JÖNKÖPING UNIVERSITY
School of Engineering

Locating faults in boundary wires for autonomous lawn mowers

An investigative study on methods used to locate faults in underground, low-voltage cables with focus on implementing Time Domain Reflectometer (TDR)

Main subject area: Computer Engineering

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Abstract

Purpose:

The purpose of this thesis was to identify a useful solution to find the location of a broken boundary wire. By useful we mean that the solution should be inexpensive, user friendly and accurate. However, this thesis will only investigate the accuracy of the method where the hypothesis is that an investigated method is applicable for all underground wires.

Method:

This study conducted a literature research in order to investigate what methods that are used in other industries to locate faults in underground, low-voltage electrical wires. After the research, the most commonly used fault locating methods were described and the one that seemed most useful was chosen as a possible solution.

For the solution to be useful the accuracy was investigated. The method used to conduct an experiment and gather data to validate the solution was Design Science Research.

Result:

Three methods were investigated as possible solutions:

Time Domain Reflectometry (TDR), Frequency Domain Reflectometry (FDR) and Murray bridge where experiments were conducted using TDR.

TDR proved to be unapplicable in locating faults in boundary wires, although it was confirmed to be a valid solution to locate faults in coaxial cables with <1% error margin.

What makes TDR and other reflectometry methods unsuitable methods within the autonomous lawn mower industry is the lack of characteristic impedance in the used boundary wires. The hypothesis that an investigated method is applicable for all underground wires is thereby refuted.

Limitations:

Experiments were conducted in laboratory environment with a signal generator and an oscilloscope. One experiment was conducted on a boundary wire in the ground which provided no reflected signal.

Keywords:

Autonomous lawn mower, electrical fault locating, final thesis work, impedance, Time Domain Reflectometry.

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1 Introduction

Maintenance and fault location of electrical wires is a difficult task, especially with aging wires that are exposed to moisture (Furse & Haupt, 2001), (Furse, Smith, Safavi, & Lo, 2005), (Isaac, Ayobami, Ayokunle, & Bassey, 2019). This is the case for almost all industries where electrical wires are used such as cars, airplanes (Yang, Liu, Li, & Shi, 2013), distribution networks (Ali, Bakar, Mokhlis, Arof, & Illias, 2014) and in homes. In many cases the wires are hidden which makes the accessibility for troubleshooting much more difficult and it is common that you only have access to one end of the wire (Auzanneau, 2013).

1.1 Background

A common problem with autonomous lawn mowers is that the boundary wire, that limits the area of which the mower can operate, is damaged for different reasons. That could be an effect of gardening, aging, environmental changes or even animals. When this happens the lawn mower can no longer operate since its boundaries are undefined.

To be informed that the wire is broken is easy and already implemented into the product (Manualslib Husqvarna Manuals, 2021). However, the problem is to locate where along the wire the damage is. There exist a few ways to locate faults along electrical wires, but once implemented, these are often quite expensive, difficult for users to use and/or requires additional tools (Islam, Oo, & Azad, 2012), and none of them has been widely implemented in the context of the lawn mower industry.

Some methods have been verified to work well to locate faults in these boundary wires. (myrobotmower.com, u.d.) However, they require some skill from the user and are also very time consuming.

There are not many publications directed specifically towards the autonomous lawn mower industry, meaning there are areas that have not been widely researched yet and locating faults in boundary wires is one of them. Methods used for locating faults in electrical wires in other areas range from reflectometry (Furse, Chung, Lo, & Pendayala, 2006) to Loop techniques (Nag, Yadav, Abdelaziz, & Pazoki, 2020) where most methods are slightly adjusted to optimize the results for the designated area of use.

An issue that follows the lack of implemented features to locate electrical faults is that service centers for retailers receive a lot of phone calls from customers who need help locating faults in the boundary wire. Service personnel then have to go to the customer and solve the issue manually, which is a time-consuming task that could be solved by the customers themselves if a proper solution were implemented.

With all this in mind, there is a clear need for a new method to locate faults in the boundary wire within the autonomous lawn mower industry. Hence, this thesis was

brought out to investigate if methods used in other areas could be applied to the lawn mower industry.

This thesis was conducted in collaboration with Husqvarna Group, a Swedish company that sells autonomous robotic lawn mowers. (Robotgräsklippare - Automower från Husqvarna, 2021)

1.2   Problem statement

Autonomous lawn mowers operate within a designated area that is limited by a boundary wire attached to the ground. A boundary wire is connected to a charging station in both ends and surrounds the working area for a lawn mower. The charging station sends electrical signals through the wire which generate a magnetic field around the boundary wire which is used to keep the lawn mower inside the designated operating area.

Over time the boundary wire is overgrown and no longer visible. This makes the wire more protected but at the same time more difficult to detect while doing gardening for example. A common cause for the boundary wire to be cut off is while shoveling in the garden and unconsciously damage the wire. Since the wire is left in the ground all year long its insulation could also be damaged by the variation in temperature or other environmental changes, which could cause the wire to be connected to ground (shorted) and no longer function properly.

However, the damage is not discovered until the lawn mower is activated, which could be hours, days or even longer after the damage was done. This makes it very difficult to visibly locate where the boundary wire was damaged, and the lawn mower is unable to operate until the problem is fixed.

There exist several methods to locate faults that also occur in the lawn mower industry, such as open circuit and short circuit and earth faults (Isaac, Ayobami, Ayokunle, & Bassey, 2019).

Methods used in other industries to locate faults in electrical wires are often a combination of several methods (Islam, Oo, & Azad, 2012) to optimize the functionality. However, none of these methods seems to have been implemented into this industry yet, and the aim of this study is to find a method that can locate the fault without much user involvement and without the use of external tools.

Other electrical networks commonly operate on high voltage and high current, but the boundary wires used for lawn mowers use low current which could rule out some fault-detecting techniques used in other areas.

1.3 Purpose and research questions

The problem statement tells that there is a damaged wire hidden from the human eye which makes it difficult to find the damage without the use of tools. There exist solutions to accurately locate faults in underground wires in other areas, but these solutions have not been adapted to boundary wires used for lawn mowers.

Therefore, the purpose of this thesis is to identify a useful solution to find the location of a broken boundary wire. By useful we mean that the solution should be inexpensive, user friendly and accurate. However, this thesis will only investigate the accuracy of the method where the hypothesis is that an investigated method is applicable for all underground wires.

In order to fulfil the purpose, two research questions were defined.

The first one is required to perform a research of existing methods to locate faults in underground, low-voltage electrical wires and evaluate these in order to find one that could be adapted to the field we are targeting.

* What methods exist to locate a fault in an underground, low-voltage electrical wire?

As a follow up to the first research question, the second one is limited to describe how accurately the fault can be located.

* With what accuracy can a fault in an underground, low-voltage electric wire be located?

1.4 Scope and limitations

* The scope of this study was limited to the lawn mower industry. Since this was a bachelor thesis and in consideration of the limited time, the study was unable to investigate all possible technologies for locating faults in the wire. Instead, it focused on methods based on the most common technologies used in other industries. This was done so that the chosen solution could be investigated in the best way possible.

* Because of the Covid-19 pandemic the study had limited access to on-site work with the stakeholders which made it difficult to discuss problems and solutions with other engineers which could often speed up the process and improve the results. It also greatly limited the access to laboratory equipment required to conduct the experiments.

* This study was not conducted with the purpose of developing a finalized product, but rather to investigate possible ways of locating faults in boundary

wires. Hence this thesis only focused on the accuracy of the investigated method.

1.5 Disposition

Chapter 2 presents theories behind the most common technologies to detect and locate wire faults.

Chapter 3 describes the chosen method and how it was implemented. The solution's validity and reliability are described as well as an explanation of how the solution works in both detail and in general.

Chapter 4 shows the results and observations from performed experiments.

Chapter 5 consists of discussions about both result and method.

Chapter 6 gathers conclusions from the thesis work. This is where the report is summarized, and further research recommendations are found here.

Chapter 7 is a list of references from literature used for this study.

Chapter 8 contains appendices.

2 Theoretical framework

There exist many methods to locate a fault in electrical wire. These methods can be categorized into different sorts depending on what perspective that is used to do that. Methods could be sorted into tracer and terminal methods (Jensen, 2014) depending on if the way used to locate the fault needs to follow the wire or if it just needs access to one or both ends of the wire. The methods could also be online or offline (Jensen, 2014), depending on whether the method is used while the system is still working or if the system must be shut down. Another categorization is destructive and non-destructive methods, an example on destructive method is "cut and try" implemented by cutting the wire to isolate the faulted section (IEEE, 2019).

2.1 Explored methods

Results from the primary research (Chapter 3.1.1) like (Islam, Oo, & Azad, 2012), (Willis, 1991), and (IEEE, 2019) mentioned both Time Domain Reflectometry (TDR) and bridge methods as fault locating techniques. Frequency Domain Reflectometry (FDR) was mentioned repeatedly among the results from the primary research in addition to TDR. Due to the limited time of this thesis, it was a reasonable choice to present these three methods in this chapter. Since this study attempted to implement these methods within a new context of autonomous lawn mower, the methods were presented in their conventional version so that as few factors as possible were involved.

2.2 Reflectometry methods

Reflectometry techniques including time domain reflectometer (TDR) and frequency domain reflectometer (FDR) are common methods for wire fault diagnosis. Both methods have been adapted to different industries and combined with each other (Shin Y.-J. , o.a., 2005) or with other technologies to enhance the accuracy of fault locating (Shi & Kanoun, 2014) (Shi & Kanoun, 2015). These methods are usually implemented offline but enhanced variants can be carried out online utilizing the waves generated by the system itself and do not need to generate their own signals to inspect the system (Lo & Furse, 2005).

2.2.1   Time Domain Reflectometer (TDR)

TDR is the most common technique to locate wire faults (Shi, Troeltzsch, & Kanoun, 2010). A TDR experiment on coaxial cables shows an accuracy between 0.3% and 0.8% (Shin Y.-J. , o.a., 2005). The accuracy of conventional TDR is about 1% according to Shi & Kanoun (2015).

The conventional TDR working principle is based on sending a signal through the inspected wire, the signal travels through the wire and it can be reflected if facing an impedance discontinuity, the reflection is proportional to the change in the impedance. A reflection coefficient can be calculated as following:

$$\rho = \frac{Zl - Z0}{Zl + Z0} \qquad (1)$$

Z0: the characteristic impedance of the wire.
Zl: the impedance of the fault.

Impedance is a combination of resistance and reactance (bot capacitive and inductive) and it is measured in Ohm (Collins, 2020).

