard. It also intended use of the standard. [10]

Part 2, *Electrical transient conduction along supply lines only*, defines the test procedures related to disturbances that are carried along the supply lines of a product. Both emission, disturbances created by the DUT, and immunity, the DUT's capability to withstand disturbances, are covered. This part defines the test pulses that are of interest for this project, and the verification of them. [11]

Part 3, *Electrical transient transmission by capacitive and inductive coupling via lines other than supply lines*, defines immunity tests against disturbances on other interfaces than the power supply. It focuses on test setups and different ways of coupling the signals. [12]

Part 5, *Enhanced definitions and verification methods for harmonization of pulse generators according to ISO 7637*, proposes an alternative verification method of the test pulses defined in ISO 7637-2. The main difference from the method described in ISO 7637-2 is that the DC voltage, U_A , should not only be 0 V during the verification, but also be set to the nominal voltage, U_N . This will not be considered deeply in this report, since it is only a proposal and makes the verification equipment more difficult. [13]

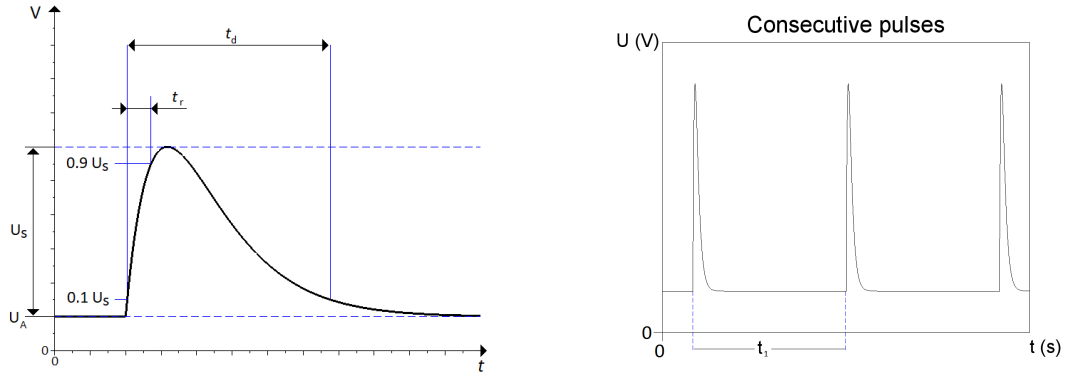
The ISO 16750, *Road vehicles – Environmental conditions and testing for electrical and electronic equipment*, concerns different environmental factors that a product might face in a vehicle, such as mechanical shocks, temperature changes and acids. Part 2 of the standard, *Electrical Loads*, deals with some electrical aspects that was previously part of the ISO 7637 standard. This is the only part of ISO 16750 that will be considered. [8, 9]

2.4 Test pulses

All test pulses defined in ISO 7637 and ISO 16750 are supposed to simulate events that can occur in a real vehicle's electrical environment, that equipment must be able to withstand. The properties of these test pulses are well defined, to allow for unified testing regardless of which test lab that performs the test. In the real world, however, the disturbances might of course differ from the test pulses since a real case environment is not controlled. [11, 9, 2]

The test pulses of interest defined in ISO 7637 are denoted *Test pulse 1*, *Test pulse 2a*, *Test pulse 3a* and *Test pulse 3b*. The test pulse of interest defined in ISO 16750 is denoted *Load dump Test A*. There are more pulses and tests defined in these standards, but those are not in the scope of this project.

The general characteristics in common for all pulses are the DC voltage U_A , the surge voltage U_s , the rise time t_r , the pulse duration t_d and the internal resistance R_i . The property *internal resistance* is only in series with the generated pulse, not in series with the DC power source. For pulses that are supposed to be applied several times, t_1 usually denotes the time between the start of two consecutive pulses. The timings are illustrated in Figure 2.1a.



(a) The surge voltage U_S is the pulse maximum voltage disregarding the offset voltage U_A . The rise t_r time is defined as the time elapsed from 0.1 to 0.9 times the surge voltage on the rising edge of the pulse. The duration t_d is defined as the time from 0.1 times the maximum voltage on the rising edge, back to the same level of the falling edge.

(b) The repetition time is defined as the time between two adjacent rising edges.

Figure 2.1: The common properties of the pulses, as defined by ISO 7637.

An important observation is that the definition of the surge voltage, U_s , differs in ISO 7637 and ISO 16750 as depicted in Figure 2.5.

Test pulse 1

This pulse simulates the event of the power supply being disconnected while the DUT is connected to other inductive loads. The other inductive loads will generate a voltage transient of reversed polarity onto the DUT's supply lines.

In the standard there are two additional timings associated to this pulse, t_2 and t_3 , which are defining the disconnection time for the power supply during the voltage transient. In practice t_3 can be very short, specified to less than 100 μs , and the step seen in Figure 2.2 might be too short to be clearly distinguishable when seen on an oscilloscope.

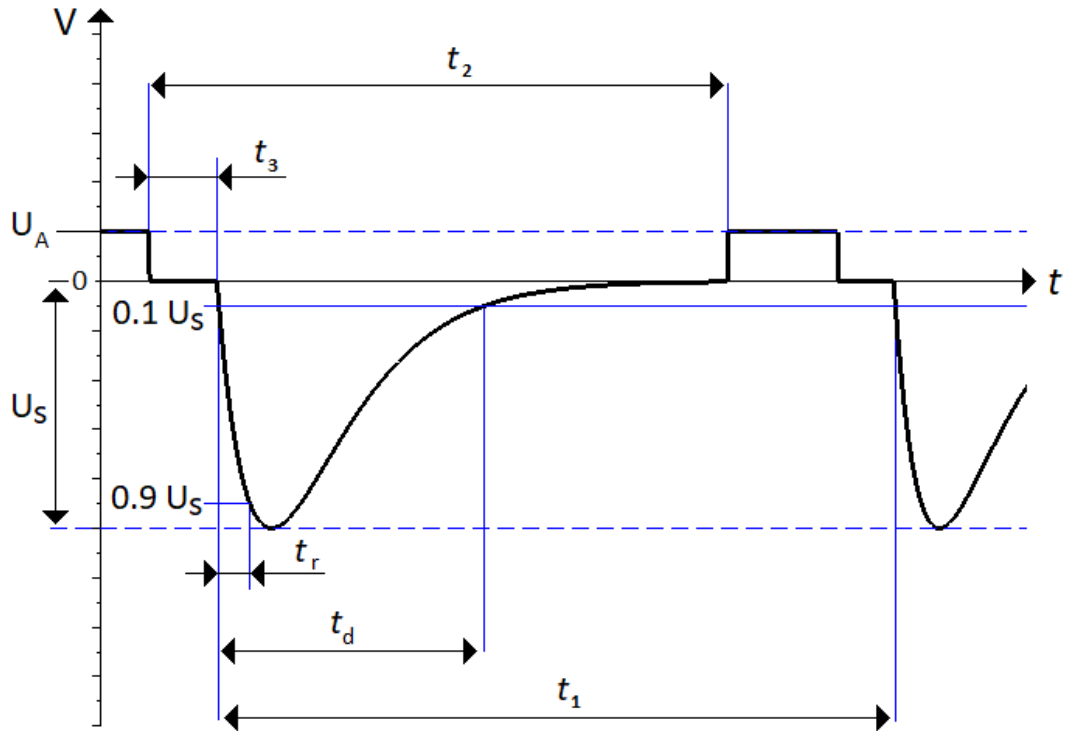


Figure 2.2: Illustration of test pulse 1.

Table 2.1: Parameter values for pulse 1

Parameter	12 V system	24 V system
U_A	13.8 V to 14.2 V	27.8 V to 28.2 V
U_S	-75 V to -150 V	-300 V to -600 V
R_i	10 Ω	50 Ω
t_d	2 ms	1 ms
t_r	0.5 μ s to 1 μ s	1.5 μ s to 3 μ s
t_1	≥ 0.5 s	
t_2	200 ms	
t_3	<100 μ s	

Test pulse 2a

This pulse simulates the event of a load, parallel to the DUT, being disconnected. The inductance in the wiring harness will then generate a positive voltage transient on the DUT's supply lines. distinguishable when seen on a oscilloscope.

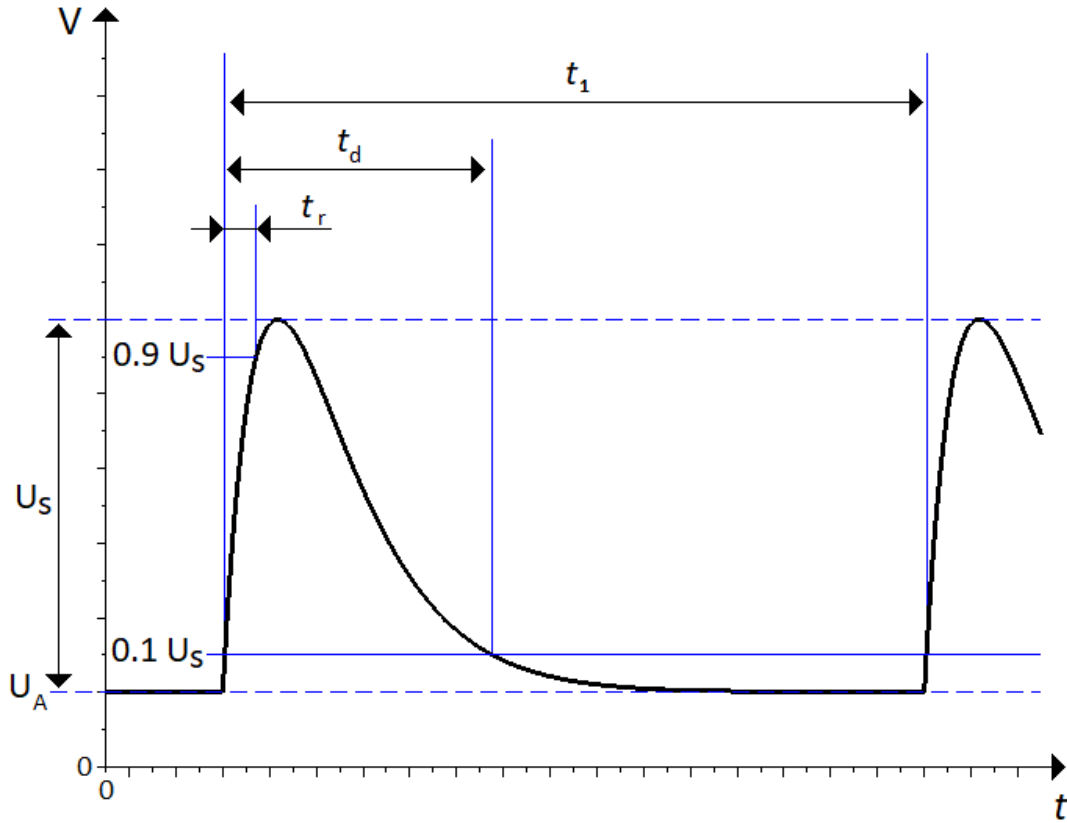


Figure 2.3: Illustration of test pulse 2a.

Table 2.2: Parameter values for pulse 2a

Parameter	12 V system	24 V system
U_A	13.8 V to 14.2 V	27.8 V to 28.2 V
U_S	37 V to 112 V	
R_i	$2\ \Omega$	
t_d	0.05 ms	
t_r	0.5 μ s to 1 μ s	
t_1	0.2 s to 5 s	

Test pulse 3a and 3b

Test pulse 3a and 3b simulates transients “which occur as a result of the switching process” as stated in the standard [11]. The formulation is not very clear, but is interpreted and explained by Frazier and Alles [2] to be the result of a mechanical switch breaking an inductive load. These transients are very short, compared to the other pulses, and the repetition time is very short. The pulses are sent in bursts, grouping a number of pulses together and separating groups by a fixed time.

These pulses contain high frequency components, up to 100 MHz, and special care must be taken when running tests with them as well as when verifying them.

