Contents

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.

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 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.* [**?**]

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

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. [**?**]

3 ISO 7637 and ISO 16750

TODO[TODO]fundera på uppdelningen av stycken och underrubriker här, och allmän formattering

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. *TODO*[TODO]Kolla upp delar 2020

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. [?]

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. [?]

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

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. [?]

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, *Electrical Loads*, of the standard 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. [?, ?]

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. [?, ?, ?]

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 internal resistance is only in series with the pulse generator, not the DC power source. For pulses that are supposed to be applied several times, t_1 usually denotes the time between two consecutive pulses.

An important observation is that the definition of the surge voltage, U_s, differs in ISO 7637 and ISO 16750 as seen in **??**. In this report, only the definition from ISO 7637 is used.

TODO[TODO]Bild med kurvornas parametrar, båda ISO standardernas definitioner

4.1 Test pulse 1

This pulse simulates the event of the power supply being disconnected while the DUT is connected to other inductive loads. This leads to the other inductive loads generating a voltage transient of reversed polarity to 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 s, and the step seen in **??** might be too short to be clearly distinguishable when seen on a oscilloscope.

TODO[TODO]Två bilder, en på kurvan och en på kretsen som orsakar den. En tabell med parametervärden.

4.2 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.

TODO[TODO]Två bilder, en på kurvan och en på kretsen som orsakar den. En tabell med parametervärden.

4.3 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 [**?**]. The formulation is not very clear, but is interperted and explained by Frazier and Alles [**?**] 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.

TODO[TODO]Fyra bilder, två på kurvorna, en på burst och en på kretsen som orsakar den? En tabell med parametervärden.

4.4 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.

Figure 1: The rise time is defined as the time elapsed from 0.1 to 0.9 times the maximum voltage on the rising edge of the function. The duration 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.

Figure 2: The repetition time is defined as the time between two adjacent rising edges, measured at 0.1 times the maximum pulse voltage.

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, $U_s = \hat{U} - U_A$.

TODO[TODO]Två bilder, en på kurvan och en på kretsen som orsakar den. En tabell med parametervärden.

4.5 Test setup

During a test, the nominal voltage is first applied between the plus and minus terminal of the DUT's power supply input. Then a series of test pulses are applied between the same terminals. The pulses are repeated at specified intervals, t_1, as depicted in 2. *TODO*[TODO]Snygg bild på uppkoppling och kopplingsnätverk..

TODO[TODO]Tryck ihop bilderna och gör dem lite mindre

4.6 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, with and without a matched load attached $R_L = R_i$. The standard omits the rise time constraint when the load is attached, except for pulse 3a and 3b. [?]

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

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

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

Table 1: These are all of the verifications that needs to be made before each use of the equipment, along with the limits for each case.

5 Differences between the new and the old standard

Since the equipment used 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 of importance between these 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* and *Pulse 5b*, this was instead introduced to the ISO 16750-2 under the name *Load dump A* and *Load dump B*.

5.1 Definitions

Since there are now two different standards, ISO 7637 and ISO 16750, that are describing the pulses some differences in definitions have been introduced.

TODO[TODO]Snygga till presentationen av definitionerna

$\boldsymbol{U_S}$

For pulse 1, 2a, 3a and 3b: $U_{TOP} - U_N$

For Load dump A: U_{TOP}

$\boldsymbol{U_A}$

For pulse 1, 2a, 3a and 3b: 13.5 ± 0.5 V, 27 ± 1 V [?]

For Load dump A: 14 ± 0.2 V, 28 ± 0.2 V [?]

5.2 Tolerances

Some of the allowed ranges on the pulses parameters has changed compared to the older version of the standard.

TODO[TODO]Gör snygga tabeller

Pulse 1 Old, 12V: $U_S - 75 - - - 100$ V Old, 24V: $U_S - 450 - - - 600$ V

New, 12V: $U_S - 75 - - - 150$ V New, 24V: $U_S - 300 - - - 600$ V

Pulse 2a Old: $U_S 37 - -50$ V

New: $U_S 37 - -112$ V

Pulse 3a and Pulse 3b Old, 12V: $U_S 112 - -150$ V Old, 24V: $U_S 150 - -200$ V

New, 12V: $U_S 112 - -220$ V New, 24V: $U_S 150 - -300$ V

Old: $t_r 100 - -200$ s

New: $t_r 105 - -195$ s

Load dump A No change, other that the definitions.