The reflection coefficient helps to detect the fault type if it is open or short end of the wire, where ρ value can vary from 1 to -1 respectively. Figure 1 shows the reflected signal in an open, shorted, and sound wire.
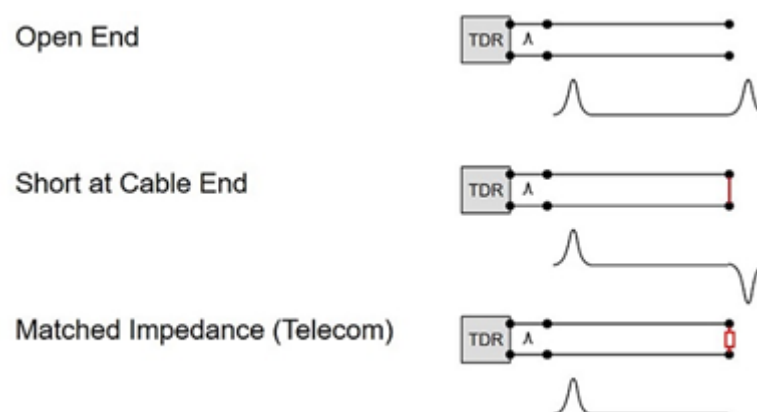

Figure 1 (everything RF, 2019)

Figure 2 shows a block diagram of a conventional TDR system that allows to measure the time interval between the incident signal and the reflected one called time of flight (TOF).
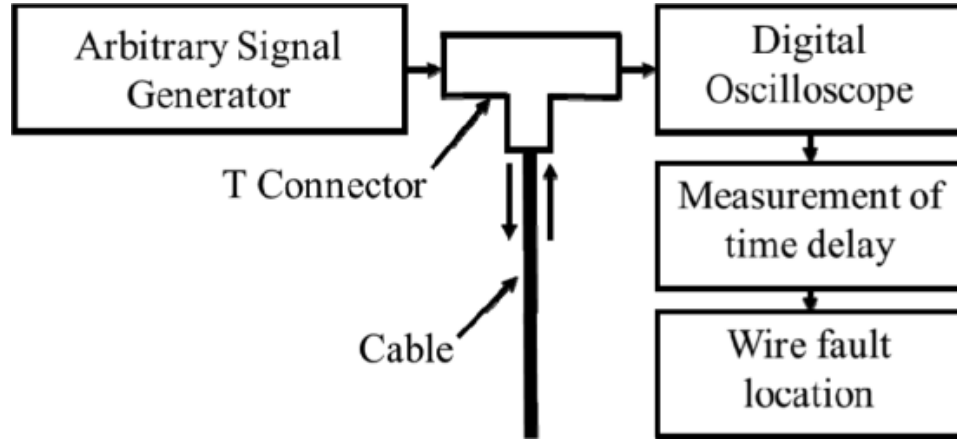

Figure 2 (Shi & Kanoun, 2015)

TOF is used to calculate the distance to the fault using the following formula:

$$d = v \cdot \left(\frac{t}{2}\right) \qquad (2)$$

Where
d: distance to the fault in meters.
v: velocity of signal propagation through the wire in meters/second.
t: time of flight which is divided by two to retain the time it took the signal to travel through the wire to reach the fault in seconds.

A retained trace of an open-ended wire is shown in Figure 3. The reflected signal has been composited with the incident one to form the trace shown in Figure 3. This occurred because the pulse width was longer than the TOF for the reflected signal which is displayed in more detail in Figure 4.
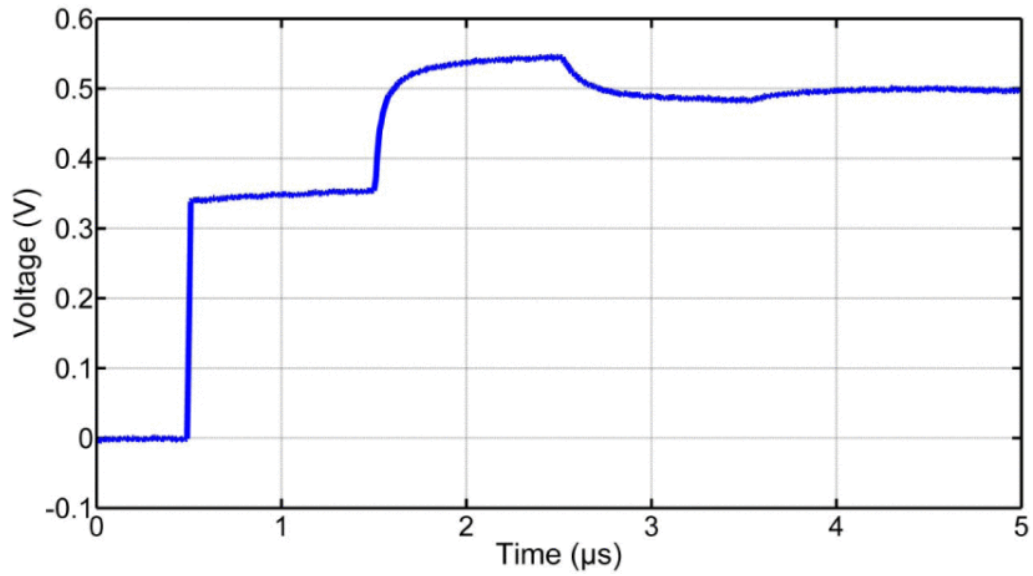

Figure 3 TDR trace of an open circuit (Shi & Kanoun, 2015), a composite signal was constructed of both the incident and the reflected signals at 1.5s when the incident signal was longer than the time of flight.

Figure 4 explains how the composite signal in Figure 3 was constructed, it shows an incident, reflected, and composite signal and the related time of flight from the start of the incident signal to the start of the reflected one. The composite signal gets this "stair-like" appearance because the pulse width of the incident signal is longer than the TOF between the incident signal and the reflected signal. This results in a composite signal with the total amplitude of the reflected signal added to the incident signal.
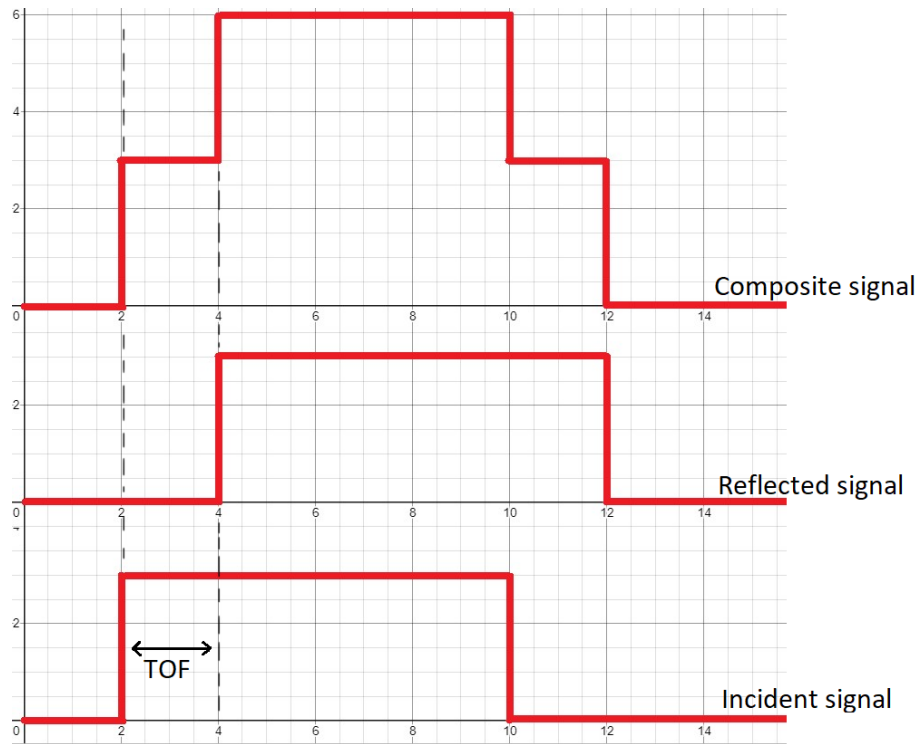

Figure 4 Composite signal with TOF

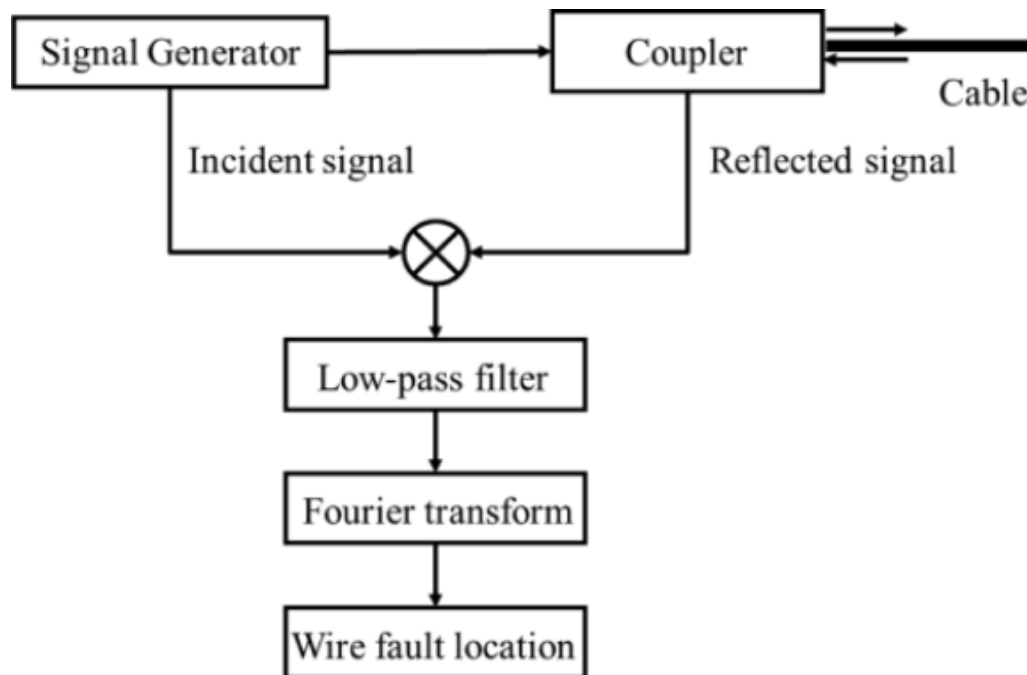## 2.2.2   Frequency Domain Reflectometer (FDR)

Figure 5 shows an FDR system.

Figure 5 (Shi & Kanoun, 2015)

The signal generator provides a set of signals stepped between two determined frequencies F_{start} to F_{end} with a certain step size. The coupler is used to separate the incident signals from the reflected ones coming back from the inspected wire. Both incident and reflected signals are then sent into a mixer to be multiplied which gives signals on the sum and the difference of the original signal's frequencies. The mixed signal is then read by an analog to digital converter (ADC) which works as a low pass filter at the same time to eliminate high frequencies. The digitalized signal coming from the ADC is analyzed, and Fourier transform is utilized to estimate the fault location using the phase shift of the reflected signal (Shi, Troeltzsch, & Kanoun, 2010).

FDR can be more sensitive in detecting damages and it returns results with better accuracy than TDR. However, it requires an expensive directional coupler and cannot determine the exact type of the faults (Shi, Troeltzsch, & Kanoun, 2010).

2.3 Bridge methods

Bridge methods are used to locate faults in underground wires. These methods are mainly based on Wheatstone Bridge to measure unknown resistance. Wheatstone Bridge was modified to locate different types of wire faults with different requirements and accuracy (IEEE, 2019).

Figure 6 shows a Wheatstone bridge circuit, where there is one unknown resistor Rx, one variable resistor R3, and two fixed and known resistors R1, R2. The variable resistance R3 is used to balance the Voltmeter V between D and C.