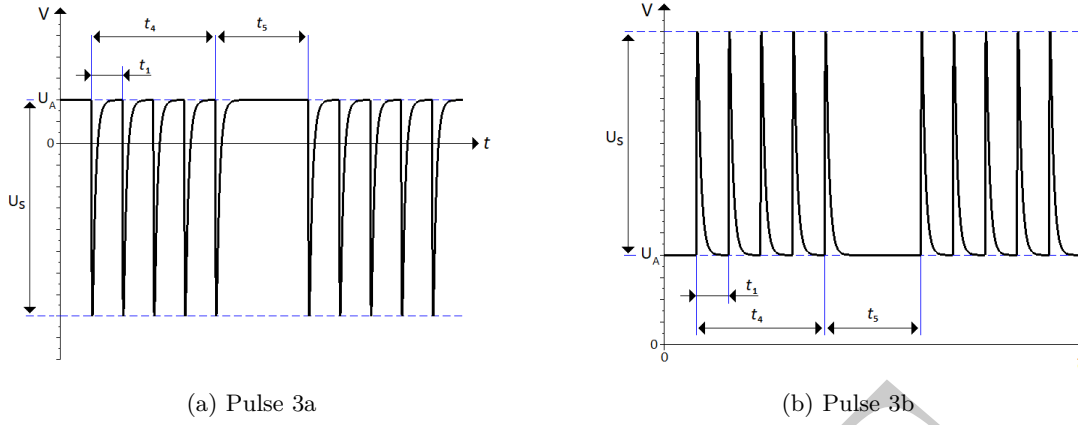


Figure 2.4: Pulse 3a and 3b are applied in bursts. Each individual pulse is a double exponential curve with the same properties, t_r and t_d , as e.g. pulse 2a

Table 2.3: Parameter values for pulse 3a and 3b

Parameter	12 V system	24 V system
U_A	13.8 V to 14.2 V	27.8 V to 28.2 V
Pulse 3a U_S	-112 V to -220 V	-150 V to -300 V
Pulse 3b U_S	75 V to 150 V	150 V to 300 V
R_i	50 Ω	
t_d	105 ns to 195 ns	
t_r	3.5 ns to 6.5 ns	
t_1	100 μ s	
t_4	10 ms	
t_5	90 ms	

Load dump Test A

The Load dump Test A simulates the event of disconnecting a battery that is charged by the vehicles alternator, the current that the alternator is driving will give rise to a long voltage transient.

This pulse has the longest duration, t_d , of all the test pulses. It also has the lowest internal resistance. These properties makes it capable of transferring high energies into a low impedance DUT or dummy load.

Prior to 2011, the Load dump Test A was part of the ISO 7637-2 standard under the name *Test pulse 5a*. The surge voltage U_s was in the older standard, ISO 7637-2:2004, defined as the voltage between the DC offset voltage U_A and the maximum voltage. In the newer standard, ISO 16750-2:2012, U_s is defined as the absolute peak voltage. Only the former definition is used in this paper, $U_s = \hat{U} - U_A$.

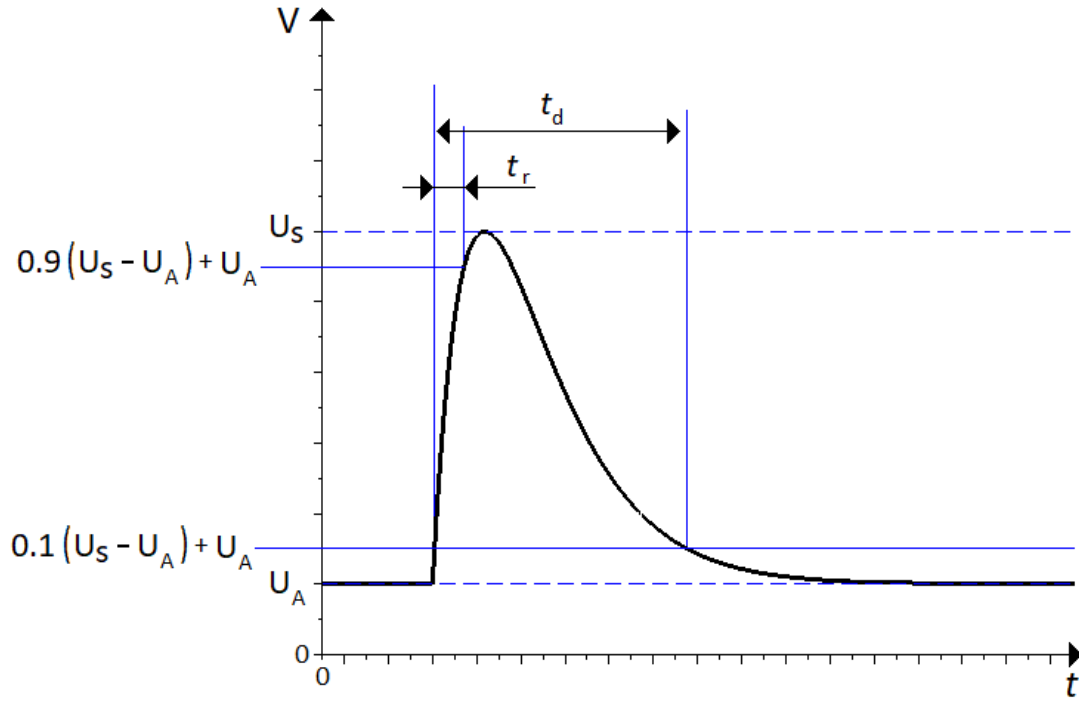


Figure 2.5: Illustration of load dump Test A. Note the different definition of U_S compared to the other pulses.

Table 2.4: Parameter values for load dump Test A

Parameter	12 V system	24 V system
U_A	13.8 V to 14.2 V	27.8 V to 28.2 V
U_S ISO 16750	79 V to 101 V	151 V to 202 V
U_S ISO 7637	64.8 V to 87.2 V	122.8 V to 174.2 V
R_i	$0.5\ \Omega$ to $4\ \Omega$	$1\ \Omega$ to $8\ \Omega$
t_d	40 ms to 400 ms	100 ms to 350 ms
t_r	5 ms to 10 ms	

Application of test pulses

During a test, the nominal voltage is first applied between the plus and minus terminal of the DUT's power supply input by the test equipment. Then a series of test pulses are applied between the same terminals. The pulses are repeated at specified intervals, t_1 , as depicted in Figure 2.1b.

An example of how a test pulse can be applied by the test equipment is depicted in Figure 2.6.

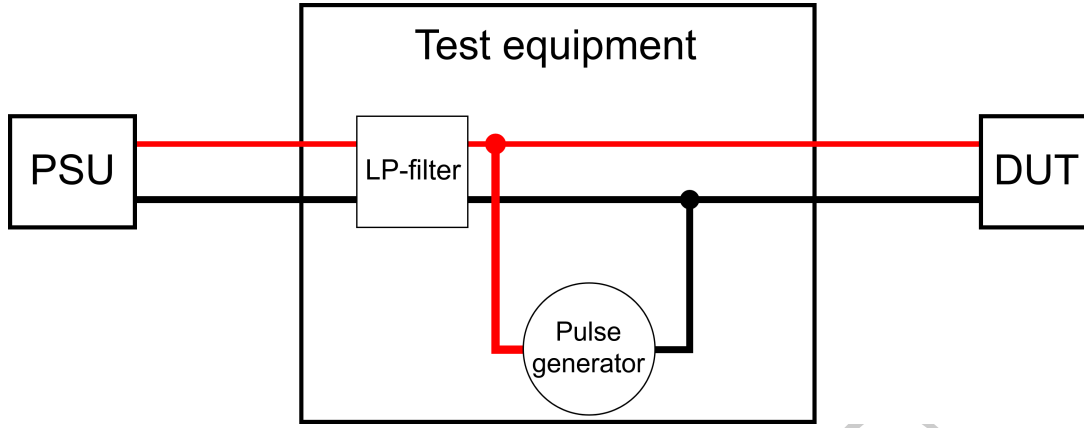


Figure 2.6: Illustration of how the test equipment can apply a test pulse to the DUT whilst also providing the DC supply through an external PSU.

Verification

The test pulses are to be verified before they are applied to the DUT. The voltage levels and the timings are to be measured both without any load, and with a matched load, $R_L = R_i$, attached. The standard omits the rise time constraint when the load is attached, except for pulse 3a and 3b. [11]

The verification is to be conducted with U_A set to 0. There is, however, a proposal to set U_A equal to the nominal voltage during the verification process, as the behaviour of the pulse generators has proven differ in this case [13]. In this project $U_A = 0$ will be used.

The limits, and tolerances, for the pulses are summarised in Table 2.5. The matched loads are to be within 1% of the nominal value. [11]

Table 2.5: These are all of the verifications that needs to be made before each use of the equipment, along with the limits for each case.

Pulse	Match resistor	U_S	Limits	
			t_d	t_r
Pulse 1, 12 V, Open	10 Ω	-110 V to -90 V	1.6 ms to 2.4 ms	0.5 μ s to 1 μ s
Pulse 1, 12 V, Matched		-110 V to -90 V	1.6 ms to 2.4 ms	0.5 μ s to 1 μ s
Pulse 1, 24 V, Open	50 Ω	-660 V to -540 V	0.8 ms to 1.2 ms	1.5 μ s to 3 μ s
Pulse 1, 24 V, Matched		-660 V to -540 V	0.8 ms to 1.2 ms	1.5 μ s to 3 μ s
Pulse 2a, Open	2 Ω	67.5 V to 82.5 V	40 μ s to 60 μ s	0.5 μ s to 1 μ s
Pulse 2a, Matched		67.5 V to 82.5 V	40 μ s to 60 μ s	0.5 μ s to 1 μ s
Pulse 3a, Open (1k)	50 Ω	-220 V to -180 V	105 ns to 195 ns	3.5 ns to 6.5 ns
Pulse 3a, Match		-120 V to -80 V	105 ns to 195 ns	3.5 ns to 6.5 ns
Pulse 3b, Open (1k)	50 Ω	180 V to 220 V	105 ns to 195 ns	3.5 ns to 6.5 ns
Pulse 3b, Match		80 V to 120 V	105 ns to 195 ns	3.5 ns to 6.5 ns
Load dump A, 12 V, Open	2 Ω	90 V to 110 V	320 ms to 480 ms	5 ms to 10 ms
Load dump A, 12 V, Matched		90 V to 110 V	320 ms to 480 ms	5 ms to 10 ms
Load dump A, 24 V, Open	2 Ω	180 V to 220 V	280 ms to 420 ms	5 ms to 10 ms
Load dump A, 24 V, Matched		180 V to 220 V	280 ms to 420 ms	5 ms to 10 ms

2.5 Resistors at high frequencies

When working with resistors at high frequencies, one must consider the parasitic properties of the resistor. Vishay presents a model which consists of the resistance R , internal inductance L , internal capacitance C , external lead inductance L_C and external ground capacitance C_G . Since the external ground capacitance is very small in comparison to the other parasitics, it has been neglected in this thesis. The model used for the simulations is depicted in Figure 2.7,

with the values $L = 0.1 \text{ nH}$, $C = 1 \text{ pF}$ and $L_C = 1 \text{ nH}$. This is a bit higher than the values in Vishays paper, but those are also for smaller packages. [16] A combined inductance of more than for the 1206 package is also supported by a technical note from AVX for capacitors, but the package lead inductance should be similar for capacitors and resistors[14].

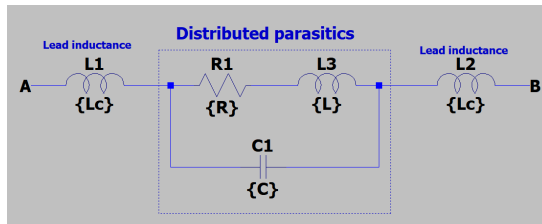


Figure 2.7: At high frequencies a resistors parasitic inductance and capacitance will affect the behavior of the circuit.

2.6 Measurement

There are several measurement methods needed during the project. To verify the test pulses, voltage has to be measured over time. To verify the dummy loads, resistance has to be measured. To verify the attenuators, their magnitude response has to be measured. This chapter describes the necessary measurement theory required for this project.

Resistance

To measure resistance, a current is fed through the resistor and the resulting voltage is measured to calculate the resistance using ohms law. This is typically carried out using a multi-meter and two probe wires connecting to each terminal of the resistor. When measuring very low valued resistors, however, the resistance in the probe wires can be significant in relation to the resistor measured and will affect the accuracy. One way of overcoming this is to perform a 4-wire measurement using a so called *Kelvin connection*. In this method the current that is fed through the resistor using one pair of wire, and the resulting voltage is measured at the desired point using another pair according to Figure 2.8.[17]

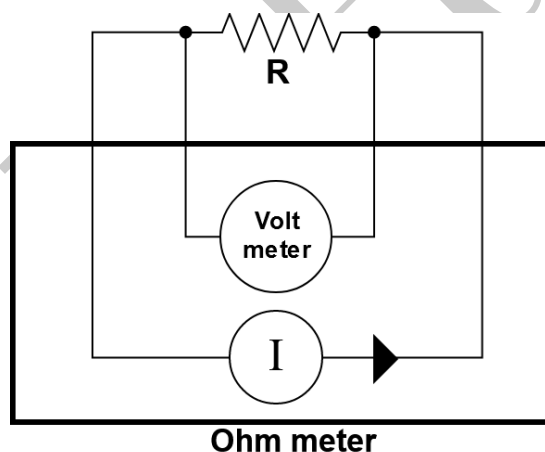


Figure 2.8: When measuring a low value resistor, the *Kelvin connection* can be used to determine the resistance at the point where the voltmeter is connected without the resistance in the probe leads affecting the result.