5.3 Tolerances for verification

Pulse 1

Old, 24V, matched: $U_S - 300 \pm 30$ V

New, 24V, matched: $U_S - 300 \pm 60$ V

Pulse 2a

Old, open: $U_S 50 \pm 5$ V, matched $U_S 25 \pm 5$ V

New, open: $U_S 75 \pm 7.5$ V, matched $U_S 35.5 \pm 7.5$ V

Pulse 3a and Pulse 3b

No change.

Load dump A No change, but according to print (or thought) error:

Old, 12 V, open: $U_S 100 \pm 10$ V, matched $U_S 50 \pm 10$ V

New, 12 V, open: $U_S 87 \pm 10$ V, matched $U_S 37 \pm 10$ V **NOTE, this can't be true**

Old, 12 V, open: $U_S 200 \pm 20$ V, matched $U_S 100 \pm 10$ V

New, 12 V, open: $U_S 172 \pm 20$ V, matched $U_S 72 \pm 20$ V **NOTE, this can't be true**

6 Resistors at high frequencies

TODO[TODO]Ta upp teori kring parasitiska effekter och icke-ideala modeller

`https://www.edn.com/design/components-and-packaging/4423492/Resistors-aren-t-resistors`

`https://www.vishay.com/docs/60107/freqresp.pdf`

Källan [**?**].

When working with resistors at high frequencies, one must care for the parasitc properties of the resistor.

7 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, the magnitude response has to be measured. This chapter describes the necessary measurement theory required for this project.

7.1 Resistance

The circuit designers companion p.99

7.2 High Voltage

The highest voltage that can be generated by the pulse generators is 1500 V, which is higher than any of the standards require but will serve as the design goal for the verification equipment. This is a higher voltage than most acquisition devices can measure without the use of external attenuators [**?**].

Resistive attenuators.. *TODO*[TODO]fyll på

7.3 Bandwidth and rise time

The shortest rise time is xxx ns, which can roughly be compared to yyy MHz. [**?**]

The relationship and requirements, addition of rise time limitations etc Combined rise time [**?**].

high speed digital design 83

7.4 Oscilloscope and probes

TODO[TODO]Put good theory here

An oscilloscope measures voltage over time, using voltage probes.

The oscilloscope has properties bandwidth...

The probe also has properties..

Commercial probes are expensive

7.5 Measurement errors

TODO[TODO]Put good theory here

7.6 RF Attenuators

Linearity, tolerances, power, combinations of resistors, impedances

7.7 Tolerances and maximum ratings

Resistors, Power, Voltages, surges, Relays, isolation, dielectric strength

8 Analysis

The data points from the measurement must be processed and evaluated to determine if the measured pulse is within the specified limits. There are several techniques to accomplish this, which have different advantages.[?]

8.1 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 1 and 1. 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. [?]

$$u(t) = k(e^{\alpha t} - e^{\beta t}) + U_A \tag{1}$$

8.2 What is good

TODO[TODO]Någonting om vad som anses bra

8.3 Curve fitting?

TODO[TODO]Läs på om ämnet och se ifall det kan vara rimligt

8.4 Max/min limits?

TODO[TODO]Användandet av max/min-fönster

8.5 Parameter extraction?

TODO[TODO]Detta är nog ett påhittat ord, kanske menar jag curve fitting?

8.6 Evaluation/simulation/robustness

TODO[TODO]Jämför och evaluera de två eller tre metoderna med hänseende till vad som står i "goodness"

—-

Essentially an embedded high voltage probe.

Bra böcker

High frequency content

Measurement & Instrumentation Principles, Alan S Morris

High-Voltage Engineering and Testing, 3rd Edition, Chapter 15 - Basic Measuring Techniques

Handbook of Measuring System Design, Peter H Sydenham and Richard Thorn

Artiklar om högspänningsmätning

High Voltage Measurements Using Slab Coupled Optical Sensors (SCOS) LeGrand Shumway, Nikola Stan, Freddy Seng, Rex King, Richard Selfridge, Stephen Schultz Department of Electrical & Computer Engineering, Brigham Young University, Provo, Utah 84602, USA

High frequency high voltage probe embedded into an extremely low inductivity high voltage supply connection D. Ketel, H. Hirsch, M. Malek University of Duisburg-Essen, Bi smarckstr. 81, 47057 Duisburg, Germany, http://www.ets.uni-due.de Tel: +49(0) 203 379 3789, email: daniel.ketel@uni-due.de