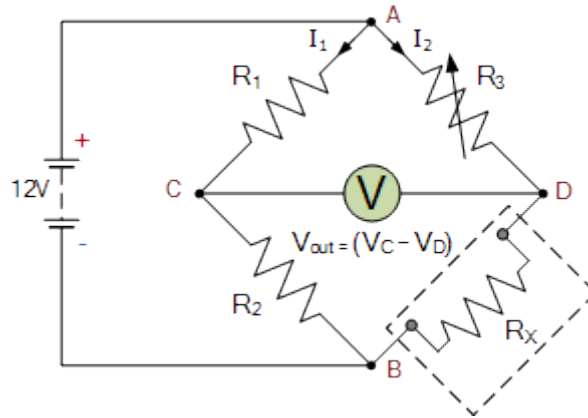Figure 6 Wheatstone bridge circuit (Wheatstone Bridge, u.d.)

Since the potential in D and C are equal, the unknown R_x can be calculated as following:

$$V \frac{R2}{R1 + R2} = V \frac{Rx}{Rx + R3} \qquad (3)$$

$$R2 \ (Rx+R3) = Rx \ (R1+R2)$$

$$R2 \cdot Rx + R2 \cdot R3 = Rx \cdot R1 + Rx \cdot R2 \qquad (4)$$

$$Rx = \frac{R2 \cdot R3}{R1} \qquad (5)$$

Murray bridge, Glaser bridge (Islam, Oo, & Azad, 2012) and Valery loop (Nag, Yadav, Abdelaziz, & Pazoki, 2020) are examples of methods based on Wheatstone bridge. Murray bridge is a good example on how to adapt Wheatstone bridge and is presented in Chapter 2.3.1.

2.3.1   Murray bridge method

Figure 7 represents a Murray bridge to locate an earth fault in a wire, to find the fault the method uses another sound wire along the damaged one and both wires are connected by a low resistance jumper at the far end. At the near end both wires are connected, as shown in Figure 7, to two ratio resistors and a galvanometer. Ra or Rb should be adjusted until the galvanometer is nulled and the bridge is balanced, and the distance to the fault can be calculated using the ratio of the resistors and the length of the wire (IEEE, 2019). According to IEEE (2019) the measurement accuracy of Murray loop can be less than 0.5% of cable length.
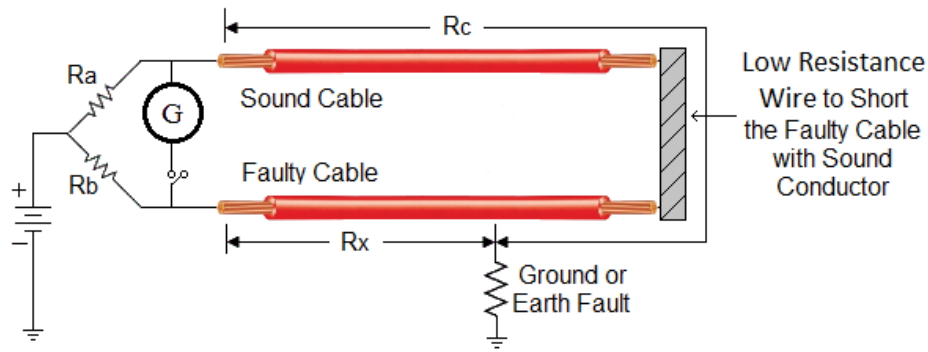

Figure 7 Murray Bridge, edited (How to locate faults in cable, u.d.)

When the bridge is in balance:

$$\frac{Ra}{Rc} = \frac{Rb}{Rx} \implies \frac{Rx}{Rc} = \frac{Rb}{Ra} \implies \frac{Rc}{Rx} = \frac{Ra}{Rb}$$

$$\frac{Rc}{Rx} + 1 = \frac{Ra}{Rb} + 1 \implies \frac{Rc + Rx}{Rx} = \frac{Ra + Rb}{Rb} \qquad (6)$$

The ratio of fault distance Lx to the length of both wires 2L is equal to the ratio of Rx to Rx + Rc:

$$\frac{Lx}{2L} = \frac{Rx}{Rx + Rc} \qquad (7)$$

From equations (6) and (7):

$$\frac{Lx}{2L} = \frac{Rb}{Ra + Rb}$$

$$Lx = 2L\frac{Rb}{Ra + Rb} \qquad (8)$$

2.4 Method selection

Due to the limited time, the second research question was only answered with one of the methods mentioned in chapter 3.1 and chapter 3.2.

Murray bridge has the highest potential accuracy and could provide a simple and effective solution once implemented. However, this method requires a second sound cable next to the inspected cable and the difference between the battery ground and the earth ground that might need to add a ground stake to the circuit to refer to the earth ground which makes the implementation of this method more complex than the other methods.

FDR has slightly better accuracy than TDR, but it requires advanced mathematical calculation which might exceed the limitations of a microcontroller unit (MCU) that could be a part of a future implementation. FDR also requires an expensive directional coupler and can not identify the type of fault.

The TDR method has a reasonable accuracy and the ability to identify the type of fault. It does not require complex implementation or calculations which makes the experiments easy enough to execute in the context of this thesis. It is also the most common method to locate wire faults according to Shi, Troeltzsch, & Kanoun (2010).

After reviewing these three methods the selected method to investigate further was TDR.

2.5 Wire description

In order to validate the functionality of the selected method it was first implemented in a cable with known characteristics to gather results that would be compared to those of a boundary wire. The two types of wires used are presented in this chapter.

2.5.1 RG58 coaxial cable

A coaxial cable is an electric cable build of an inner conductor surrounded by a conducting shield. The conductors are separated by an insulating material and the hole

cable is protected with an insulating sheath (John Crisp, 2002). Figure 8 illustrates how a coaxial cable is constructed.
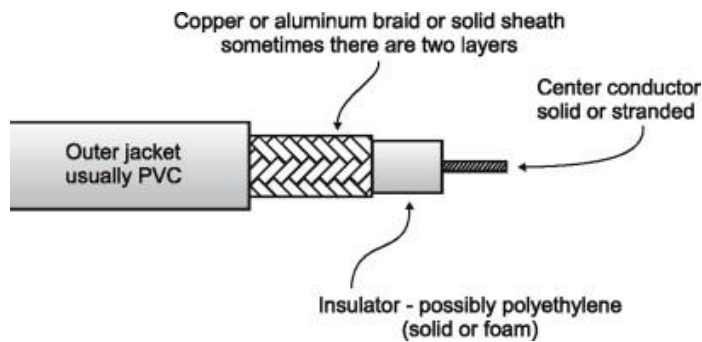

Figure 8 Coaxial cable (John Crisp, 2002)

Datasheet of RG58 used in this experiment: *Appendix 4.*

2.5.2   Boundary wire

Boundary wire is an electrical cable constructed of a single conductor surrounded by an insulating material. The conductor is made from copper clad aluminum/magnesium with tin coating. Figure 9 illustrates how a boundary wire is constructed.

Diameter of conductor: 0,9mm
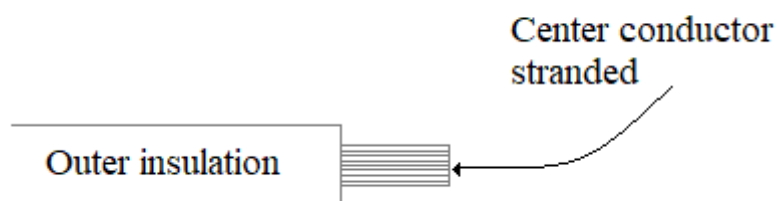
Diameter of insulation: 2,4mm

Figure 9 Boundary wire

3   Method and implementation

The first research question was approached through a literature research to find methods used to locate faults in electrical wires. (Chapter 3.1.1)

Design Science Research (DSR) was used to approach the second research question. According to (Wieringa, 2014), DSR method has an objective and two main activities. The objective is to deliver an artifact in a certain context. DSR first main activity is the investigation of the artifact, this was a continuation from the literature study performed for the first research question, where a technology was decided on to develop the artifact with, more can be read about this investigation in Theoretical framework (Chapter 2). The second main activity is to design the artifact, where both stakeholder requirements and limitations of the method are taken into consideration. This research method is well suited for the work done for this thesis since the framework of our work process is very similar to the one displayed in Figure 10.
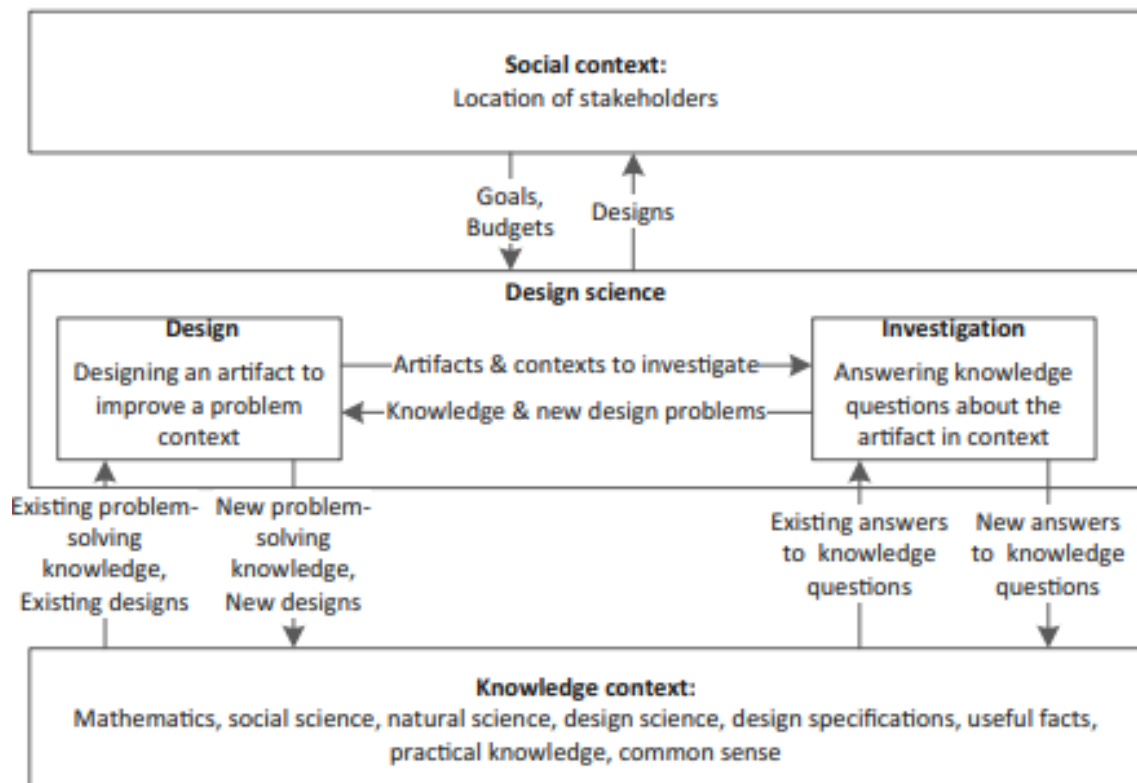

Figure 10 A framework for design science (Wieringa, 2014)

This thesis aimed to find a solution to locate faults in electrical wires in the context of the autonomous lawn mower industry. The objective of the DSR method in this thesis is to measure the accuracy of the investigated method.