Oscilloscopes, bandwidth, rise time and probes

When using an oscilloscope to measure voltage over time, there are several limiting factors to how fast signals one can measure. The oscilloscope itself has a specified bandwidth, as do the probe and any attenuators used. All of these combined determine how short rise times that can be measured accurately. The rise time of the measured will be affected by these properties and the rise time displayed on the oscilloscope screen will be approximately according to Equation 2.1, where T_N is the 10 % to 90 % rise time limit for each part in the chain. [15]

$$T_{rise\ composite} = \sqrt{T_1^2 + T_2^2 + \dots + T_N^2} \quad (2.1)$$

Since Equation 2.1 is based on the rise time limitation but the specification usually tells the 3 dB bandwidth, a conversion can be made according to Equation 2.2. [15]

$$T_{10-90} = \frac{0.338}{F_{3\text{dB}}} \quad (2.2)$$

RF Attenuators

RF attenuators are characterized by Linearity, tolerances, power, combinations of resistors, impedances *TODO*

TODO:
Fyll på

2.7 Analysis

The data points from the measurement must be processed and evaluated to determine if the measured pulse is within the specified limits.

Mathematical description

All of the test pulses applied to the vehicle equipment can individually be described mathematically by variations of the double exponential function shown in Equation 2.3. The properties of interest, the ones which are specified in the standards, are the surge voltage U_s , the rise time t_r , the duration t_d and the repetition time t_1 . [11]

$$u(t) = k(e^{\alpha t} - e^{\beta t}) + U_A \quad (2.3)$$

It is not in the scope of this report to actually fit this function to the measured pulse, and further analyze it.

2.8 Instrumentation and control

The following chapter describes the different instruments that were used, and their control interfaces.

GPIO

IEEE-488, or GPIO which it is often called, is a parallel bus interface. It is mainly used to interconnect lab instrumentation such as multimeters, signal generators and spectrum analyzers.

Tektronix TDS7104 Oscilloscope

The oscilloscope that is available is a Tektronix TDS7104, with specifications as seen in ?? . It has GPIO interface and TekVISA GPIO, an API for sending GPIO commands over ethernet, available for remote control. *TODO*

TODO:
Lägg till specs eller ta bort helt



(a) Front.



(b) Back.

Figure 2.9: The MPG 200 is used to generate test pulse 1 and 2a.

xxxxxx Isolated differential probe*TODO***TODO:**Peta in kort beskrivning av
prob och dess data**EM Test MPG 200 Micropulse generator**

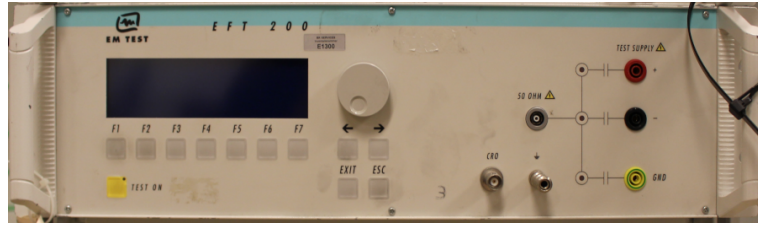
The MPG 200 is used to generate *Test pulse 1* and *2a*. MPG is an abbreviation for *MicroPulse Generator*. The instrument is designed to generate test pulses according to the older ISO 7637-2:1990 version, but the parameters can be adjusted to comply with the new ISO 7637:1990 standard. The adjustable parameter ranges are shown in Table 2.6. The instrumentation panels can be seen in Figure 2.9.

Table 2.6: Adjustable parameters in the MPG 200

Parameter	Range
U_S	20 V to 600 V
U_S polarity	+, -
R_s	2 Ω , 4 Ω , 10 Ω , 20 Ω , 30 Ω and 50 Ω
t_1	0.2 s to 99.0 s
t_2	0 s to 10 s

EM Test EFT 200 Burst generator

The EFT 200 is used to generate *Test pulse 3a* and *3b*. EFT is an abbreviation for *Electrical Fast Transient*. The instrument is designed to generate test pulses according to the older ISO 7637-2:1990 version, but the parameters can be adjusted to comply with the new ISO 7637:1990 standard. The adjustable parameter ranges are shown in Table 2.7. The instrumentation panels can be seen in Figure 2.10.



(a) Front.



(b) Back.

Figure 2.10: The EFT 200 is used to generate test pulse 3a and 3b.

Table 2.7: Adjustable parameters in the EFT 200

Parameter	Range
U_S	25 V to 1500 V
U_S polarity	+, -
Coupling	any combination of +, - and GND

EM Test LD 200 Load dump

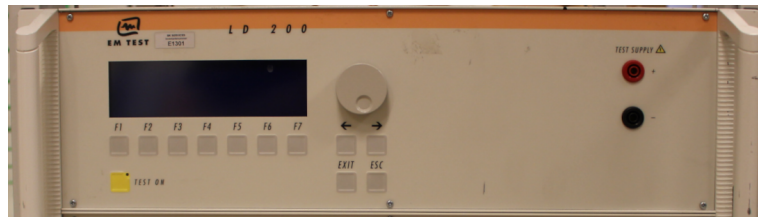
The LD 200 is used to generate *Load dump Test A*. LD is an abbreviation for *Load Dump*. The instrument is designed to generate test pulses according to the older ISO 7637-2:1990 version, but the parameters can be adjusted to comply with the new ISO 16750:2012 standard. The adjustable parameter ranges are shown in Table 2.8. The instrumentation panels can be seen in Figure 2.11.

Table 2.8: Adjustable parameters in the LD 200

Parameter	Range
U_S	20 V to 200 V
R_s	0.5 Ω , 1 Ω , 2 Ω and 10 Ω
t_d	50 ms to 400 ms

EM Test CNA 200 Coupling Network

The SNA 200 is a coupling network used to multiplex the pulse generators outputs. It contains several relays to select the appropriate generator output. The SNA 200 has one interface for each pulse generator, but no interface for a computer. It is automatically controlled by the pulse generators. This allows the DUT to be connected only to the CNA 200 and not to each individual pulse generator. Figure 2.12 shows the connections between the instruments in this setup. There is also a coaxial connection for calibration of pulse 3a and pulse 3b on the front panel. The instrumentation panels can be seen in Figure 2.13.



(a) Front.



(b) Back.

Figure 2.11: The LD 200 is used to generate load dump test a.

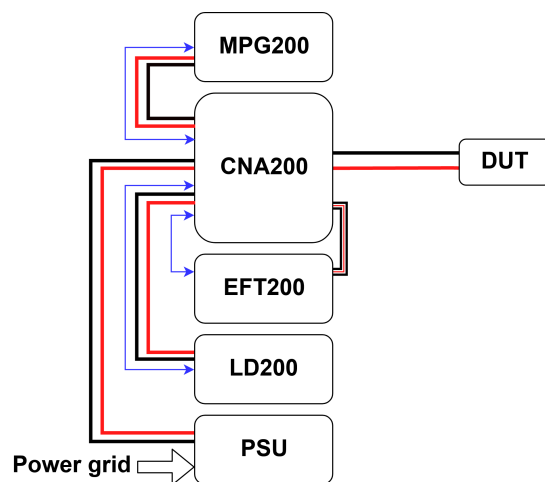


Figure 2.12: The CNA 200 allows each pulse generator to output their pulses through a common interface towards the DUT.

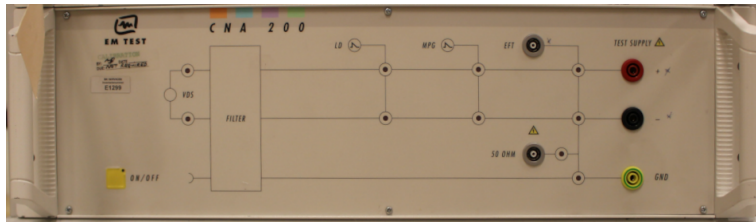
Rohde & Schwarz ZVL13

The ZVL13 is a vector network analyzer that operates in the frequency range 9 kHz to 13.6 GHz. It is, in this project, used to measure the magnitude and phase response between its two ports.

PAT 50 and PAT 1000

TODO

TODO:
Skriv någonting bättre här!



(a) Front.



(b) Back.

Figure 2.13: The CNA 200 is used to couple all of the other pulse generators outputs to a common output.



Figure 2.14: The two attenuators that were used in the project.



3 Methods

This chapter covers the methodologies used during the project.

3.1 Prestudy

During the project efforts were made to find relevant research using Linköping University Library's¹ and Google Scholar's² search engines.

Since the equipment intended for this project was untested before the project start, the first step was to hook it up and make some initial measurements to be able to decide the continuation of the project.

If the equipment seem to be mostly in line with the new standard requirements, the project plan was to go along the following path:

1. Investigate test architectures suitable for automatic testing and verification.
2. Design any utilities needed for the test and verification setup.
3. Implement the test architecture and any necessary utilities.
4. Measure and evaluate the system and the utilities.

If the equipment proved to deviate to much from the standard requirement, the project should go along the following path:

1. Investigate possible causes and fixes for the failure.
2. Design any utilities needed for the equipment to pass.
3. Implement these utilities.
4. Measure and evaluate the system with these utilities manually.

In either case, the following tasks should be considered if there is time:

¹<https://liu.se/en/library>

²<https://scholar.google.se/>

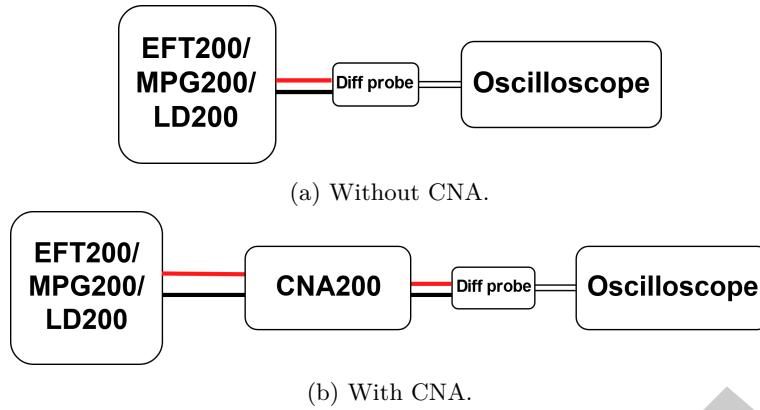


Figure 3.1: The setup for measuring for pulse 1, pulse 2a and Load dump A.

1. Investigate possible methods, or algorithms, that can automatically verify the pulse shapes and parameters.
2. Implement a number of these methods.
3. Evaluate these methods.

3.2 Comparison between the old and the new standard

Since the equipment used in the project is designed for the older version of the standard, ISO 7637-2:2004 and possibly even ISO 7637-1:1990 together with ISO 7637-2:1990, the differences will be examined. This is done simply by comparing the standards side by side and noting the differences.

3.3 Examination and initial measurement of the old equipment

To decide the forthcoming of the project, the equipment first had to be checked to see if it is capable to operate within the limits for use with the newer standard. Because there is no dummy loads available at this point of the project, only open load measurements could be done.

With exception for Pulse 3a and Pulse 3b, all of the pulses were measured with the use of the high voltage differential probe described in section 2.8. The pulses are measured both directly on each generator connected according to Figure 3.1a and also through the coupling network CNA 200, as depicted in Figure 3.1b.

Pulse 3a and Pulse 3b was measured using the attenuators described in section 2.8 connected directly to the coaxial connector according to Figure 3.2a without the CNA. They were also measured connected through the CNA, directly to the coaxial connector according to Figure 3.2b. Thanks to the 50-ohm attenuator, PAT-50, this pulse could be measured in its matched state. The measurement in open state is a compromise, since a passive attenuator that does not load the input would be impossible to make, and was made as a 1000-ohm attenuator instead.

3.4 Test architecture

The total number of tests needed to verify the testing equipment before each product test is 14, according to Table 2.5. There are in total three different values for dummy loads. In practice these could be represented by two high frequency attenuators for pulse 3a and pulse 3b, since

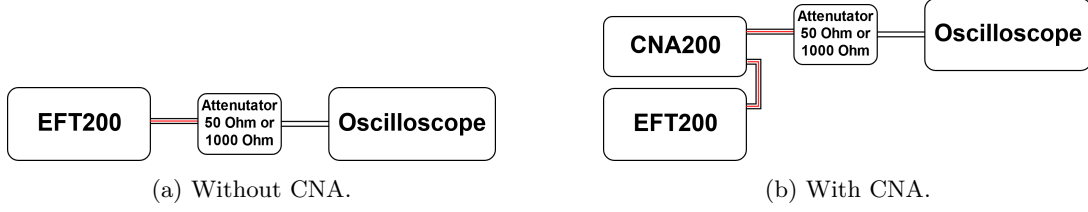


Figure 3.2: The setup for measuring for pulse 3a and pulse 3b.

these have really short rise times that will be affected much by parasitics of components, and three different high power dummy loads for the slower pulses where the parasitic effects might be negligible but the withstand power must be higher.

The following test architectures were considered, together with the external supervisor at the company.