Optical measurement of current and voltage on power systems AJ. Rogers

Application of the Pockels Effect to High Voltage Measurement Fei Long Jianhuan Zhang Chunrong Xie Zhiwei Yuan Mechanical Electrical Engineering Department, Xiamen University, Xiamen, 361005 China

Curve fitting och Double exponential pulse function

Shape Properties of Pulses Described by Double Exponential Function and Its Modified Forms

On the Design and Generation of the Double Exponential Function S. C. Dutta Roy and D. K. Bhargava

9 Instrumentation and control

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

9.1 GPIB

IEEE-488, or GPIB 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. *TODO*[TODO]fyll på och hitta källor, lägg in bild på interface

9.2 Tektronix TDS7104 Oscilloscope

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

TODO[TODO]Lägg in bild på utrustning, och tabell med data

9.3 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.

TODO[TODO]Lägg in bild på utrustning, och tabell med data

9.4 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.

TODO[TODO]Lägg in bild på utrustning, och tabell med data

9.5 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.

TODO[TODO]Lägg in bild på utrustning, och tabell med data

9.6 EM Test CNA 200 Coupling Network

The SNA 200 is a coupling network, used to multiplex the pulse generators into one box. 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.

TODO[TODO]Lägg in bild på utrustning, och tabell med data

9.7 Rohde & Schwarz ZVL13

The ZVL13 is a vector network analyzer. It is, in this project, used to measure the magnitude and phase response between its two ports.

TODO[TODO]Lägg in bild på utrustning, och tabell med data

9.8 PAT 50 and PAT 1000

Methods This chapter covers the methodologies used during the project.

10 Prestudy

During the project efforts were made to find relevant research using Linköping University Library's[1] and Google Scholar's[2] search engines. Among the keywords used in searching were;

verification equipment, *test equipment*, *automatic test*, *automatic verification*, *iso equipment*, *electrical verification*, *curve fitting*, *double exponential function*, ,

TODO[TODO]Skriv färdigt nyckelordsdelen och presera dem på ett snyggt men platseffektivt sätt

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. 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.

[1] `https://liu.se/en/library`
[2] `https://scholar.google.se/`

11 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's performance were 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 these pulses were measured with the use of the high voltage differential probe described in **??**. The pulses are measured both directly on each generator connected according to **??** and also through the coupling network CNA 200, as depicted in **??**. *TODO*[TODO]figure of connection Pulse 3a and Pulse 3b was measured using the attenuators described in **??** connected according to **??**. Thanks to the 50-ohm attenuator this pulse could be measured in its matched state. The measurement in open state is a compromise, since there was no such attenuator available, and was made into a 1000-ohm attenuator instead.

12 Test architecture

Alternatives and choices. Try finding articles on human error maybe. Make plenty of nice figures. The total number of tests needed to verify the testing equipment before each product test is 14, according to 1. There are in total three different values for dummy loads, in practice these will be represented by three different high power dummy loads and two high frequency attenuators for pulse 3a and pulse 3b.

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.

12.1 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.

TODO[TODO]försök hitta källor på följande påståenden

The main advantage of this is that it would probably require the least amount of time for development of the automation software. 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 very 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, $1\,\mathrm{k}\Omega$ high frequency.

12.2 Alternative 2 – Fully automatic rig 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 [?] *TODO*[TODO]find source to this. 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 power dissipation needed. The proposed architecture is depicted in **??**.

TODO[TODO]Fint schema här

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.

12.3 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. **??**.

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.

TODO[TODO]Fint schema här

The advantage of this, on top of the advantages of alternative 2, is 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.

13 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. [?]

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.

13.1 Components

At first the momentary worst case powers and voltages were calculated by hand, to the values seen in 2. But to find components that can handle these momentary powers proved very difficult, and it is not necessary since the pulse power is only high for a very short time.

One manufacturer of thick film resistors, namely Vishay, specifies its overload capability in a graph with energy over time in the datasheet, which was easier to compare against using LTSpice to simulate the energies for the different loads, according to **??**. The simulated value was then divided by the value specified in the datasheet to get the minimum number of resistors required to share the load. Some possible combinations of available resistor values were considered to reach the desired load resistance, before the final configuration were decided according to **??**.

TODO[TODO]ltspice-bild på de tre olika dummy loadsen

The voltages used in the calculations are specified in 2, they are slightly higher than the specified voltages on the equipment to allow for some margins. The worst case voltage must always be tolerated to prevent arching or serious degrading of the components.