Figure 11 was inspired by the engineering cycle described by (Wieringa, 2014) and the research process model from (Vaishnavi, Kuechler, & Petter, 2004/19). The figure shows step by step how this study was planned to be accomplished. This thesis only covered the encircled part of the cycle.
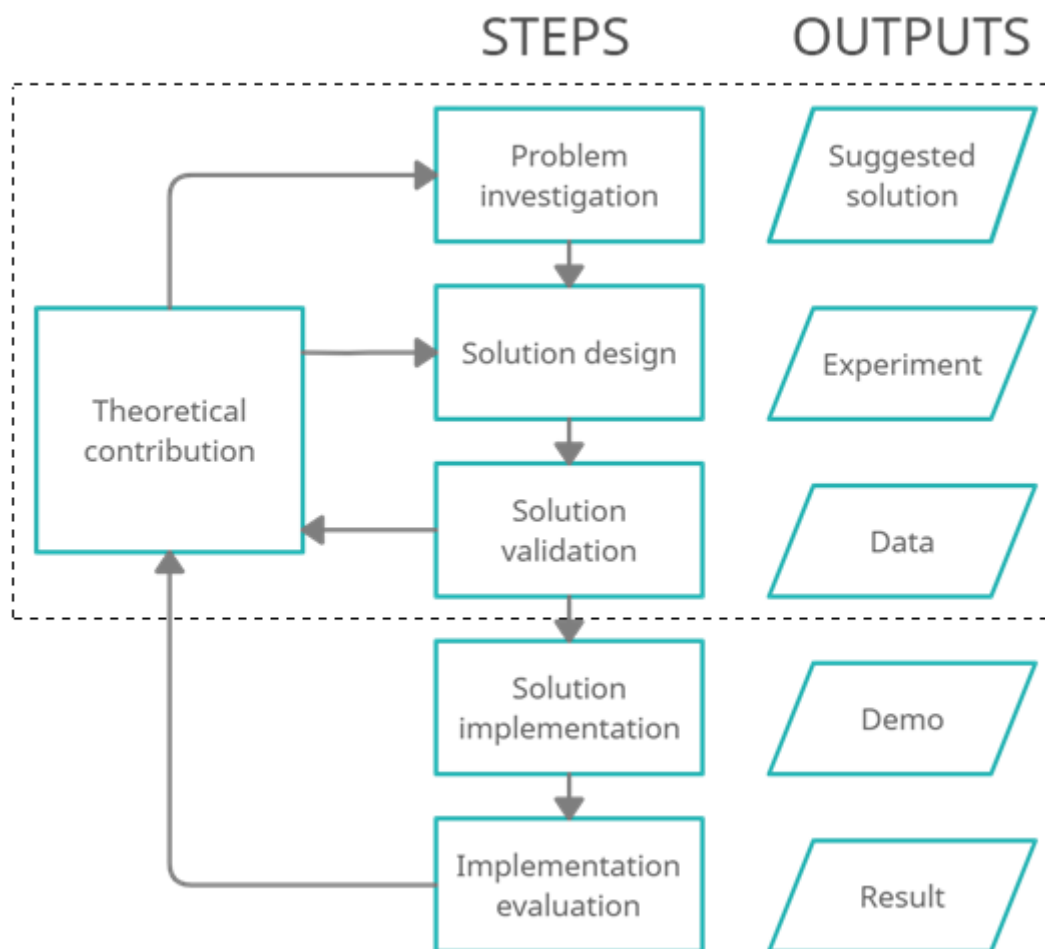

Figure 11 Engineering cycle designed for this thesis based on (Wieringa, 2014) and (Vaishnavi, Kuechler, & Petter, 2004/19)

Problem investigation:

One of the methods reviewed in the theoretical framework was selected to answer the second research question. (Chapter 3.3 Method selection)

Solution design:

The suggested solution was used to design an experiment to gather data to answer the second research question. (Chapter 2.1.2 Experiment)

Solution validation:

The designed experiment was conducted to gather data. This data was compared with theoretical calculations and used to validate the solution. (Chapter 4 Results)

Solution implementation:

Was not covered in this thesis.

Implementation evaluation:

Was not covered in this thesis.

3.1 Data collection

3.1.1 Literature study

To answer the first research question, a literature study was conducted in order to gather information about existing methods used to locate faults in electrical wires. A number of search words (Chapter 4.1 Literature study) were used for the primary research on JU Primo, where articles were deemed relevant or not by reading the abstract for each article. Since this was a bachelor thesis and in consideration of the limited time, searches where the number of results exceeded 50 were sorted based on the title before the abstracts were read.

Relevant articles were fully read, and knowledge was added to the theoretical framework. From the relevant articles a number of methods were found that was the foundation of a deeper research (Chapter 2.1 Explored methods). As an outcome from the methods found in the primary research, new search words (Chapter 4.1 Literature study) were generated that were more focused on the method itself which led to a secondary research.

Results from both the primary and secondary research that were deemed relevant and used to answer the first research question were referred to in (Chapter 2. Theoretical Framework)

3.1.2 Experiments

To gather data to answer the second research question, experiments were designed and conducted to determine the accuracy of the method. The focus was on gathering test results and comparing these to the expected outcomes from the theoretical framework.

The suggested solution in this thesis was based on the TDR method (Chapter 3.3 Method selection).

Experiment 1

Equipment:

Oscilloscope (Keysight InfiniiVision MSO-X 3034T), pulse generator (Teledyne T3AFG80) and coaxial wire with 50Ω impedance (RG58).

Experiment setup:

A t-connection was connected to the oscilloscope, the other two ends of the t-connection was connected to the pulse generator and the inspected coaxial wire. Figure 12 illustrates the setup.
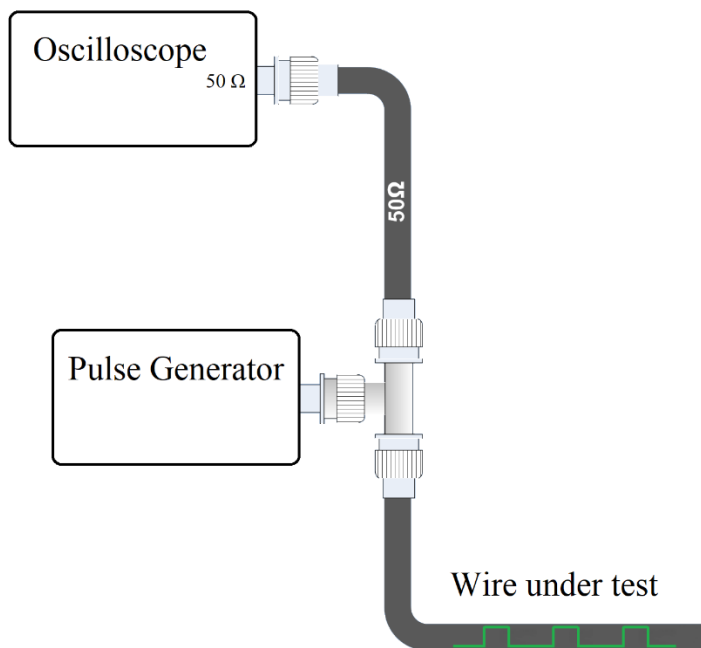

Figure 12 Experiment setup

Experiment execution:

A square signal of 10Vpp was generated by the pulse generator (100KHz frequency, 20ns pulse width and 8.4ns rise time) and sent through the electrical wire. This signal was called the Start signal. The expected outcome was a reflected signal, caused by a damage in the wire or a total break-off that returns back to the oscilloscope, called the Stop signal. The time between the Start signal and the Stop signal, time of flight (TOF) was measured using an oscilloscope. TOF was then used to calculate the distance to the fault. The shape of the reflected signal can be used to determine the type of the fault (Figure 1). Experiments were repeated for wires that are both broken (open end) and damaged (shorted).

The gathered data was saved in a table and represented in a chart to be analyzed in Results (Chapter 4).

Experiment 2

The second experiment was executed in the same way as Experiment 1 except that a boundary wire (Chapter 2.5.2) was used instead of the RG58 coaxial cable (Chapter 2.5.1) for Experiment 2. To connect the boundary wire to the setup shown in Figure 12, the stranded center conductor of the boundary wire (Figure 9) was soldered together with the center conductor of a short piece of coaxial cable (Figure 8) that was connected to the pulse generator.

3.2   Data analysis

The designed experiment was conducted to gather data, the gathered data of this experiment was TOF that was used to calculate the length of the wire. An error margin was calculated by dividing the difference between the actual length of the wire and the calculated length by the actual length.

$$error\ margin = \frac{acual\ length - calculated\ length}{acual\ length} \times 100\% \qquad (9)$$

Both the actual and the calculated lengths of the wire represent the distance to the fault. Formula (9) was used to calculate the calculated length.

The data was organised in a table, that can be found in Results (Chapter 4), that specifies actual- and calculated length and the error margin.

3.3 Validity and reliability

The validity is the extent to measure what a work is intended to measure, and the reliability is about getting the same results when repeating some work (Carmines & Zeller, 1979).

The validity of this thesis was demonstrated in both the theoretical and the practical parts. In the theoretical part, the sources used and referred to were relevant and used to gain more knowledge and understanding of methods used to locate faults in boundary wires and how they work. All sources were found in JU Primo. The validity in the practical part was retrieved by conducting the experiment in laboratory environment to optimize the results. This ensures that the experiment was measuring what it was supposed to measure.

Furthermore, the experiments are carefully described in Data collection (Chapter 2.1) with complete transparency as to allow others to repeat the experiments and reach the same results. By explaining the conditions during which the experiments were conducted and listing all the equipment used, and with descriptions in both text and with figures show how the equipment was used, the results will be the same when the experiments are repeated.

3.4 Considerations

The scientific considerations of this study were to compare some of the most commonly used methods to locate faults in electrical wires followed by the development of a selected solution that seemed most suitable to the intended area of use.

By doing this, this study looked to add more knowledge to the area of fault locating in electrical wires that could be of use to further research.

Mainly this study looked to some societal considerations. By targeting the lawn mower industry, this thesis aimed to improve the efficiency of autonomous lawn mowers by speeding up the error handling. In addition to this, there is a fairly high cost involved if you hire professionals to locate the fault and repair it for you.

4 Results

4.1 Literature study:

Primary research key search words:

Table 1 Primary search results

Keywords	Relation	Field	Results
Wire, fault, locating	And	Title	12
Wire, fault, location	And	Title	31
Cable, fault, locating	And	Title	62
Cable, fault, location	And	Title	257
Electrical, fault, locating	And	Title	218
Electrical, fault, location	And	Title	1065
Underground, wire, fault	And	Title	0
Underground, cable, fault	And	Title	167

From the results in Table 1, 51 results were deemed relevant.