Additionally there needs to be some sort of measurement fixture for evaluating the verification equipment.

Alternative 1 – Human assisted

The test can be performed semi-automatically by means of the existing equipment complemented by some dummy loads and, in the same manner the manual performance tests were executed. A computer could control the equipment and compare the results, by the assist of a human that can make the necessary reconnections between the tests. A proposed setup for this is shown in Figure 3.3.

The main advantage of this alternative is that it would require the least amount of hardware development time. It also doesn't need any extra hardware except from the dummy loads needed to do the verification.

The biggest disadvantage is that it would be very cumbersome to perform and also prone to human error. If the verification list is studied carefully one can minimize it to five reconnections after the initial connections are made, for example in the following order: No load, $2\ \Omega$, $10\ \Omega$, $50\ \Omega$ low frequency, $50\ \Omega$ high frequency, $1\ \text{k}\Omega$ high frequency.

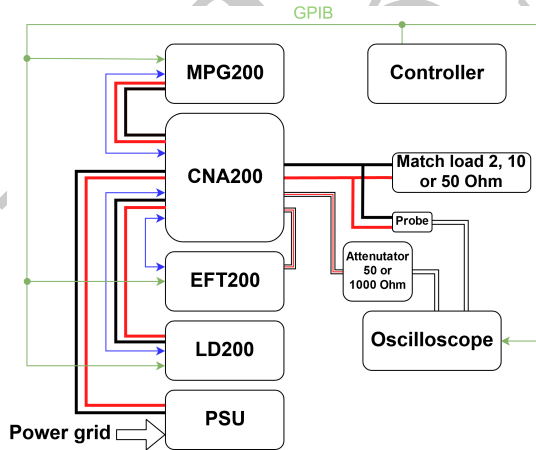


Figure 3.3: The proposed setup for alternative must be connected in different ways by a human during the verification process.

Alternative 2 – Fully automatic rig with external attenuators

To accurately measure Pulse 3a and Pulse 3b, the probes should be attached as close as possible to the generator because of the high frequency, to avoid influence of the connecting wires. This

could be accomplished by the means of a fixture that is attached directly to the generator, which can switch the pulses to the different loads or to the measurement outputs.

The dummy loads for all pulses, but Pulse 3a and Pulse 3b, will need to be put in a separate enclosure because of the high power dissipation. The proposed dummy loads for pulse 3a and pulse 3b is the external attenuators PAT 50 and PAT 1000. A proposed setup is depicted in Figure 3.4.

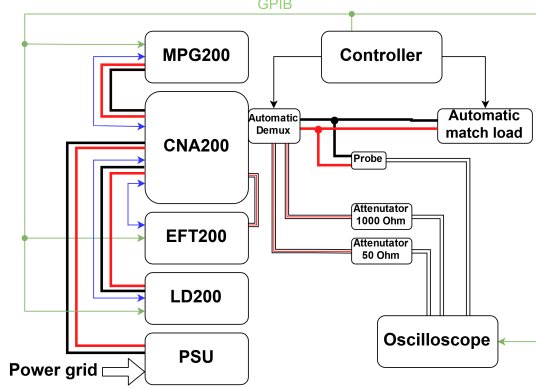


Figure 3.4: The proposed setup for alternative 2 is fully automatic, but exposes high voltage connectors between the demultiplexer and the two attenuators, marked with a red line.

The advantage of this method is that the verification can be performed fully automatically, except for the initial connection of the test rig. This also uses the commercially created attenuators that are already available.

The disadvantage to this setup is that the fixture needs to be designed, making the development costs greater. The fixture that attaches to the generator will expose high voltage on its measurement connectors, making it a safety hazard.

Alternative 3 – Fully automatic rig with embedded attenuators

To cope with the high voltage exposure, of alternative 1, the high frequency attenuators can be embedded inside the switching fixture, removing the need for high-voltage connectors. Figure 3.5.

To design Alternative 3 some utilities needs to be designed, namely:

- Relay box, the fixture with embedded attenuators that are to be attached to the front of the CNA.
- Match box, the dummy loads with some relays to be able to switch between them.

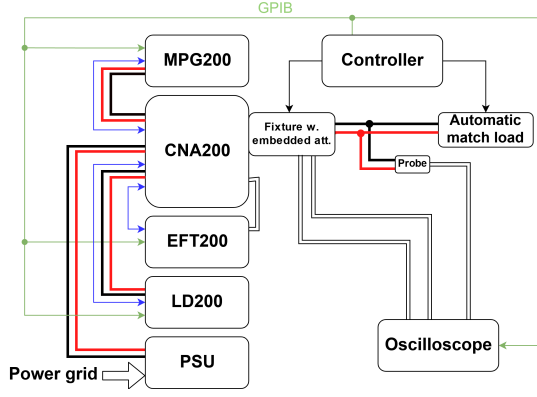


Figure 3.5: The proposed setup for alternative 3 have no high voltage connectors exposed during the calibration.

The advantages of this, in addition to the advantages of alternative 2, are that there is no longer need for external attenuators and that the connectors will no longer expose high voltage.

The disadvantage of this would be that the embedded attenuators might prove difficult to design. They need to be accurate up to high frequencies, be tolerable to high voltage, dissipate the power necessary and also be electrically safe.

3.5 Design of dummy loads

Each dummy load must withstand the applied test pulses, and preferably the worst possible test pulse for the specific dummy load even though it might not be intended. The dummy loads must have a tolerance of 1% or less and be non-inductive. [11]

The dummy loads consists of one or more resistors. When determining whether the resistors withstands the test pulses, the parameters of interest are power dissipation, maximum voltage and maximum energy applied over time.

Since the pulse generators in most cases can generate a higher voltage than required by the standard, the dummy loads should be designed for the worst case setting on the generator. This mitigates the risk of overloading the dummy load caused human error or an error in the control system.

Three different dummy loads are needed. One 2Ω load for load dump A and for pulse 2a, one 10Ω load for pulse 1 in 24V systems and one 50Ω load for pulse 1 in 24V systems.

Components

At first the momentary worst case powers and voltages were calculated by hand, using Equation 3.1. But to find components that withstand these high momentary powers proved very difficult, and it is not necessary since the pulse power is only high for a very short time.

$$P_{peak} = \left(\frac{U_S}{R_S + R_L} \right)^2 R_L \quad (3.1)$$

Instead of selecting components based on peak power they can be selected based on energy over time. Although, not all manufacturers specify this data in the datasheet. To get the proper values for this project, a simulation was made with LTSpice. The simulated circuit can be seen in Figure 3.6. There are preconstructed models for all of the relevant pulses, but the parameters are not tweakable. Thus, the pulse offset is removed, the magnitude is normalized and then multiplied by the desired U_S using the behavioural voltage source. The

power dissipated in the dummy load is then integrated over time to achieve the energy. The simulated circuit translates to the calculation shown in Equation 3.2.

$$E_{dummyload} = \int_{t_0}^{t_1} P(t)dt \quad (3.2)$$

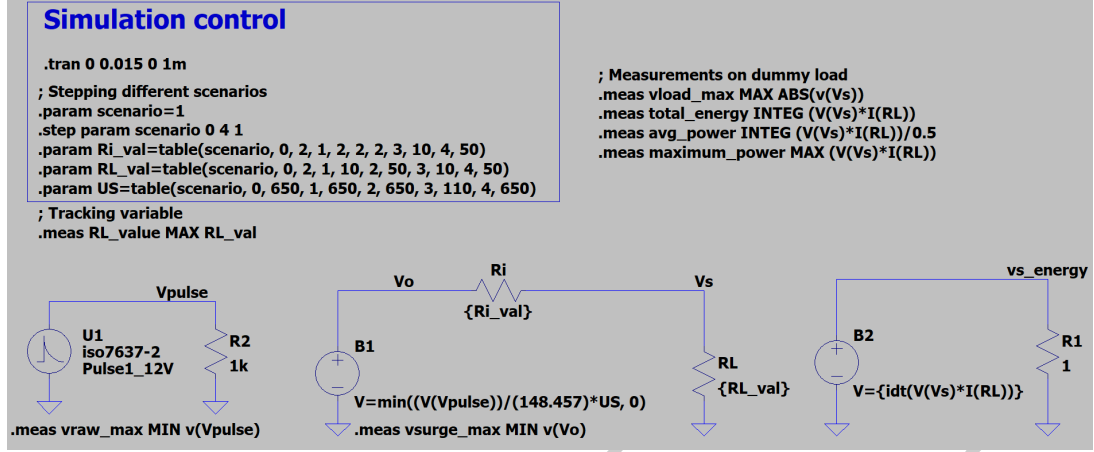


Figure 3.6: The energy transferred to the dummy load was simulated using the above LTSpice circuit for pulse 1. Similar circuits was used for the other pulses.

Based on the energy in each load, the minimum number of resistances could be achieved by dividing the energy from simulation by the energy specified in the resistor's datasheet.

PCB

Since most of the test pulses exceeds the properties of most resistors available, the dummy loads will be constructed of many resistors to share the power. It was decided to design a circuit board to connect all the discrete resistors. Not only does a PCB ease the connectivity of many components, it also gives good mechanical control of the resistors and the possibility to design for good heat dissipation.

Both the circuit schematic and layout editing of the board were performed in the free EDA, Electronic Design Automation, tool KiCad¹.

Before ordering the PCB, it was printed in 1:1 scale and attached to a piece of card board. The card board was then populated with the components already at hand to ensure that the footprints are correct and that the placement of the components makes sense and does not collide.

Measurements

When the dummy loads had been assembled, their resistances were determined using four wire resistance measurement directly at the PCB's connection points, as described in section 2.6.

3.6 Design of the switching fixture and the embedded attenuators

The chosen implementation requires a fixture with switches and attenuators, which purpose is to multiplex the pulse to the desired attenuator or to the dummy load. The principle is shown in Figure 3.7.

¹KiCad EDA <http://kicad-pcb.org/>

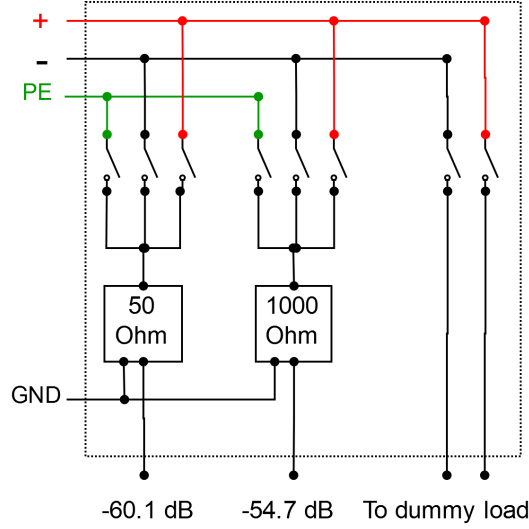


Figure 3.7: The multiplexing relay box can couple each of the three inputs through any of the attenuators. It can also connect the external dummy load to the + and - signal.

Only Pulse 3a and Pulse 3b were considered when designing these attenuators, since all other test pulses will be coupled to the separate dummy load. The attenuators must be able to withstand the pulse energies and voltages and should not distort the pulses. Preferably, the attenuators should also be able to withstand the worst case settings in the pulse generator with regard to voltage and power.

Components

The same methods were used for the attenuators as for the dummy loads to determine the number of resistors needed to share the power and voltage.

The relays were chosen based on high breakdown voltage between open contacts.

Attenuators

The target attenuation was decided to mimic the commercial attenuators, introduced in section 2.8, where the 50Ω attenuator has an attenuation of 54.7 dB and the 1000Ω attenuator has an attenuation of 60.1 dB.

The two attenuators were implemented as Π -attenuators. The values for the attenuators were retrieved from an online calculator¹, and then simulated in LTSpice to verify the values.

By dividing the attenuators into two Π -networks, the series resistance required is lower compared to realizing them in a single Π -link. This is desirable because the parasitic capacitance, which is dependent of the resistor package and not the resistance value, will influence a high value resistor at lower frequencies than it would on a low value resistor, as explained in section 2.5.

When the ideal resistor values had been achieved, the power over time and maximum voltage for each resistor was retrieved by simulation in a similar way as for the dummy load described in section 3.5. Based on this, the minimum number of discrete resistors needed to withstand the pulse energy was calculated. The minimum number of series resistors to withstand the maximum pulse voltage was also retrieved from the simulation.

¹ Π attenuator calculator <https://chemandy.com/calculators/matching-pi-attenuator-calculator.htm>

With the minimum number of discrete resistors needed for each ideal resistor known, a constellation of available resistor values was constructed to approximate the nominal value with as few resistors as possible.

When the number of resistors and their constellations was decided, all of the discrete ideal resistors were replaced with non-ideal models in the simulation software. Each lead inductance was set to 1 nH, the internal inductance was set to 0.1 nH and the internal capacitance was set to 1 pF. Then the attenuators were checked in frequency domain, as well as how the pulses were affected in time domain. If the required 400 MHz bandwidth could not be achieved, frequency compensation with capacitors was attempted.