Dummy load (Ω)	Pulse	R_S (Ω)	Generator voltage (V)	Peak voltage (V)	Peak power (W)	Mean power (W)
2	Pulse 1	2	650	325	45 k	5
10	Pulse 1	2	650	600	5 k	5
50	Pulse 1	2	650	600	5 k	5
50	Pulse 1	2	650	600	5 k	5

Table 2: Calculated momentary worst cases for each dummy load.

TODO[TODO]Rätta till värdena i tabellen!

TODO[TODO]input graph of energy

13.2 PCB

Since the dummy loads consists of many discrete resistors, it was decided to design a PCB, printed circuit board, to connect them. This also gives good mechanical control of the resistors and the possibility to design for good heat dissipation.

Because of the high voltages present on the board it was decided to keep a minimum of 3mm functional isolation creepage distance between all traces on the board, in line with the EN 60664-1 standard [?]. The board was perforated to allow for better air flow past the resistors, improoving the heat dissipation. The mounting holes for the card was placed in a 105×105 mm square, allowing for 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 PCB was ordered with 60 µm 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 functional isolation distance.

Both the circuit schematic and layout editing of the board were performed in the free EDA, Electronic Design Automation, tool KiCad[1].

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, see **??**.

When the PCB was delivered, it was visually inspected before assembling. Some modification was made to improve the isolation distance by drilling away the plating and pads of the ventilation holes.

TODO[TODO]Fin bild på designprocess av PCB, säkerhetsavstånd etc

13.3 Measurement

When the dummy loads had been assembled, their resistances were determined using four wire resistance measurement directly at the PCB's connection points, as seen in **??**. With this technique, one can neglect the resistance in the cables used for measuring which can have a significant affect when measuring low resistance loads [?].

14 Design of the switching fixture and the embedded attenuators

The chosen implementation requires a fixture that switches and attenuators, which purpose is to switch the pulse to the desired attenuator or to the dummy load. It must be able to handle the momentary pulse energies and voltages and should not distort the pulse.

14.1 Attenuators

TODO[TODO]Massa illustrationer i den här delen

[1] KiCad EDA `http://kicad-pcb.org/`

The target attenuation was decided to mimic the commercial attenuators, described in 9.8, where the $50\,\Omega$ attenuator has an attenuation of 54.7 dB and the $1000\,\Omega$ attenuator has an attenuation of 60.1 dB.

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 two attenuators were implemented as Π-attenuators. The values for the attenuators were retrieved from an online calculator[1], and then they were simulated in LTSpice to verify the values.

By dividing the attenuators into two Π-networks, the series resistance required will get a bit 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, will influence a high value resistor at lower frequencies that it would on a low value resistor, as explained in 6.

A resistor with high pulse power and high voltage properties had to be chosen.

When the ideal resistor values had been derived, the energy over time and maximum voltage for each resistor was retrieved by simulation, as seen in **??**. Based on this, the minimum number of discrete resistors needed to withstand the pulse energy was calculated. In the same way the minimum number of series resistors to withstand the maximum pulse voltage was calculated. These numbers are presented in **??**.

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 its constellations was decided, all of the discrete ideal resistors were replaced with non-ideal models in the simulation software. Then the attenuators were checked in frequency domain, as well as how the pulses were affected in time domain.

14.2 PCB for the relay box

TODO[TODO]Fin bild på designprocess av PVB, säkerhetsavstånd etc

Since the attenuators consits of SMD, surface-mount device, resistors, it was decided to design a PCB for this purpose. This also gives good control of the lengths of the conductors, which is of importance when designing for higher frequencies.

First, the circuit is drawn in the schematic part of the EDA tool KiCad[2]. When this is done, the schematic is exported to the PCB layout.

The measurement connectors that will be accessible on the outside of the encapsulation must 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 [**?**]. The EDA tool has functionality for design rule checking, DRC, but there are some limitations in this function that inhibit its

[1] Π attenuator calculator `https://chemandy.com/calculators/matching-pi-attenuator-calculator.htm`

[2] KiCad EDA `http://kicad-pcb.org/`

use for 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 are to be considered safe. It is allowed for one high voltage trace to be close to another high voltage trace, only the functional isolation of 3 mm applies here, and it is also allowed for the output signal and the output ground to be close to each other. To aid the design process without the DRC, the high voltage traces was placed on the top layer of the PCB, while all signal traces were placed on the bottom layer. To ensure that enough clearance was kept to the relay pad's, the 6 mm clearance was added to the package footprint as a ring on a user layer in the EDA, as seen in **??**. This is not an enforced rule, but it helps during the manual design process.