Secondary research key search words:

Table 2 Secondary research results

Keywords	Relation	Field	Results
Time, Domain, Reflectometry, wire, fault	And	Title	8
Time, Domain, Reflectometry, cable, fault	And	Title	26
Frequency, Domain, Reflectometry, wire, fault	And	Title	1
Frequency, Domain, Reflectometry, cable, fault	And	Title	11
Bridge, method, wire, fault	And	Title	1
Bridge, method, cable, fault	And	Title	4
Wheatstone, Bridge, cable, fault	And	Title	0
Wheatstone, Bridge, wire, fault	And	Title	0
Wheatstone, Bridge	And	Title	210

From the results in Table 2, the following 10 results were deemed relevant and investigated closer:

(Amloune, o.a., 2019)

(Bang & Shin, 1982)

(Franchet, Ravot, & Picon, 2013)

(Henneberger & Edwards, 1931)

(Kwon, o.a., 2017)

(Lelong & Carrion, 2009)

(Lim, Kwon, & Shin, 2021)

(Shi & Kanoun, 2014)

(Shin Y.-J. , o.a., 2005)

(Smith, Furse, & Gunther, 2005)

Data analysis

From the primary research many methods were discovered. Most of these were based on either reflectometry or bridge methods where the most frequently used reflectometry methods were Time Domain Reflectometer (TDR) and Frequency Domain Reflectometer (FDR). Bridge methods in general, but especially Murray bridge were frequently mentioned as effective methods. The secondary research provided more knowledge about the methods and was used to verify that the discovered methods were valid.

4.2   Experiment 1:

Data presentation

Table 3 Results from experiment 1.

Actual length of the wire	TOF with open-end (ns)	TOF with shorted end (ns)
40 m	405,40	405,72
30 m	304,16	304,58
20 m	202,86	203,60
10 m	101,20	102,02

Data analysis

The data from Table 3 was used to calculate the length of the wire. Table 4 shows both actual and calculated length and the error margin.

The error margin was calculated using formula (9).

The velocity of a signal in an RG58 coaxial cable is a factor of 0,66 times the speed of light, which was rounded up to $3 \cdot 10^8$:

$$0,66 \cdot 3 \cdot 10^8 \; m/s$$

Using formula (2) the length of the wire is calculated where:

v = the signal propagation in an RG58 coaxial wire measured in m/s.

t = TOF measured in seconds.

Table 4 Error margin of TDR

Actual length of the wire	Calculated length of an open-ended wire.	Error margin in %	Calculated length of a short-ended wire.	Error margin in %
40 m	40,13 m	0,33%	40,17 m	0,43%
30 m	30,11 m	0,37%	30,15 m	0,5%
20 m	20,08 m	0,4%	20,16 m	0,8%
10 m	10,02 m	0,2 %	10,10 m	1%

The error margin retrieved of this experiment varies between 0,2% to 0,4% for an open-ended wire and between 0,43% to 1% for a short-ended wire. Presented values were exact and the same result was measured every time.

Results from this iteration were encouraging to go through another iteration and repeat the experiment using a boundary wire to collect more data that could be used to either confirm or refute the hypothesis that this method (TDR) would be applicable on a boundary wire (Chapter 3.1.2).

4.3 Experiment 2

Data presentation

Repeating experiment 1 with changing the coaxial cable to a boundary wire did not generate reflected signals that were clear enough to be measured and listed in a table.

Data analysis

Figures 13 and 14 shows the oscilloscope traces from the experiment on a boundary wire compared to traces taken from experiment 1 on a coaxial cable under exactly the same conditions. The reflected signal through the boundary wire was very hard to identify or measure. In Figure 13 it was not even possible to recognize the reflected signal.
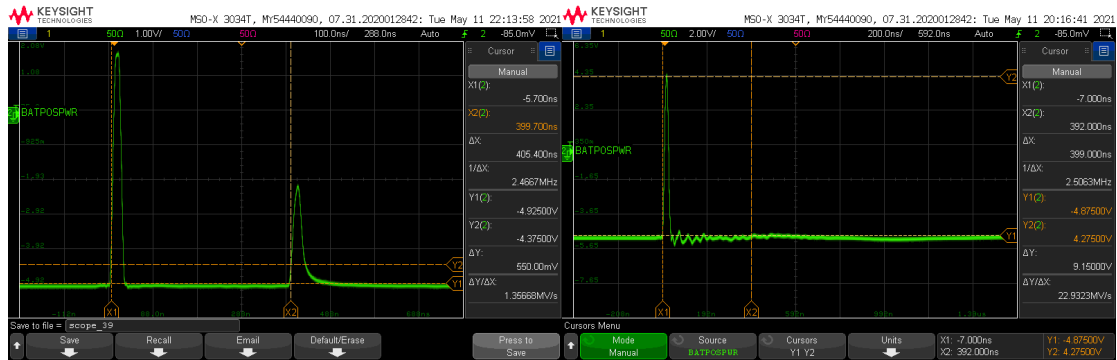
Figure 13 TDR traces from a coaxial(left) and boundary(right) wire, both are 40m

In Figure 14, a reflected signal can hardly be recognized. However, comparing the amplitudes of the reflected signal shows that the reflected signal for the coaxial cable was at approximately 60% of the incident signal. While for the boundary wire, the amplitude of the reflected signal was at 10% of that of the incident signal for very short wires. The size of the reflected signal in a boundary wire was significantly decreased for longer wires, making it unidentifiable.
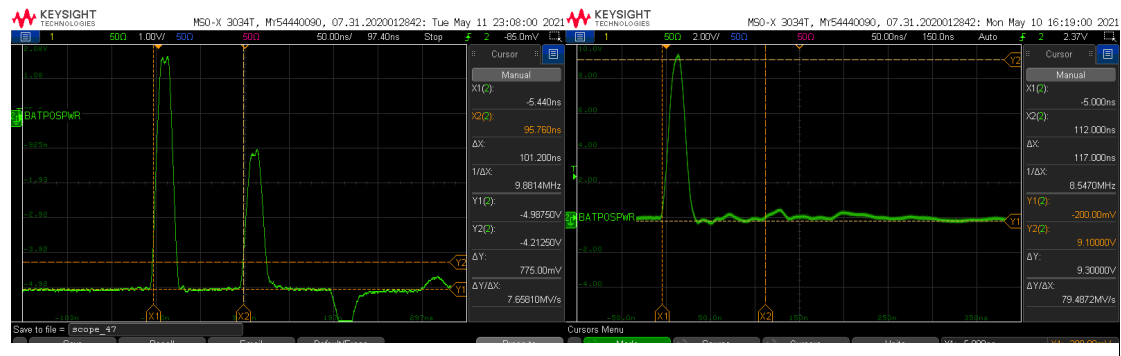
Figure 14 TDR traces from a coaxial(left) and boundary(right) wire, both are 10m

The results from this experiment led to further repetitions with the purpose of enhancing the reflected signal, where different factors that might affect the amplitude of the reflected signal such as frequency, incident signal, rise time and pulse width where changed.

Frequency:

Increasing the frequency of the incident signal from 1KHz to 1MHz did not show any noticeable change on the amplitude of the reflected signal. Figure 15 shows two TDR traces, the frequency in the one to the left is 1KHz and in the one to the right is 1MHz, no improvement in the reflected signal was noticed while stepping between the two frequencies.
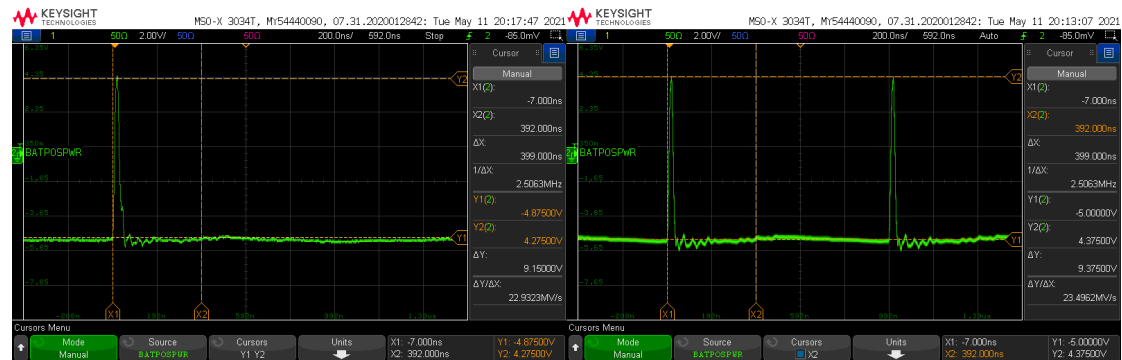

Figure 15 TDR traces from the same boundary wire with low(left) and high(right) frequency

Rise time:

Rise time is the time it takes a signal to switch from low to high. The function generator that was used in this study was not able to deliver a rise time faster than 8,4 ns. Therefore, a slower rising time was used in an experiment on a well reflected signal in a coaxial cable to compare how a slower rise time might affect the amplitude of the reflected signal. In this repetition of the experiment, rise time was increased from 8,4ns to 50ns but no difference of amplitude of the reflected signal was observed. Figure 16 shows two traces where the left image shows an 8,4ns rise time and the right image shows the 50ns rise time.
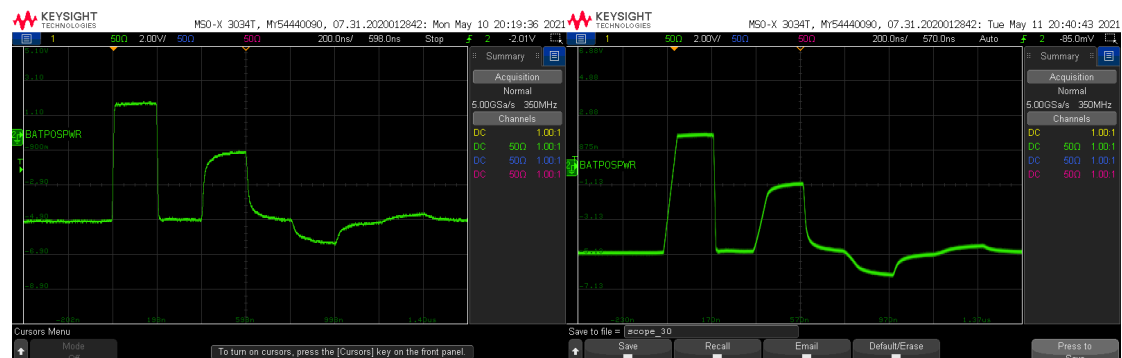

Figure 16 Comparison of low and fast rise time

Pulse width:

The repetition of the experiment with different pulse widths was conducted on a boundary wire, pulse width was stepped up from 100ns to 300ns. The observations of this repetition showed an increasing amplitude of the reflected signal from 0,625V when 100ns pulse width to 1,25V when 300ns. Figure 17 shows the retained TDR traces from this repetition.
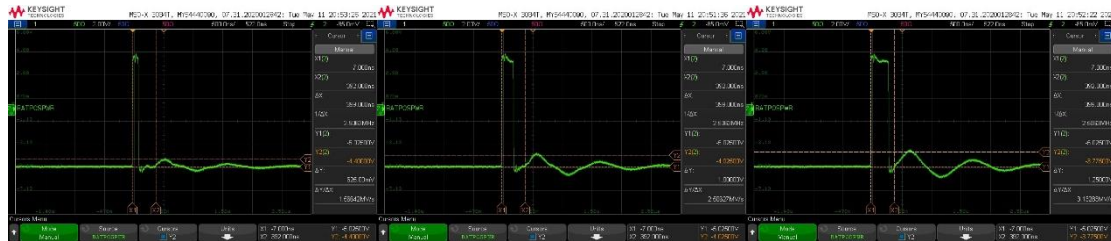

Figure 17 TDR trace shows an increasing amplitude of the reflected signal by increasing pulse width of the incident signal

In ground:

One more repetition of this experiment was done by mounting the boundary wire into the ground, the purpose of this repetition was to observe if the ground and grass around the boundary wire can generate any shielding effect which can contribute with clearer reflected signal. No recognizable reflection was retained in this repetition while using a 200 ns pulse width, the trace is shown in Figure 18.
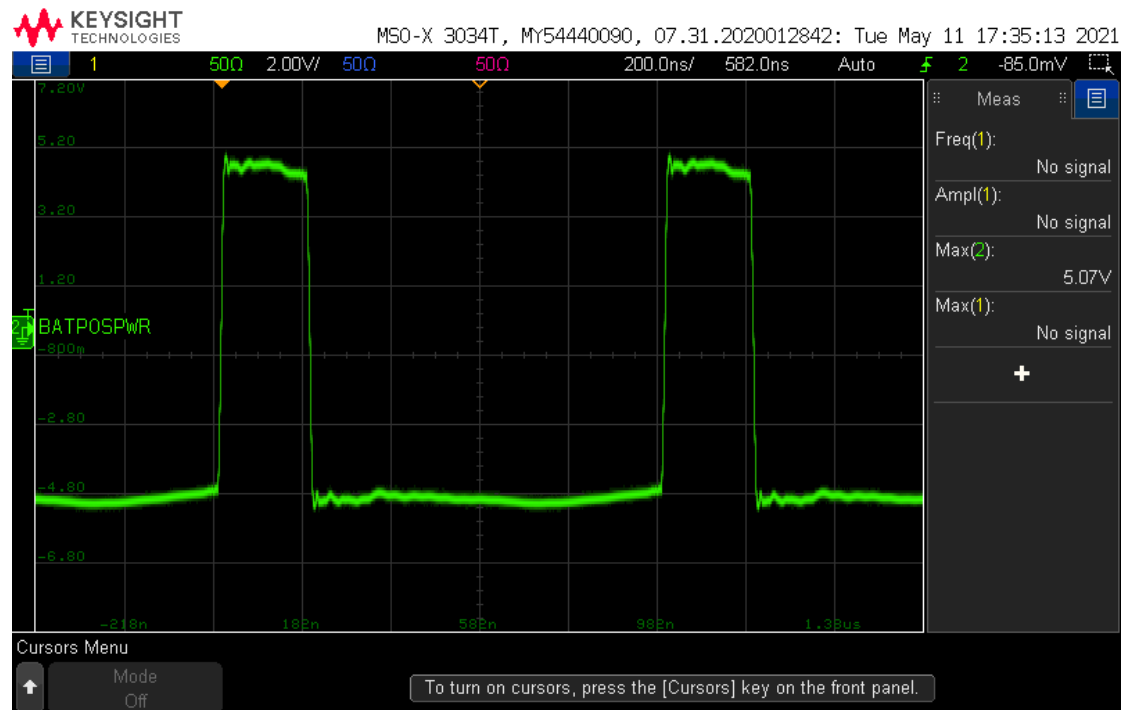

Figure 18 40m boundary wire in grass, 200 ns pulse width

Sending an incident signal with a longer pulse width did not make much difference on the reflected signal. A trace with 400 ns incident signal is shown in Figure 19.
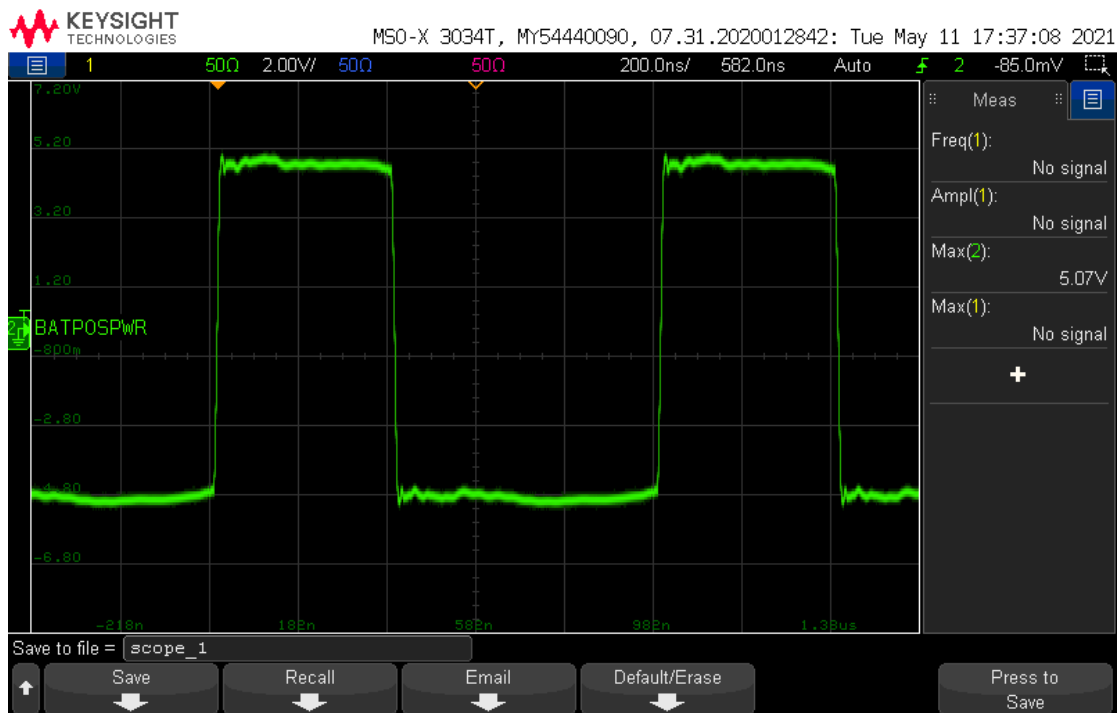
Figure 19 40m boundary wire in grass, 200 ns pulse width

The resulted data from Experiment 2 shows that no significant reflected signal was retained from this experiment in its different iterations. Even though the reflected signal did increase in amplitude following a longer pulse width, iterations done in this experiment shows that there was no simple optimization to be done in purpose to enhance the reflected signal in the boundary wire. Hence, results from this experiment shows that TDR cannot be easily implemented on a boundary wire. The reason why no reflected signal was retained when using a boundary wire is explained in discussion (Chapter 5)

Results from Experiment 1 shows that TDR method is a valid technology to detect cable fault using a coaxial cable or similar shielded cables. The second experiment showed that TDR cannot be implemented and utilized in the same way to detect fault in a boundary wire. These results refute the hypothesis of the second research question.

The next chapter discusses the results and motivates why these results were found.

5   Discussion

The literature research in this study presented the most common technologies to locate faults in underground low-voltage cables. These technologies were widely used in many industries and repeatedly mentioned during the literature research as described in Chapter 2.1 (Explored methods). No research that studies fault locating in a boundary wire was found to compare the results from this literature research with. The explored methods in this study were deemed reasonable to be explored by the authors based on the current understanding of the domain. The absence of previous research in this area made the choice of basic and conventional methods, away from any machine learning or combined technologies, reasonable.

Results from Experiment 1 (error margin between 0,2% and 1%) were reasonable and can be related to similar experiments in previous articles were the error margin of TDR using RG142 and RG 400 coaxial cables was between 0.3% and 0.8% (Shin Y.-J. , o.a., 2005) and about 1% (Shi & Kanoun, 2015).

The results from Experiment 2 showed that TDR can not be applicable on a boundary wire in the same way as on a coaxial cable. No previous research was found that tried to implement TDR on boundary wire to compare the results with.

This study showed that TDR is not applicable on a boundary wire in the same way as on a coaxial cable. The results applies for other reflectometry technologies like (FDR) since no significant reflected signal was retrieved and the lack of characteristic impedance for the boundary wire makes any method that uses resistance comparation, such as the Murray Bridge, very unlikely to be applicable.

5.1   Result discussion

The purpose of this thesis was to identify a useful solution to find the location of a broken boundary wire.

In order to fulfill the purpose, two research questions were defined.

The first one was required to perform a research of existing methods to locate faults in underground, low-voltage electrical wires and evaluate these in order to find one that could be adapted to the field we are targeting.

- What methods exist to locate a fault in an underground, low-voltage electrical wire?

  As a follow up to the first research question, the second one is limited to describe how accurately the fault can be located.

- With what accuracy can a fault in an underground, low-voltage electric wire be located?

The purpose was not fulfilled since the investigated method did not prove useful when applied to a boundary wire.

The first research question was answered by describing the most common methods for locating faults in electrical wires in chapter 2. These methods were identified through a literature research where no previous research was found on the use of fault locating in boundary wires used in the lawn mower industry.

Chapter 2.4 (Method selection) argues for the choice of TDR as a method to answer the second research question to find out how accurate this method can locate a fault in an electrical wire. The arguments to investigate TDR were strong enough to choose it as the method that would be most useful if applicable.

Experiments were conducted to answer the second research question where previous research on the TDR method applied in coaxial cables was found. (Shin Y.-J. , o.a., 2005), (Shi & Kanoun, 2015) To confirm that the experiment execution was valid for this thesis, the measurements from *Experiment 1* (chapter 4.2) were compared to the previous research. These results confirmed that the method does work with an RG58 coaxial cable and that the expected error margin mentioned in Chapter 2 was correct.

In *Experiment 2* (chapter 4.3) the RG58 coaxial cable was replaced with a boundary wire and the result from this experiment shows that TDR does not work when applied to a boundary wire.

Areas where TDR is implemented as a fault locating method uses wires with a characteristic impedance, which the boundary wire does not have due to the lack of an insulating layer and shielding layer as ground reference.

Impedance:

The characteristic impedance of a cable is the ratio of the voltage to the current measured in Ohm(Ω) of a single wave travelling through a cable (Barsoukov & Macdonald, 2005), meaning the cables with higher impedance shows more opposition to let the wave through.

Experiment 2 shows that TDR is not applicable on a boundary wire in the same way as in a coaxial cable. The different construction of the coaxal and the single core boundary wire explains this result. Since the signal travels through the coaxial cable between the inner conductor and the shield that is connected to the ground, this protects the signal from interfering with most noise and provides the signal a medium with stable impedance to travel through, which helps to maintain the amplitude. While in a boundary wire there is no shield to protect the signals from interfering with other noise signals or to keep a ground reference of the signal. In this case the signal travels in the wire with the surrounding earth as a ground reference, this makes the signal encounter a very alternating impedance medium which in its turn could cause a big loss in the amplitude of the signal. Since the reason TDR is not applicable on a boundary wire is that there was no significant reflected signal, other reflectometry method could be considered not applicable on boundary wire for the same reason.

MATLAB simulation

In order to simulate the lack of reflection in the boundary wire a script was written (Appendix 2) that uses Formula (1) to calculate how much of the incident signal that is reflected back when encountering an impedance change. The script simulates an incident signal of 10V transmitted into a 100m long wire where there is an impedance variation that alternates every meter.

Table 5 shows the result from four simulations with different changes of impedance per meter. It also shows how much of the incident signal that remains at three different lengths of the wire. Figure 20 shows a diagram of the decrease in remaining voltage when there is a 0.5Ω variation per meter and Figure 21 shows the decrease when there is a 5Ω variation per meter.