PCB

A PCB was designed for the attenuators and the switches. This gives good control of the lengths of the conductors, which is of importance when designing for higher frequencies. It is also possible to use the PCB for other mechanical purposes. For example to fit connectors in a desired constellation.

The design process followed the same methods as for the dummy load PCB. But because of the higher voltages some special considerations had to be made.

The measurement connectors accessible on the outside of the encapsulation must be safe at all times. This involves keeping a minimum creepage distance of 6 mm to any trace that carry a high voltage, according to the regulations in EN 60664-1 [1].

The EDA tool has functionality for design rule checking, DRC, but there are some limitations in this function that inhibit its use in this case. The DRC in KiCad only allows to set the clearance for a specified net to all other nets. In this case it is only desired to restrict the clearance between the high voltage traces to the traces that must be considered safe. It is allowed for one high voltage trace to be close to another high voltage trace, it is only the functional isolation requirement of 3 mm that applies here. The output signal and the output ground can also be close to each other, since both are considered safe.

The high voltage traces were placed on the top layer of the PCB, while all signal traces were placed on the bottom layer. To aid the design process without the DRC, a workaround was used to ensure that that enough clearance was kept between the pads and the traces. The 6 mm clearance was added to the package footprint as a graphical circle on a user layer in the EDA, as seen in Figure 3.8. This is not an enforced rule, but it helps during the manual design process.

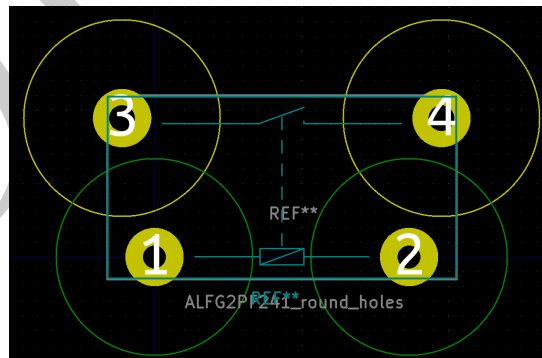


Figure 3.8: Decorational circles were made on the relay footprint to mark the creepage and clearance distance required.

The layout was printed in 1:1 scale to verify the layout in the same way as for the dummy load. This was especially important due to the critical positioning of the 4 mm banana connectors that will attach to the test equipment.

When the PCB was delivered, it was visually inspected before assembling. Some modifications were required to fulfill the clearance criteria, these were made using a rotary multitool to machine away the undesired part of the traces.

Measurements

Since the relay card will be used in measuring pulses with short rise times, it is of importance to know that it does not distort the signal too much. It is desired to measure the magnitude response in the frequency domain, as well as the test pulse in time domain.

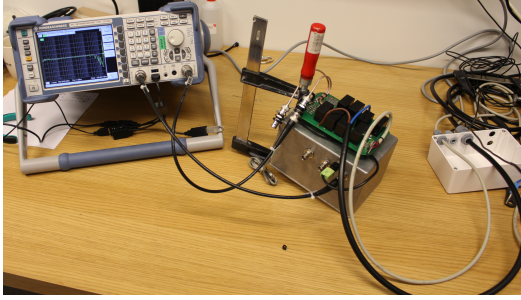
To measure the magnitude response, an S21 measurement was performed using the ZVL network analyzer. A fixture was made to mimic the front panel of the CNA 200 to allow for a representative connection of the relay card. The setup can be seen in Figure 3.9a. This setup proved to be unstable at first, as moving the coaxial wires and the grounding wire greatly affected the results for the higher frequencies. Because of the unstable results early in the measuring process, a modification was made to shorten the ground connection by attaching a braid as close as the attenuator grounds as possible and then grounding it directly to the fixture case, as depicted in Figure 3.9b. All subsequent measurements were performed with this modification.

The signal was measured for each output terminal through each of the attenuators to get the magnitude response for the intended use, Figure 3.10a shows this for the + terminal. To see how well the design suppresses unconnected signals, the magnitude response was also measured when the signal was disconnected completely, i.e. all the relays in the fixture were opened as in Figure 3.10b. In addition to this, the magnitude response was also measured with all but the relays on the current terminal closed, seen in Figure 3.10c, to see if there was any overhearing on the circuit board from the other terminals and the traces after the relays. The results were saved both as an image and as raw data in the form of complex numbers in a CSV file to allow for further analysis and plotting.

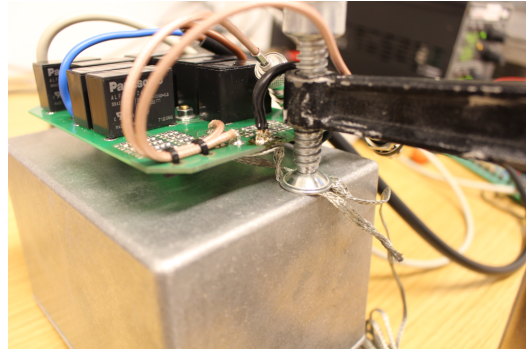
A single relay was also measured using the network analyzer to get a perception of its high frequency properties. The setup was made by soldering coaxial cable directly to the relay, with as short connecting wires as possible to prevent any influence on the result from the wires. The setup can be seen in Figure 3.9c.

To measure the test pulses through the attenuators, the switching fixture was connected to the CNA 200 and the pulses were measured on the intended connectors using an oscilloscope, as seen in Figure 3.9d. The results were saved both as an image and as data points in a CSV file, for further analysis.

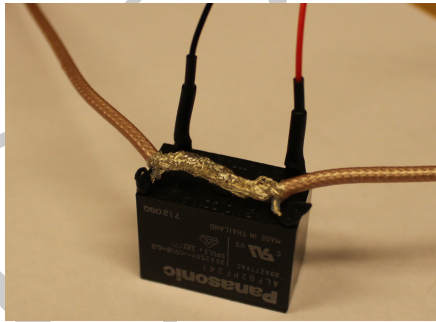
For comparison, the commercial attenuators were also measured in frequency domain with the ZVL and in time domain using the oscilloscope.



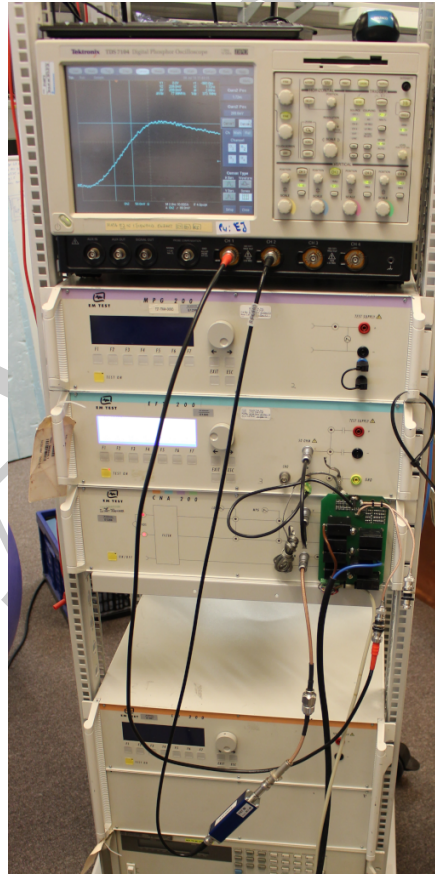
(a) The network analyzer sends its signal into the attenuator through the metallic test rig and receives it back through the BNC outlet of the attenuator.



(b) The modified grounding path.



(c) The relay measured with coaxial wires.



(d) The time measurement setup. Both the commercial and the constructed attenuators were measured in this setup.

Figure 3.9: The test setups for frequency and time measurements of the attenuators.

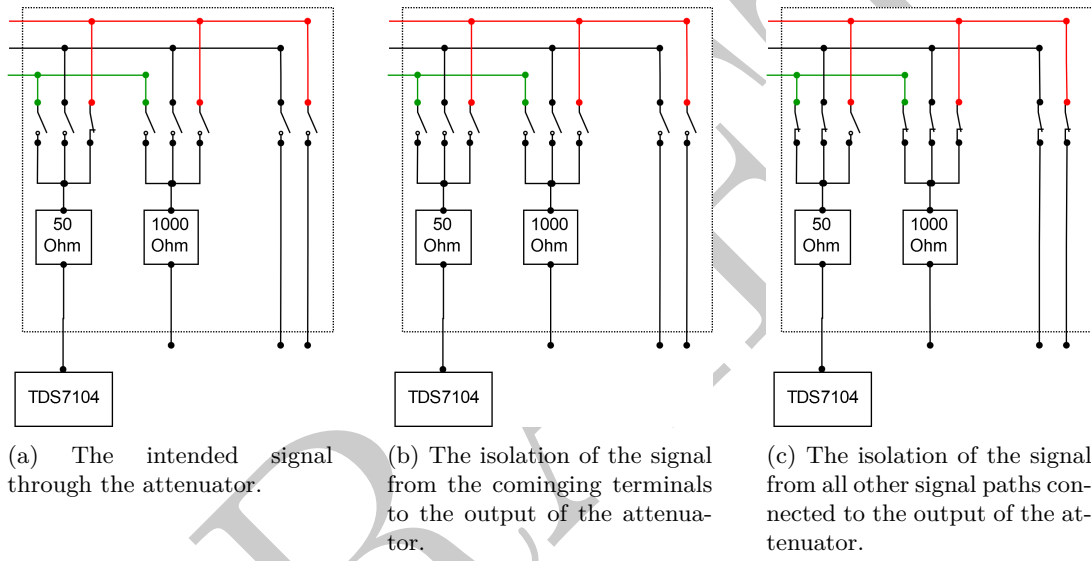


Figure 3.10: The different scenarios that were measured in frequency domain for the + terminal to the 50 Ω attenuator. Corresponding measurements were made for the - and the PE terminal as well as for the 1000 Ω attenuator.



4 Results

This chapter presents the results achieved using the methods described in chapter 3. Each section in this chapter corresponds to a section in the method chapter with the same name.

4.1 Prestudy

Since not much was known about the project at this time, it was difficult to find relevant papers on the topic of the standards. Most of the literature was found during the project as new problems were found along the way.

Since the test equipment was mostly in line with the new standards, the first project path was chosen. There was not enough time available to investigate any of the extra tasks as intended.

4.2 Comparison between the old and the new standard

The differences of importance between the old and new standards will be presented in this chapter to see what parameters might be a problem for the older equipment to fulfil.

One of the most notable differences is the removal of a test pulse from ISO 7637-2 that was called *Pulse 5a*. This was instead introduced to the ISO 16750-2 under the name *Load dump A*.

Only the properties that were found to differ are mentioned in the results.

Supply voltages

The specification of the DC supply voltage for the DUT differs in some cases between the older and the newer versions of the standard. There are two different supply voltage definitions. U_A represents a system where the generator is in operation and U_B represents the system without the generator in operation. These have different values for 12 V and 24 V systems. U_B is only relevant for Load dump Test A and is thus not defined in ISO 7637 anymore.

Table 4.1 presents the supply voltage specifications from the different standards. The supply voltages are provided by an external PSU and will thus not be dependent on the test equipment.

Table 4.1: Comparison of the different supply voltage specifications.

Standard	Supply voltage	
	$U_N = 12\text{ V}$	$U_N = 24\text{ V}$
U_A		
ISO 7637-2:2004	13 V to 14 V	26 V to 28 V
ISO 7637-2:2011	12 V to 13 V	24 V to 28 V
ISO 16750-1:2018	13.8 V to 14.2 V	27.8 V to 28.2 V
U_B		
ISO 7637-2:2004	12.3 V to 12.7 V	23.6 V to 24.4 V
ISO 16750-1:2018	12.3 V to 12.7 V	23.8 V to 24.2 V

Surge voltages

Several of the surge voltages has a wider specified range, as can be seen in Table 4.2. Notice how the old pulse 5a and the new load dump A have different specifications for U_S , but they describe the same pulse because of the different definition of U_S in ISO 7637-2 and ISO 16750-2.

Table 4.2: Comparison of the different surge voltage specifications.

Standard	U_S	
	$U_N = 12\text{ V}$	$U_N = 24\text{ V}$
Pulse 1		
ISO 7637-2:2004	-75 V to -100 V	-450 V to -600 V
ISO 7637-2:2011	-75 V to -150 V	-300 V to -600 V
Pulse 2a		
ISO 7637-2:2004	37 V to 50 V	
ISO 7637-2:2011	37 V to 112 V	
Pulse 3a		
ISO 7637-2:2004	-112 V to -150 V	-150 V to -200 V
ISO 7637-2:2011	-112 V to -220 V	-150 V to -300 V
Pulse 3b		
ISO 7637-2:2004	75 V to 100 V	150 V to 200 V
ISO 7637-2:2011	75 V to 150 V	150 V to 300 V
Pulse 5a/Load dump A		
ISO 7637-2:2004	65 V to 87 V	123 V to 174 V
ISO 16750-2:2012	79 V to 101 V	151 V to 202 V
ISO 16750-2:2012 ¹	65 V to 87 V	123 V to 174 V

Time constraints

The only time constraint that is stricter in the newer standard is the risetime of pulse 3a and pulse 3b, t_r , as shown in Table 4.3

Table 4.3: Comparison of the different time constraints.