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.

Before the PCB was sent for manufacturing, it was also printed in 1:1 scale as the dummy load PCB described in 13.2. This also helps to ensure the critical positioning of the 4 mm banana connectors that will attach to the test equipment, as seen in **??**.

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.

14.3 Measurement of the relay box

Since the relay card will be used in measuring pulses with short rise times, it is of importance to know that it does not distorts 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, a so called S21 measurement was performed using the network analyzer ZVL that is introduced in 9.7. To be able to connect the network analyzer, a fixture was made to mimic the front panel of the CNA 200. A programmable relay card was used to control the relays during the testing. The setup can be seen in **??**.

This setup proved to be unstable, 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 **??**. 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. 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 control relays were open. In addition to this, the magnitude response was also measured with all but the relays on the current terminal closed, to see if there was any overhearing on the circuit board from the other terminals and the traces after the relays. An illustration of the measurements can be seen in ??. The results were saved both as an image and as raw data in the form of complex numbers in a CSV, coma separated values, 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 ??.

To measure the test pulses through the attenuators, the relay card was connected to the CNA 200 and the pulses were measured on the intended connectors using an oscilloscope, as seen in ??. The results were saved both as an image and as data points in a CVS file, for further analysis.

To have something to compare the results to, the commercial attenuators were also measured in frequency domain with the ZVL and in time domain using the oscilloscope.

15 Analysis

Didn't have no time for this. Yet...

16 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 was found along the way.

17 Initial measurement of the old equipment

The result from the initial measurements are presented, along with the limits, in 3 without the CNA 200 connected and in 4 with the CNA 200 connected.

	Limits			Measured		
Pulse	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	red!60 208 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 3: The initial manual measurements, measured directly at each generator's output.

	Limits			Measured		
Pulse	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	red!60 450 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	red!60 222	red!60 200 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

Table 4: The initial manual measurements on the equipment, including the CNA 200.

18 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.

19 Design of dummy loads

19.1 Components

TODO[TODO]förklara komponentval

19.2 PCB

TODO[TODO]Peta in bilder

19.3 Measurement results

The resistance at the dummy loads are presented in 5.

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

Table 5: The measured resistance of the dummy loads, and the tolerance compared to the nominal values.

20 Design of the switching fixture and embedded attenuators

Vishay's CRCW-HP series fitted this description and were easily available.

20.1 Attenuators

The 54.7 dB attenuator was divided into two 27.35 dB Π attenuator links. When the closest values for the resistors had been chosen, using 56 Ω as shunt resistors and 560 Ω in series, the final attenuation was 53.66 dB for the two links according to the simulation, seen in **??**. The input and output resistance was

The 60.1 dB attenuator was divided into one 27.35 dB Π attenuator links 32.75 dB. When the closest values for the resistors had been chosen, using 56 Ω as shunt resistors and 56 Ω in series, the final attenuation was 53.66 dB for the two links according to the simulation, seen in **??**. The input and output resistance was 24.2

20.2 Measurements

21 Analysis

Nah

(a) Plus terminal closed, all other open

(b) Plus terminal open, all other open

(c) Plus terminal open, all other closed

(d) Minus terminal closed, all other open

(e) Minus terminal open, all other open

(f) Minus terminal open, all other closed

(g) Ground terminal closed, all other open

(h) Ground terminal open, all other open

(i) Ground terminal open, all other closed

Figure 3: The measurements made on the attenuators

22 Results

23 Initial measurement of the performance of the old equipment

As can be seen in **??** and **??**, 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.

24 Method

It was suprisingly difficult to find and choose apropriate components for the dummy load. The resistors had to tolerate extreme surges and the relays had to have high insulation voltages between the contacts.

24.1 Dummy Loads

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

24.2 Attenuators

During the project, the attenuation was considered as the voltage attenuation $att = 20log_{10}\left(\frac{V_{in}}{V_{out}}\right)$ dB. However, lots of information and many tools for RF applications, including the calculator used for the attenuators in this project, assume power attenuation $att = 10log_{10}\left(\frac{P_{in}}{P_{out}}\right)$ 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 ended thereby 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.

24.3 Desired vs implemented (simulation)

Parasitic effects. (real life, back to simulation)

25 The work in a wider context

Ethical aspects

26 References

Source critisism