Table 5 Simulation results

Impedance change	Remaining voltage 10m	Remaining voltage 50m	Remaining voltage 100m
0.5Ω	95.1%	77.8%	60.4%
1Ω	90.3%	60.2%	36.2%
2Ω	81.4%	3.57%	12.7%
5Ω	58.2%	6.7%	0.4%
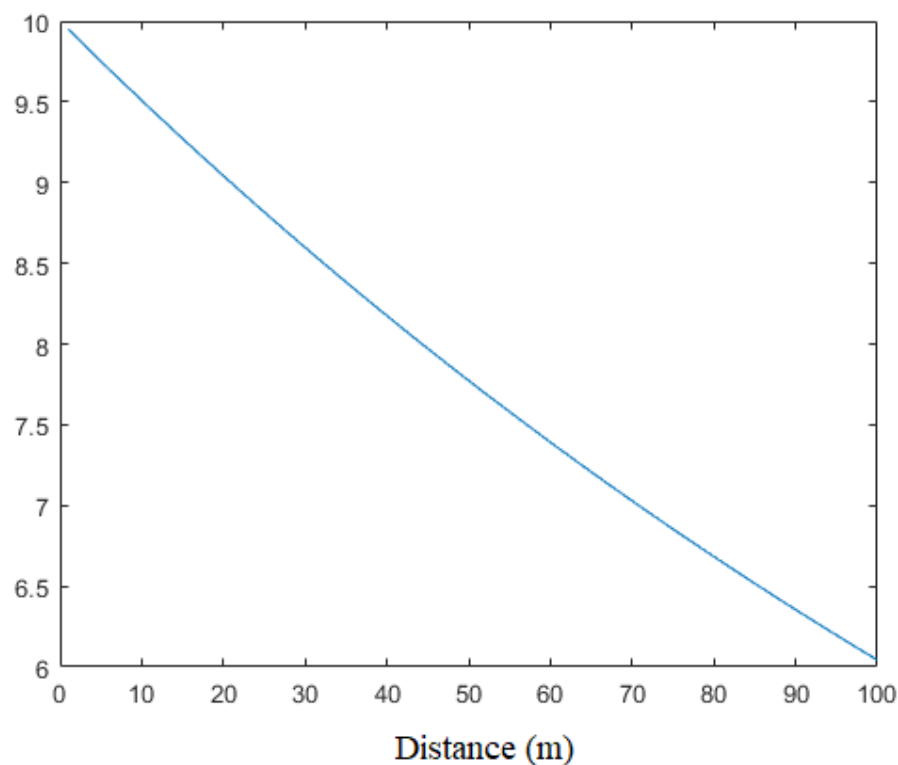
Figure 20 0.5Ω variation per meter
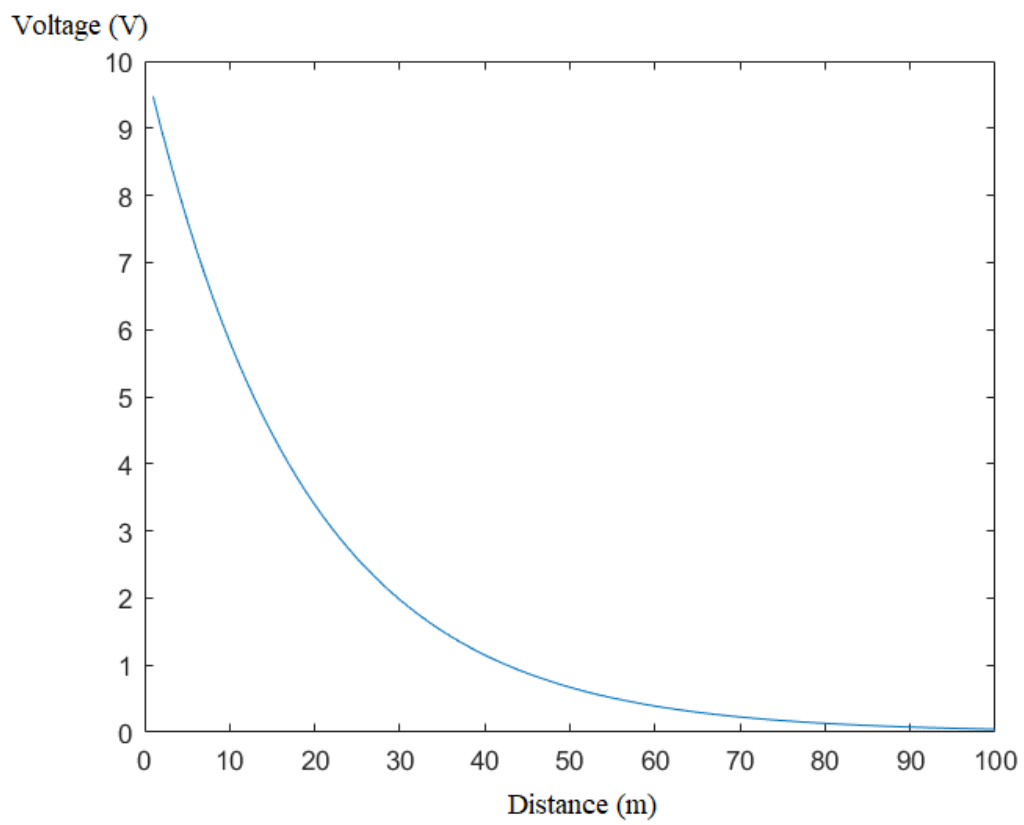
Figure 21 5Ω variation per meter

To simulate the impedance change when applying a pulse to a wire, the program
Simulink in MATLAB was used to simulate Experiment 1 for a 100m RG58 coaxial
cable with many impedance changes. Figure 22 shows the simulation model in
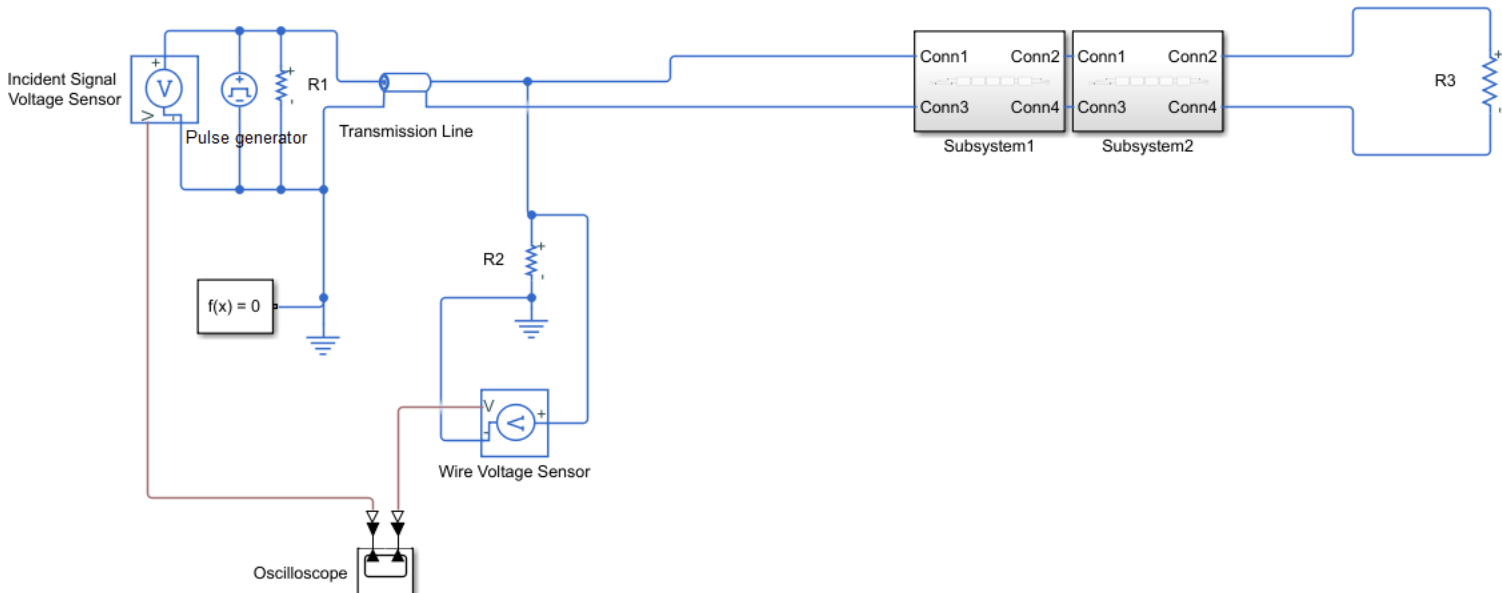Simulink.

Figure 22 Simulation model in Simulink

The pulse generator transmits a 10V pulse trough the transmission line that goes into
Subsystem1 and Subsystem2. Each subsystem consists of 50 segments where each
segment simulates 1m of RG58 coaxial cable connected in series to each other. That
makes in total 100m of transmission line where the impedance can be manually
adjusted.

R1 and R2 are 50Ω resistors.

R3 is 1GΩ to simulate an open end in the wire.

Incident Signal Voltage Sensor reads the signal generated from the pulse generator
and is displayed as yellow in Figures 26, 27 and 28.

Wire Voltage Sensor reads the signal that travels through the transmission lines and is
displayed as blue in Figures 26, 27 and 28.

Figure 23 shows an example of how each segment was set up.
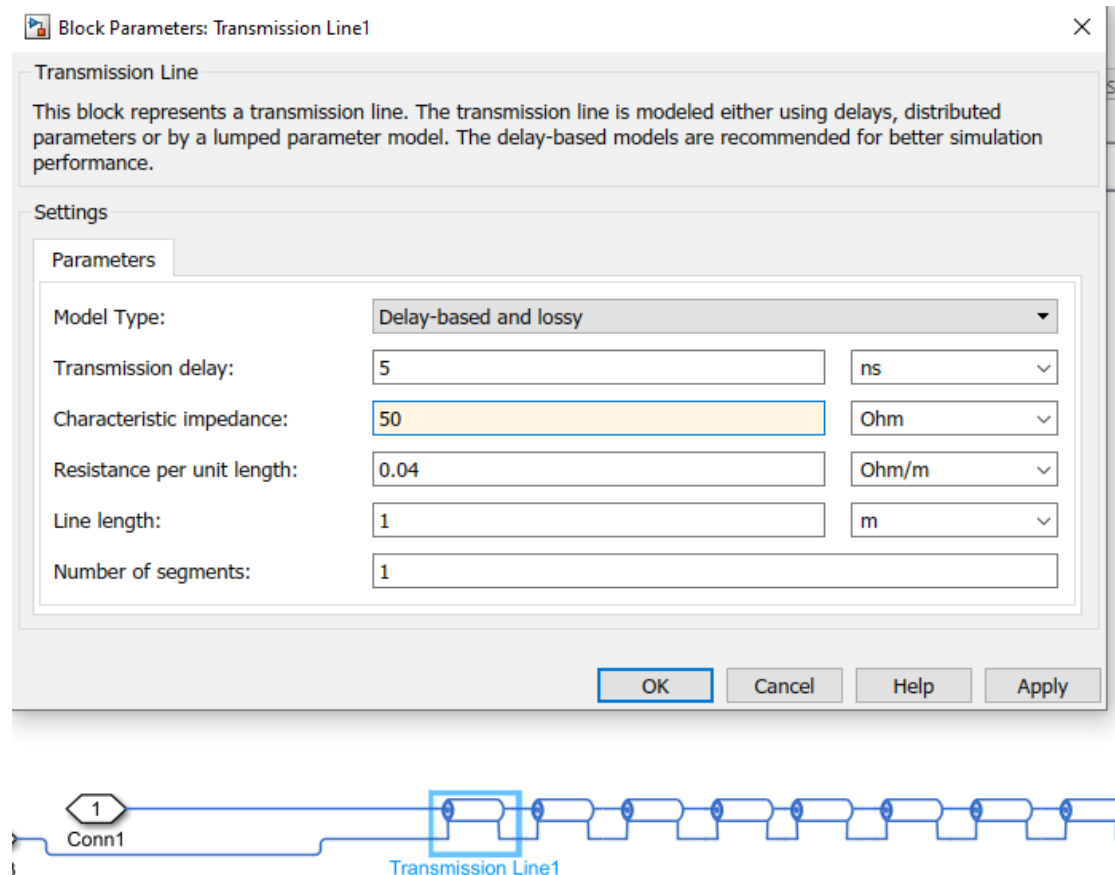
Figure 23 Settings for transmission line segments

Transmission delay is set to 5ns since this is the time it takes for a signal to travel 1m in an RG58 coaxial cable.