Standard	Timing t_d
ISO 7637-2:2004	100 μs to 200 μs
ISO 7637-2:2011	105 μs to 195 μs

¹Recalculated values to fit the same U_S definitions as the older standard. $U_{S7637} = U_{S16750} - U_{N16750}$

Limits in verification

Most of the limits are the same in all standards. The only differences found are presented in Table 4.4. The tolerances for pulse 1 has been widened to 20 %. The nominal voltage for pulse 2a has been changed to 75 V for calibration but the tolerance is still 10 % with no load.

Table 4.4: Comparison of the limits for calibration.

Pulse 1, U_S , 24 V, 50 Ω load	
ISO 7637-2:2004	-300 V $\pm$ 30 V
ISO 7637-2:2011	-300 V $\pm$ 60 V
Pulse 2a, U_S , no load	
ISO 7637-2:2004	50 V $\pm$ 5 V
ISO 7637-2:2011	75 V $\pm$ 7.5 V
Pulse 2a, U_S , 2 Ω load	
ISO 7637-2:2004	25 V $\pm$ 5 V
ISO 7637-2:2011	37.5 V $\pm$ 7.5 V

4.3 Examination and initial measurement of the old equipment

At first, the test equipment itself needed some care before it was possible to operate it. A couple of screws were loose inside of the LD 200 and a bridge had to be made for the optional external resistor on the MPG 200 for the pulses to even reach the pulse output connectors.

The result from the initial measurements are presented, along with the limits, in Table 4.5 without the CNA 200 connected and in Table 4.6 with the CNA 200 connected.

Table 4.5: The initial manual measurements, measured directly at each generator's output.

Pulse	Limits			Measured		
	U_S (V)	t_d (s)	t_r (s)	U_S (V)	t_d (s)	t_r (s)
Pulse 1, 12 V, Open	[-110, -90]	[1.6, 2.4] m	[0.5, 1] μ	-99.0	2.10 m	540 n
Pulse 1, 24 V, Open	[-660, -540]	[0.8, 1.2] m	[1.5, 3] μ	-630	1.18 m	2.6 μ
Pulse 2a, Open	[67.5, 82.5]	[40, 60] μ	[0.5, 1] μ	76.0	51.0 μ	750 n
Pulse 3a, Open (1k)	[-220, -180]	[105, 195] n	[3.5, 6.5] n	-202	163 n	5.2 n
Pulse 3a, Match	[-120, -80]	[105, 195] n	[3.5, 6.5] n	-104	134 n	5.0 n
Pulse 3b, Open (1k)	[180, 220]	[105, 195] n	[3.5, 6.5] n	202	208 n	5.1 n
Pulse 3b, Match	[80, 120]	[105, 195] n	[3.5, 6.5] n	102	166 n	5.0 n
Load dump A, 12 V, Open	[90, 110]	[320, 480] m	[5, 10] m	93.4	390 m	5.8 m
Load dump A, 24 V, Open	[180, 220]	[280, 420] m	[5, 10] m	190	365 m	5.2 m

Table 4.6: The initial manual measurements on the equipment, including the CNA 200.

Pulse	Limits			Measured		
	U_S (V)	t_d (s)	t_r (s)	U_S (V)	t_d (s)	t_r (s)
Pulse 1, 12 V, Open	[-110, -90]	[1.6, 2.4] m	[0.5, 1] μ	-99.2	2.00 m	450 n
Pulse 1, 24 V, Open	[-660, -540]	[0.8, 1.2] m	[1.5, 3] μ	-632	1.18 m	2.6 μ
Pulse 2a, Open	[67.5, 82.5]	[40, 60] μ	[0.5, 1] μ	76.0	50.0 μ	770 n
Pulse 3a, Open (1k)	[-220, -180]	[105, 195] n	[3.5, 6.5] n	-213	163 n	6.2 n
Pulse 3a, Match	[-120, -80]	[105, 195] n	[3.5, 6.5] n	-93.2	138 n	6.0 n
Pulse 3b, Open (1k)	[180, 220]	[105, 195] n	[3.5, 6.5] n	222	200 n	6.3 n
Pulse 3b, Match	[80, 120]	[105, 195] n	[3.5, 6.5] n	94.0	171 n	5.7 n
Load dump A, 12 V, Open	[90, 110]	[320, 480] m	[5, 10] m	93.2	394 m	5.8 m
Load dump A, 24 V, Open	[180, 220]	[280, 420] m	[5, 10] m	186	400 m	5.1 m

4.4 Test architecture

The 3rd alternative was chosen because of the convenience of a fully automatic system and because of the electrical safety hazard that alternative 2 would pose due to its live measurement connectors.

4.5 Design of dummy loads

The design of the dummy loads is described in this chapter.

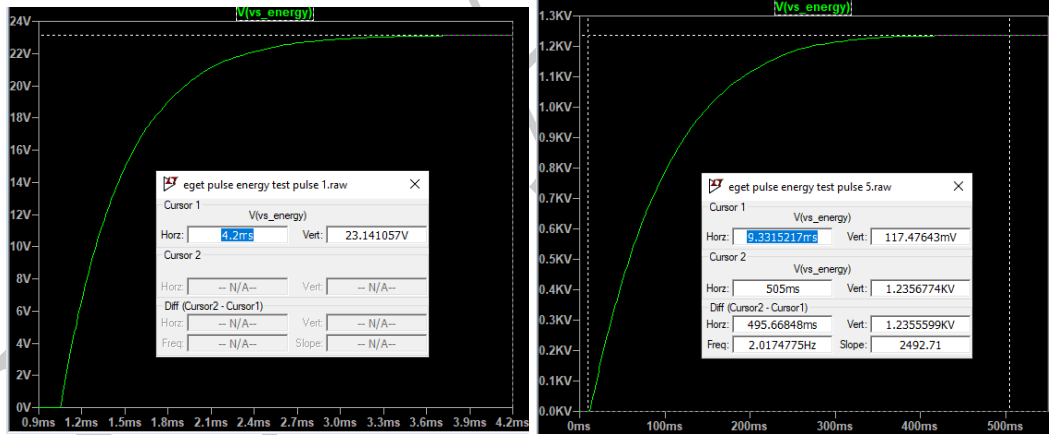
Components

The results of the maximum momentary power is shown in Table 4.7. The MPG 200 can generate much higher voltage than the LD 200 which yields a higher momentary power to the dummy loads with these values.

Table 4.7: Calculated momentary worst cases for each dummy load. The LD 200 is included for comparison to the MPG 200 even though it does not result in the highest power.

Dummy load	Generator	R_S	Generator voltage	Resistor peak voltage	Peak resistor power
2 Ω	LD 200	0.5 Ω	200 V	160 V	12.8 kW
2 Ω	MPG 200	2 Ω	600 V	300 V	45 kW
10 Ω	MPG 200	2 Ω	600 V	500 V	5 kW
50 Ω	MPG 200	2 Ω	600 V	577 V	266 W

The maximum energy transferred to the 2 Ω , however, is delivered by the LD 200 generator as shown in Figure 4.1.



(a) The MPG 200 transfers approximately 23 J to the dummy load. (b) The LD 200 transfers approximately 1.2 kJ to the dummy load.

Figure 4.1: The maximum energies transferred from the pulse generators to the 2 Ω dummy load. The vertical scale represents the energy in Joule, but is presented in voltage because of the way it is calculated in the simulation.

The LTO100 family¹ from Vishay was chosen because of its high power characteristics and because the maximum overload energy curve was specified in its datasheet. With the datasheet and simulation side by side, a worst ratio between the simulated energy and the energy specified in the datasheet was determined. The worst case found for the different pulses and dummy loads can be found in Table 4.8.

¹<https://www.vishay.com/docs/50051/lto100.pdf>

Table 4.8: The worst case ratio between the simulation energies and the datasheet specification. The ratio equals the minimum number of resistors needed to share the energy.

Dummy load	Ratio	Limiting property
$2\ \Omega$	26	Pulse 5 energy after 50 ms
$10\ \Omega$	10	Pulse 5 energy after 100 ms
$50\ \Omega$	2	Pulse 5 energy after 50 ms

When the least number of resistors required had been determined, some different resistor topologies were considered before settling on the configuration seen in Figure 4.2. The number of different resistor values was kept as low as considered possible to keep things easy.

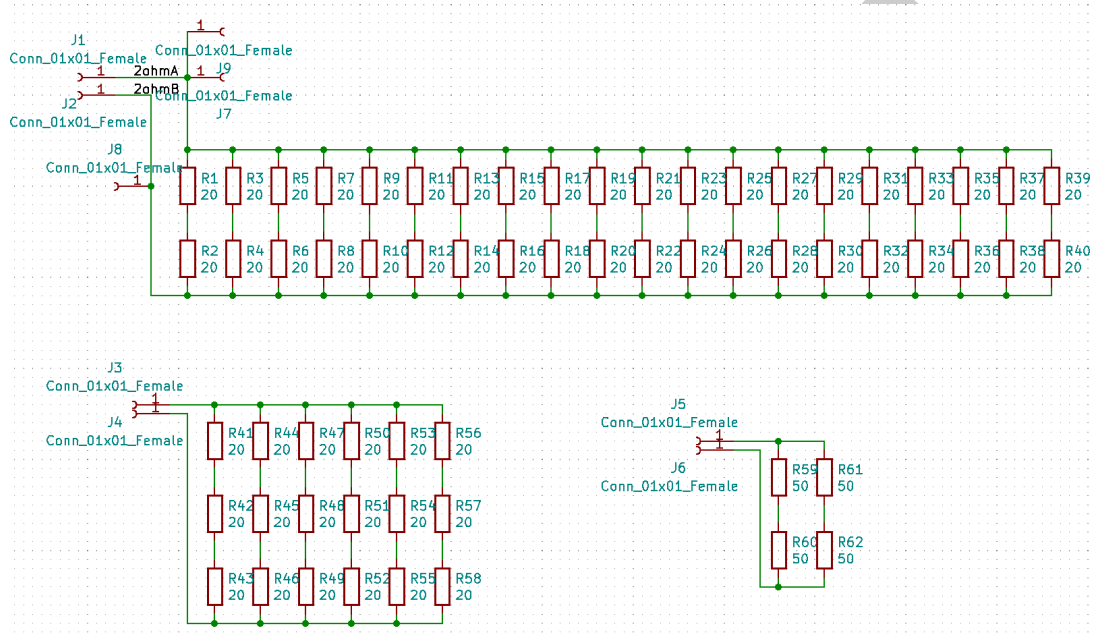


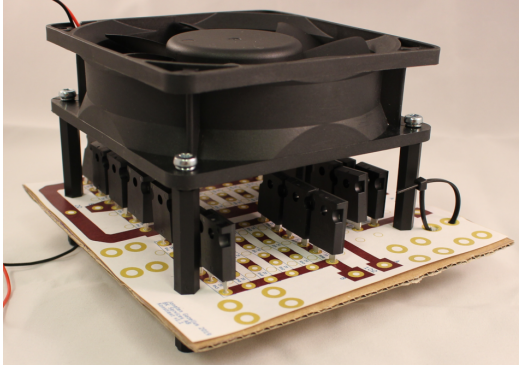
Figure 4.2: The topology chosen for the $2\ \Omega$, $10\ \Omega$ and $50\ \Omega$ dummy loads.

PCB

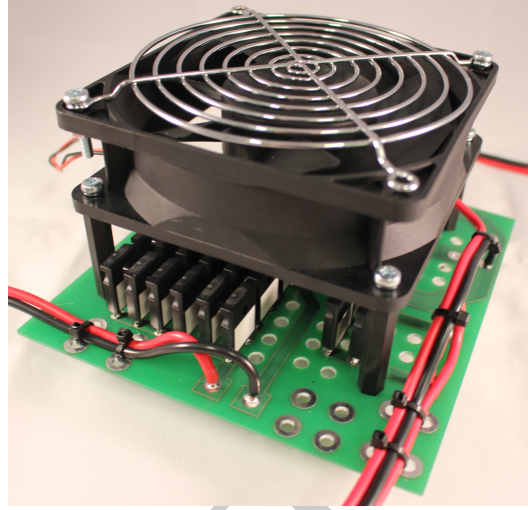
Because of the high voltages present on the board, a minimum creepage of 3mm was used. This is in line with the EN 60664-1 standard [1]. The board was perforated to allow for better air flow past the resistors, improving the cooling. The mounting holes for the card was placed in a $105 \times 105\text{ mm}$ square, allowing a 120 mm fan to be mounted on top of the card using mounting hardware.

A two layer board was chosen, and all of the traces were mirrored on both layers to get as much conductive cross sectional area as possible, and thus lowering the resistance and power dissipation in the traces. The default copper thickness from the manufacturer¹, was $18\ \mu\text{m}$, but this PCB was ordered with $60\ \mu\text{m}$ thick copper layer to further extend the cross sectional areas. The width of the traces for the $2\ \Omega$ load was chosen as wide as possible without violating the 3 mm creepage distance.

¹Cogra Pro AB <https://www.cogra.se/produkter/monsterkort/>



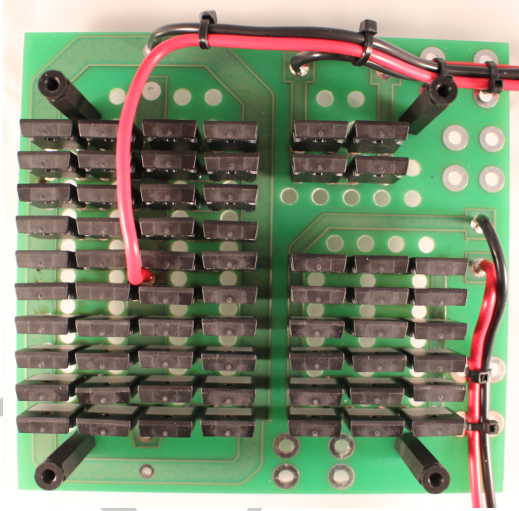
(a) Card board was used to test the PCB layout before it was sent to manufacture.



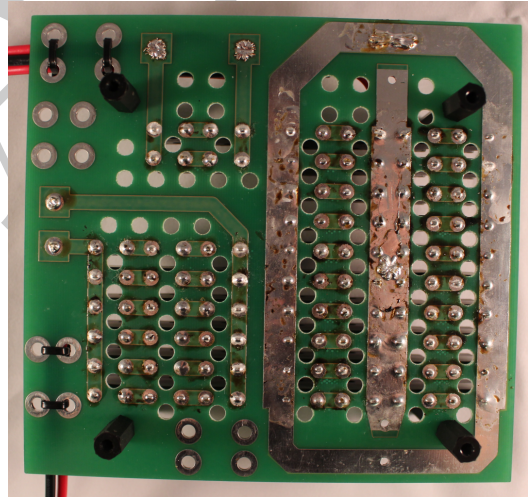
(b) The assembled dummy load.

Figure 4.3: The resulting board was predicted using a card board mockup PCB.

When the PCB was delivered, it was visually inspected before assembling. The component placement was correct, but some modification was made to improve the isolation distance by drilling away the plating and pads of the ventilation holes. The modified board's top and bottom side can be seen in Figure 4.4a and Figure 4.4b respectively.



(a) Top.



(b) Bottom.

Figure 4.4: The plating in the ventilation holes was removed by hand using a drill.

Measurements

The resistance of the dummy loads are presented in Table 4.9.

4.6 Design of the switching fixture and the embedded attenuators

The design of the switching fixture and its attenuators is described in this chapter.

Table 4.9: The measured resistance of the dummy loads, and the error compared to the nominal values.

Nominal (Ω)	Measured R (Ω)	Error (%)
2	2.004	+0.2
10	9.973	-0.27
50	49.954	-0.09

Components

The 1206 package from Vishay's CRCW-HP series¹ was used for the embedded attenuators. They are high pulse tolerant thick-film resistors. However, they don't specify the maximum energy vs time as the LTO100 that were used for the dummy loads, but only power and voltage limits. The maximum voltage allowed for the short duration of Pulse 3, 200 ns, is specified to 700 V and the maximum power to 900 W.

The maximum power dissipated into the 50 Ω attenuator will be approximately $\frac{750 \text{ V}^2}{50 \Omega} = 11\,250 \text{ W}$. For the 1000 Ω attenuator it will be approximately $\frac{1429 \text{ V}^2}{1000 \Omega} \approx 2042 \text{ W}$, where 1429 V is the approximate voltage that would result over a 1000 Ω load from a 1500 V source with 50 Ω series resistance.

The Panasonic's LF-G relays were chosen as switching elements as they have a high break-down voltage between the open contacts and had a small form factor making them suitable for the relay box.

Attenuators

The 54.7 dB attenuator was divided into two 27.35 dB Π attenuator links. The values obtained from the online calculator was 54.48 Ω as the parallel resistors and 581.62 Ω as the series resistor. Then the closest values for the resistors was chosen to 54.67 Ω as parallel resistors and 560 Ω as series resistors. The final attenuation was 53.76 dB for the two links according to the simulation, as seen in Figure 4.5a. The design was realized as seen in Figure 4.5c, based on the maximum voltages and powers. Capacitors were placed in the schematic to allow for phase compensation.

Since the uncompensated circuit had its 3 dB limit at only 190 MHz, as seen in Figure 4.5b, the circuit had to be compensated. The results after the compensation can be seen in Figure 4.5d where the new 3 dB limit is instead at 1.7 GHz. The values used for compensating the circuit was 130 pF for the first parallel resistance and 10 pF for the second parallel link as seen in Figure 4.5c.

The 60.1 dB attenuator was divided into one 27.35 dB Π attenuator link, the same as used in the 54.7 dB attenuator, preceded by a 32.75 dB Π link with 1000 Ω in-impedance. When the closest values for the resistors had been chosen, using 56 Ω as parallel resistors and 56 Ω as series resistor, the final attenuation was 60.33 dB for the two links according to the simulation, seen in Figure 4.6a. The attenuator was then realized as seen in Figure 4.6c, based on the maximum voltages and powers.

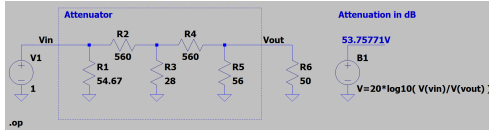
Since the uncompensated circuit had its 3 dB limit at only 130 MHz, as seen in Figure 4.6b, the circuit had to be compensated. The results after the compensation can be seen in Figure 4.6d where the new 3 dB limit is instead at 2.2 GHz. The values used for compensating the circuit was 40 pF for the first parallel resistance and 30 pF for the second parallel link as seen in Figure 4.6c.

PCB

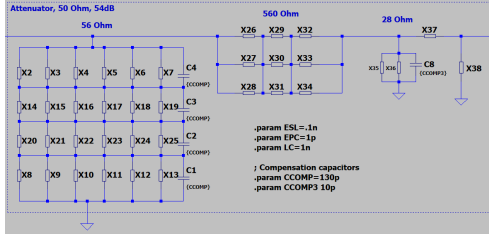
TODO

¹<https://datasheet.octopart.com/CRCW120682R0FKEAHP-Vishay-datasheet-8359436.pdf>

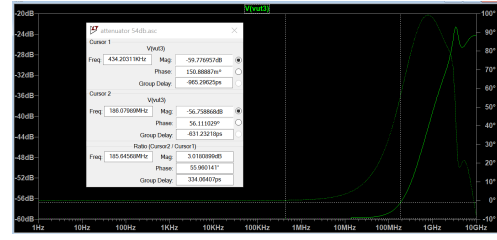
TODO:
Fyll i den här delen så att det liknar det ovan..



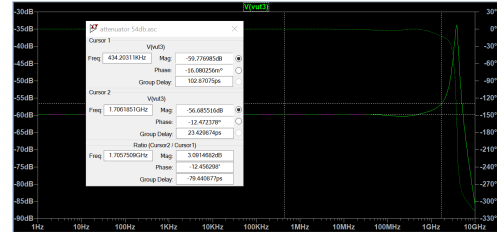
(a) The ideal circuit simulated.



(c) Chosen topology simulated with parasitics and compensation capacitors. The components with designator X are the non-ideal resistors depicted in Figure 2.7



(b) Frequency response of the circuit with parasitics without compensation.



(d) Frequency response of the circuit with parasitics with compensation capacitors.

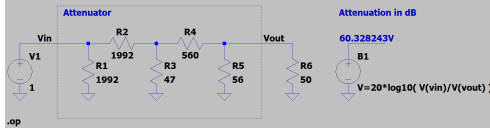
Figure 4.5: The 50 Ω attenuator simulated.

To attach the relay card fixture to the 4 mm banana connectors on the CNA 200, three banana plugs was designed to be screwed directly to the PCB. This makes the conductors as short as possible, and also act as mechanical fastening of the PCB to the case.

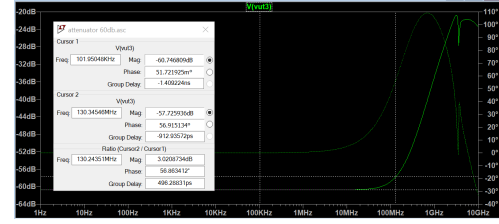
Measurements

The results of the magnitude response measurements can be seen for the 50 Ω attenuator in Figure 4.8 and for the 1 k Ω attenuator in Figure 4.9. The PAT 50 and PAT 1000 attenuators were measured as reference and their results can be seen in Figure 4.10a and Figure 4.11d respectively. The frequency response of the single relay is shown in Figure 4.10c.

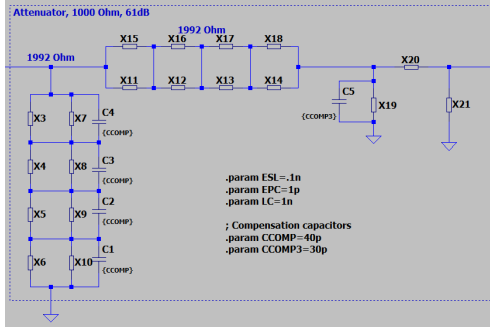
The time measurements are shown in Figure 4.11



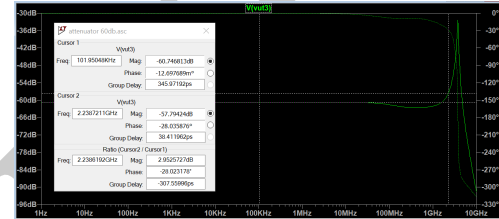
(a) The ideal circuit simulated.



(b) Frequency response of the circuit with parasitics without compensation.



(c) Chosen topology simulated with parasitics and compensation capacitors. The components with designator X are the non-ideal resistors depicted in Figure 2.7



(d) Frequency response of the circuit with parasitics with compensation capacitors.

Figure 4.6: The 1000 Ω attenuator simulated.

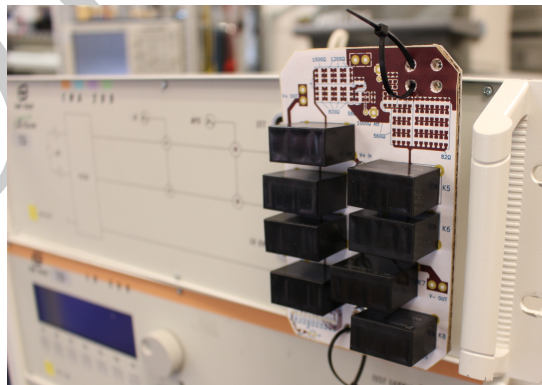


Figure 4.7: Card board was used to test the PCB layout before it was sent to manufacture.

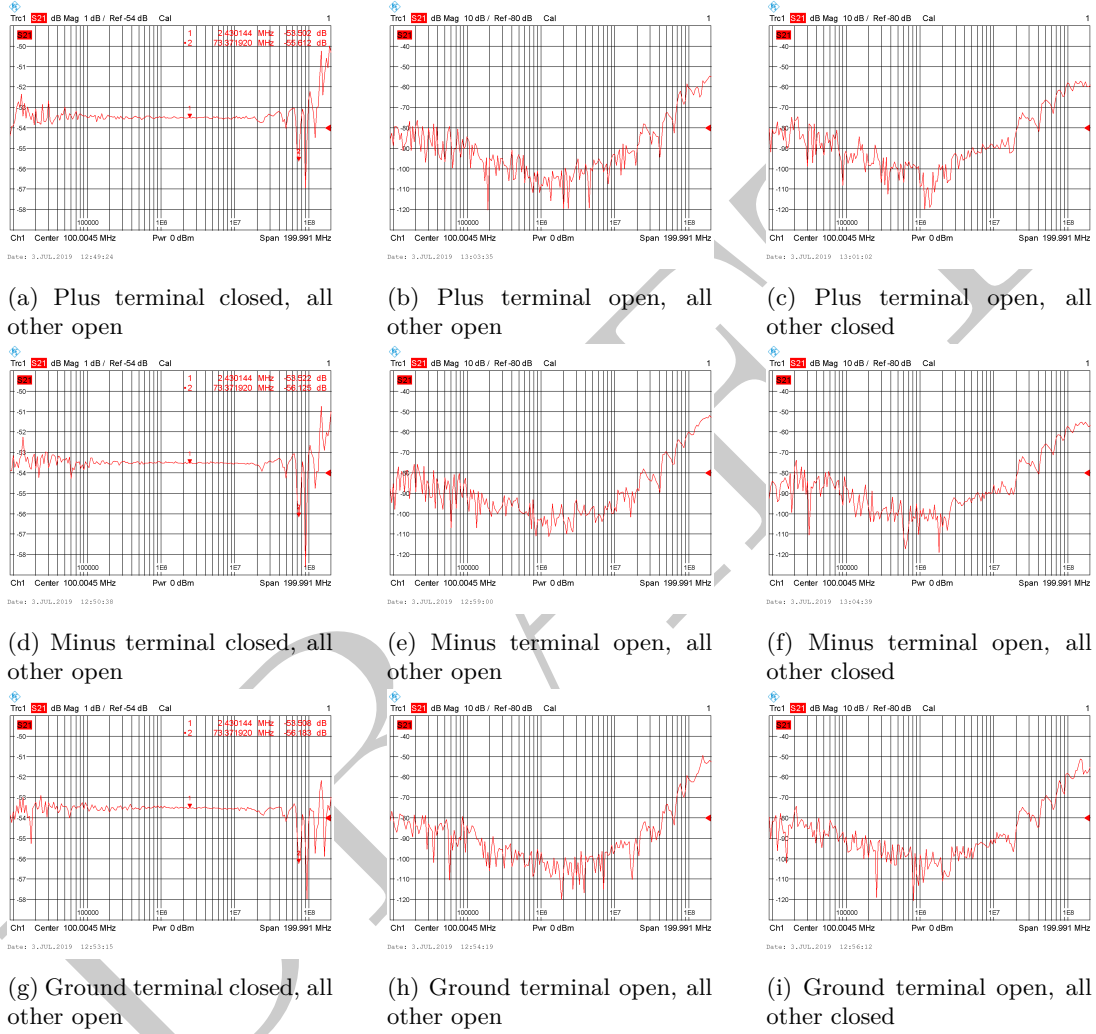


Figure 4.8: The S21 measurements for the 50Ω attenuators

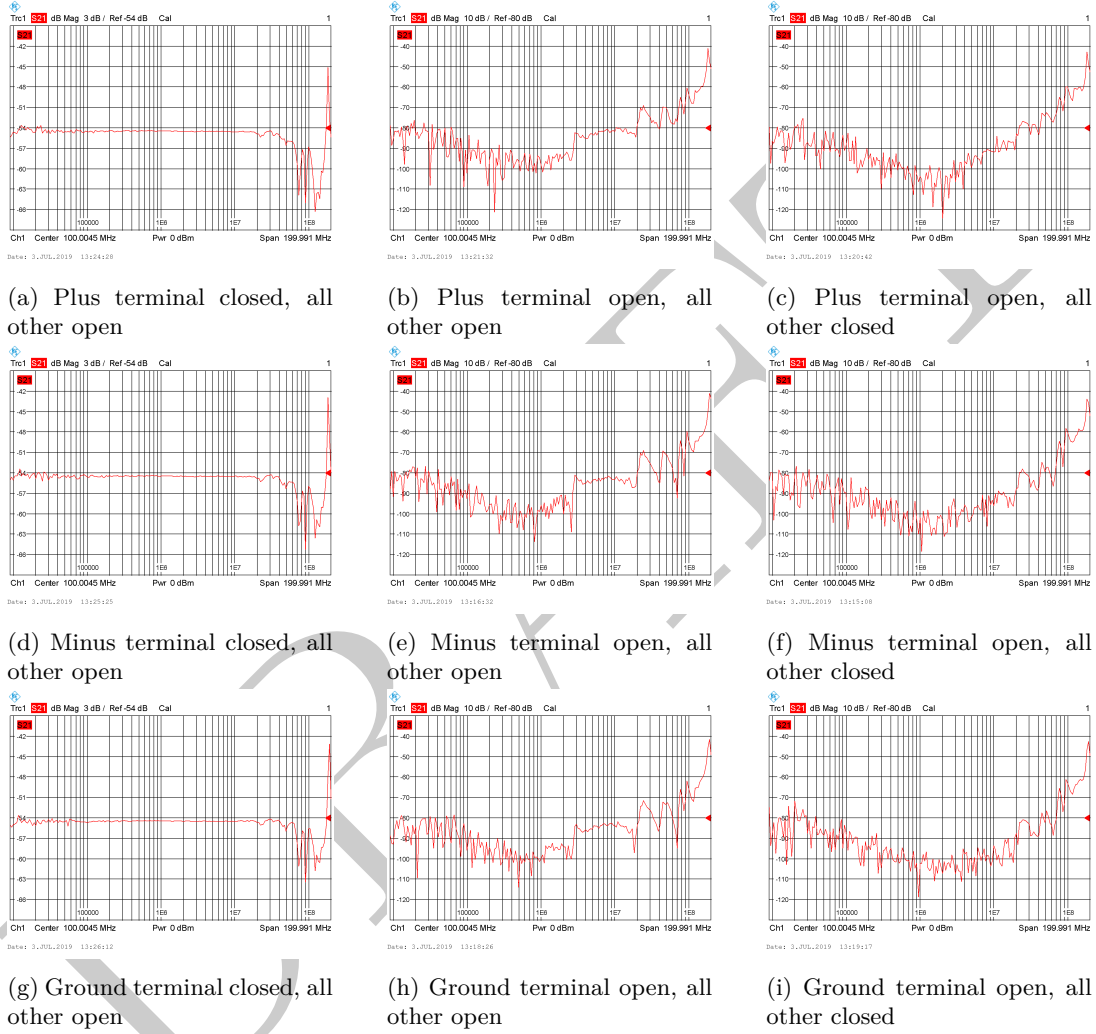
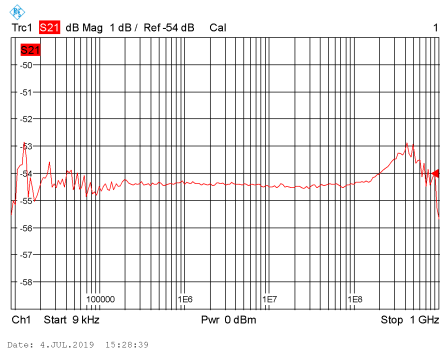
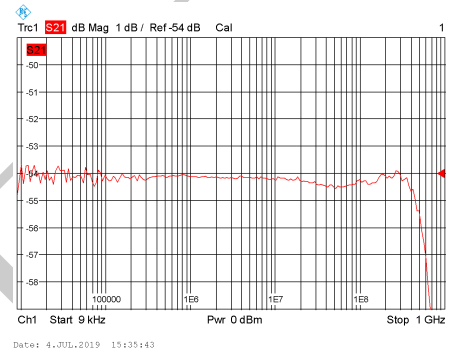


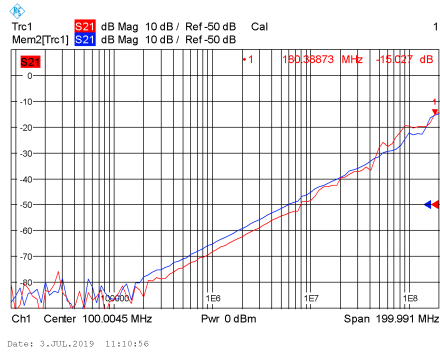
Figure 4.9: The S21 measurements for the 1 kΩ attenuators



(a) PAT 50

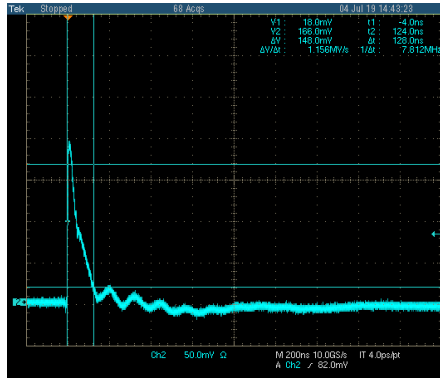


(b) PAT 1000

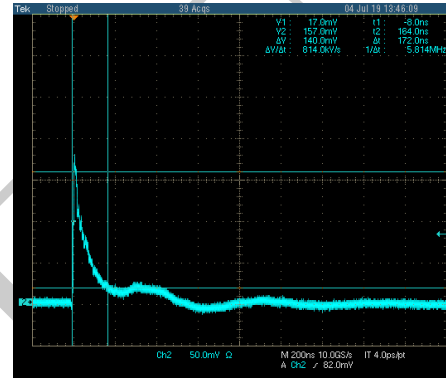


(c) The relay's magnitude response.

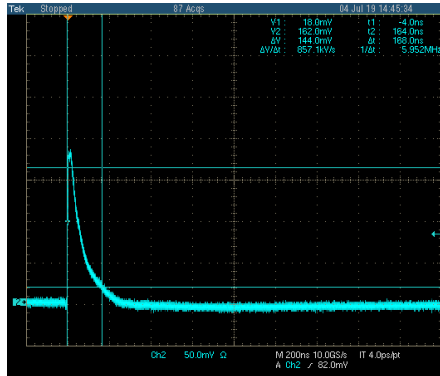
Figure 4.10: The S21 measurements on the commercial attenuators and the solo relay.



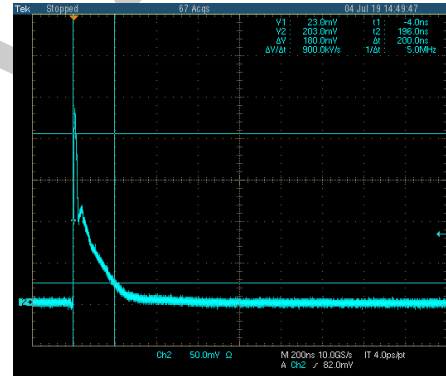
(a) The constructed 50 Ω attenuator



(b) The constructed 1 k Ω attenuator



(c) PAT50



(d) PAT1000

Figure 4.11: The attenuator measurements in time domain, measured with the oscilloscope.

5 Discussion

TODO This chapter

TODO:
skriv nåt bra i det här kapitlet

5.1 Results

5.2 Initial measurement of the performance of the old equipment

As can be seen in Table 4.5 and Table 4.6, some values exceeded the limits (marked in red). Three of these values even exceeds the old standard's limits, thus indicating that the equipment should probably be usable with the new standard after some service or calibration. With this in mind, the course of the project will be targeted towards the design of an automated verification system, as described in ???. With such a verification equipment at hand, the calibration of the generators might be easier to perform as well.

5.3 Method

It was surprisingly difficult to find and choose appropriate components for the dummy load. The resistors had to tolerate extreme surges and the relays had to have high insulation voltages between the contacts. Even finding the encapsulation for the relay box proved to be a challenge, since the filtering options available at the retailers web stores were not always consistent.

The usage of the energy curve in the datasheet might have been wrong *TODO*

TODO:
explain interval, not absolute time. All intervals must be checked.

Dummy Loads

The results are well within the 1 % specified by the standard [11].

Attenuators

During the project, the attenuation was considered as the voltage attenuation $att = 20 \log_{10} \left(\frac{V_{in}}{V_{out}} \right)$ dB. However, lots of information and many tools for RF applications, including the calculator used for the attenuators in this project, assume power attenuation $att = 10 \log_{10} \left(\frac{P_{in}}{P_{out}} \right)$ dB. The result of these two properties coincides when the input and output impedance, as well as the driving and loading impedance, are all the same.

The fact that these two ways of expressing attenuation could be mixed up was not noticed until very late in the project. Thus the values provided by the online attenuator tool did not give the desired results in the simulator, for the $1000\,\Omega$ attenuator. This was at the time manually tweaked until the desired attenuation was acquired, but the out impedance was not considered during the tweaking and thereby ended up being a bit mismatched for the next Π link.

There are infinitely many constellations to approximate the nominal value, in this project it was tried to use as few resistors as possible. This process was performed manually, since no suitable software for solving the problem was found. Thus the chosen constellations might not be optimal.

Desired vs implemented (simulation)

Parasitic effects. (real life, back to simulation)

5.4 The work in a wider context

Ethical aspects

5.5 References

Source criticism

6 Conclusion

This chapter contains a summarization of the purpose and the research questions. To what extent has the aim been achieved, and what are the answers to the research questions? The consequences for the target audience (and possibly for researchers and practitioners) must also be described.

Besvara frågeställningen

The main goal of this thesis was to examine the potential of resusing old test equipment with newer standards and how to assure that the results are reliable. A method to verify the test equipment according to the latest standard was suggested in this thesis and some considerations for automating this procedure was made.

TODO

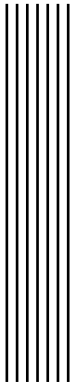
TODO:
Lägg in fin lista med svar på
research questions här

6.1 Future work

There should be a section on future work where ideas for continued work are described. If the conclusion chapter contains such a section, the ideas described therein must be concrete and well thought through.

Sätt av ett kort kapitel sist i rapporten till att avrunda och föreslå rikningar för framtida utveckling av arbetet.

Measurement errors
Mathematical analysis
Automation



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