The characteristic impedance is set to 50Ω here, but it will be changed for each segment to simulate impedance changes.

Resistance per unit length is 0.04Ω/m for an RG58 coaxial cable.

Line length is set to 1m.

Number of segments is 1.

The first simulation was made with 50Ω impedance for all segments to validate that the simulation imitates an RG58 coaxial cable. Figure 24 shows an experiment with an actual RG58 coaxial cable where the first peak is the incident signal, and the second peak is the reflected signal.
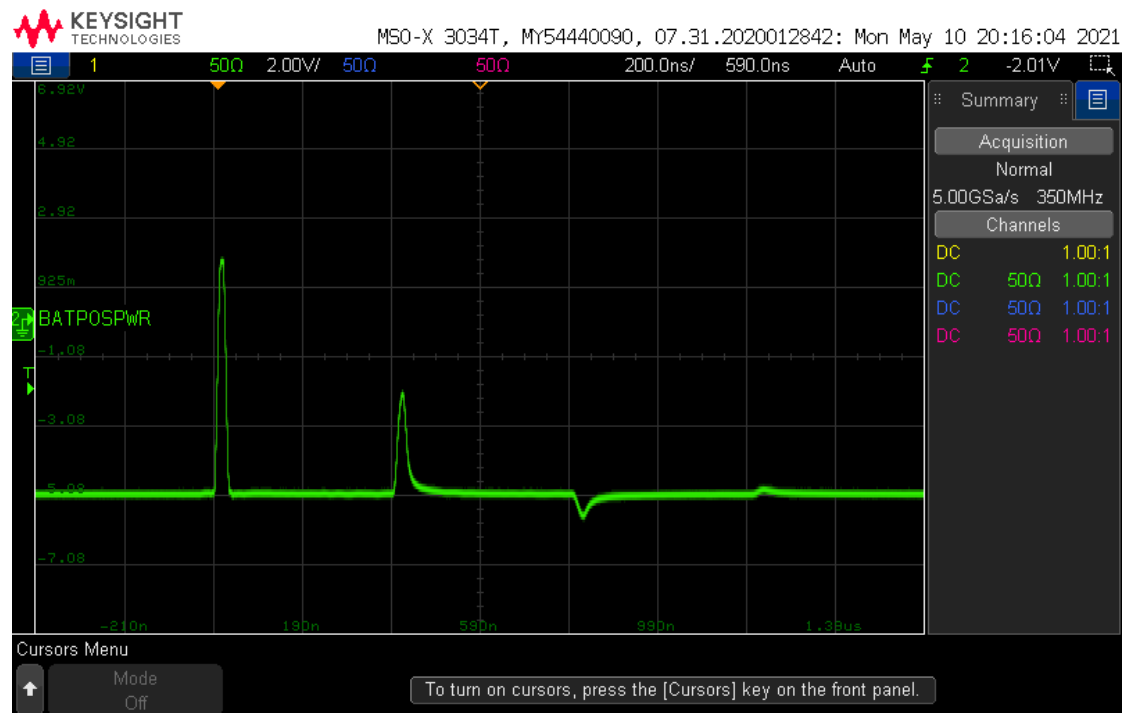
Figure 24 Incident signal and reflection in 40m RG58

Figure 25 shows the simulated model of the RG58 where the characteristic impedance is unchanged. The simulation imitates an RG58 very well.
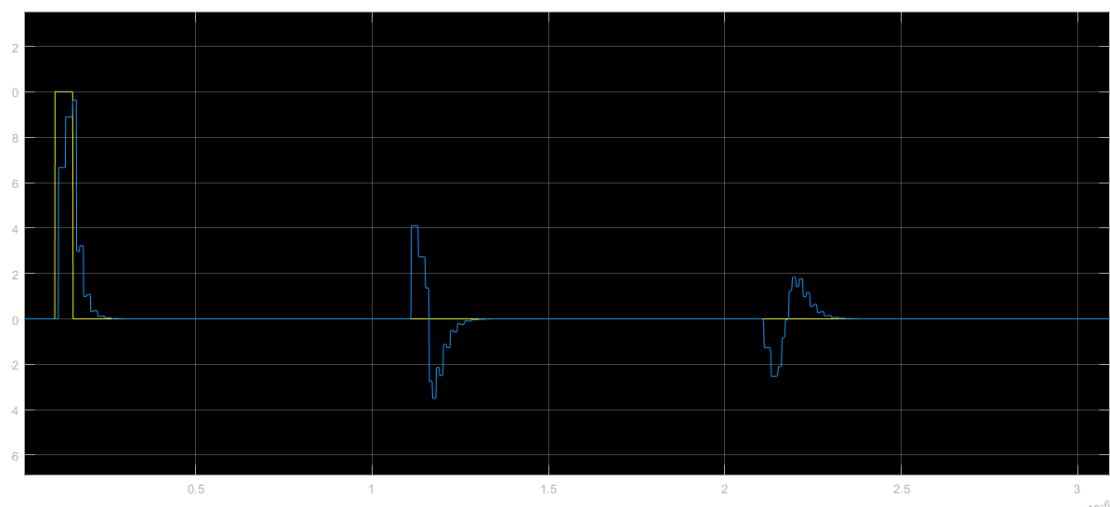
Figure 25 Simulated model of incident signal and reflection in 40m RG58

A simulation was then made where the impedance alternates between 45Ω and 50Ω as to compare the results from Figure 21 with the results from a simulated wire. This is displayed in Figure 26:
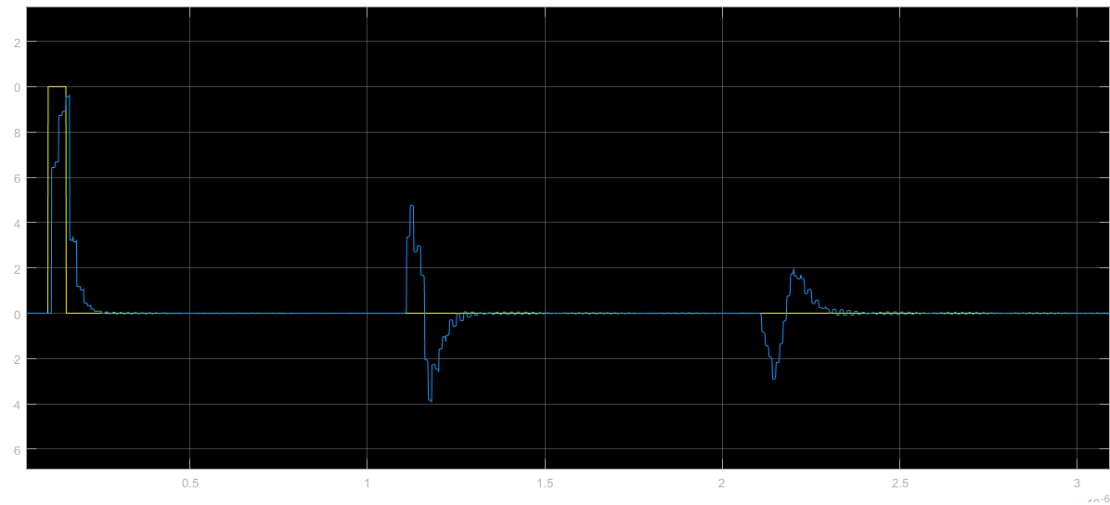
Figure 26 Simulation of 5Ω variation every meter for 100m long RG58

This result did not replicate that of Figure 21 and shows that formula (1) might not work when calculating many impedance changes in the same wire.

Further on, simulations were made where the impedance could vary between 25Ω to 75Ω. To simulate this, 10 random numbers were generated by using the randi() function in MATLAB (Appendix 1). These 10 numbers were used as impedance values and put into one segment each in the simulation. This sequence was then repeated 10 times to simulate larger impedance changes every meter for a 100m long RG58.

5 sets of random numbers were generated:

1. 25 44 47 40 39 37 72 68 45 49

2. 53 49 38 75 34 68 26 41 63 57

3. 33 73 52 37 54 71 70 49 47 40

4. 27 63 31 43 45 70 26 68 39 37

5. 49 62 35 36 74 55 40 74 70 34

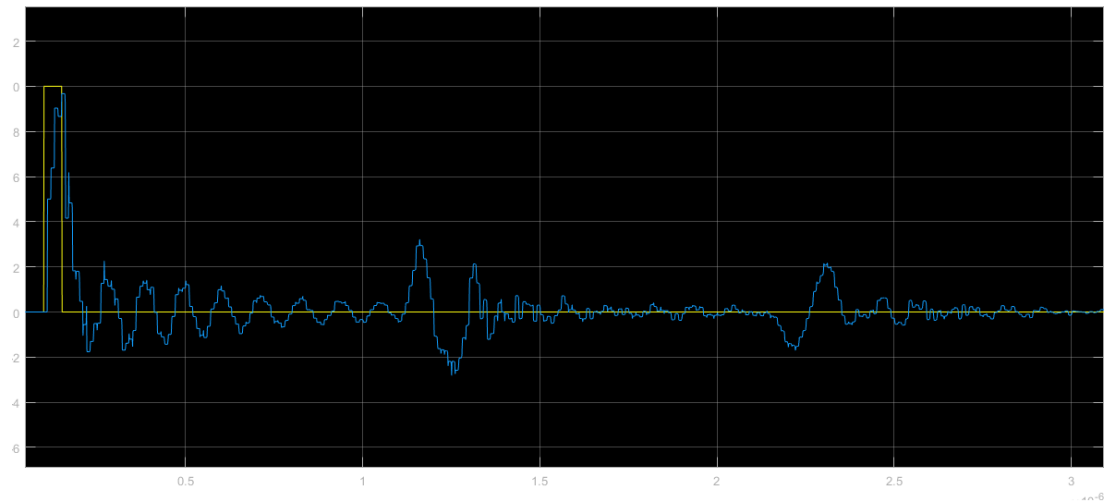Figure 27 shows the first set of random numbers put in sequence ran in the simulation.

Figure 27 Simulation of the first set of random numbers put as impedance change in sequence

Figure 28 shows the second set of random numbers put in sequence ran in the simulation.
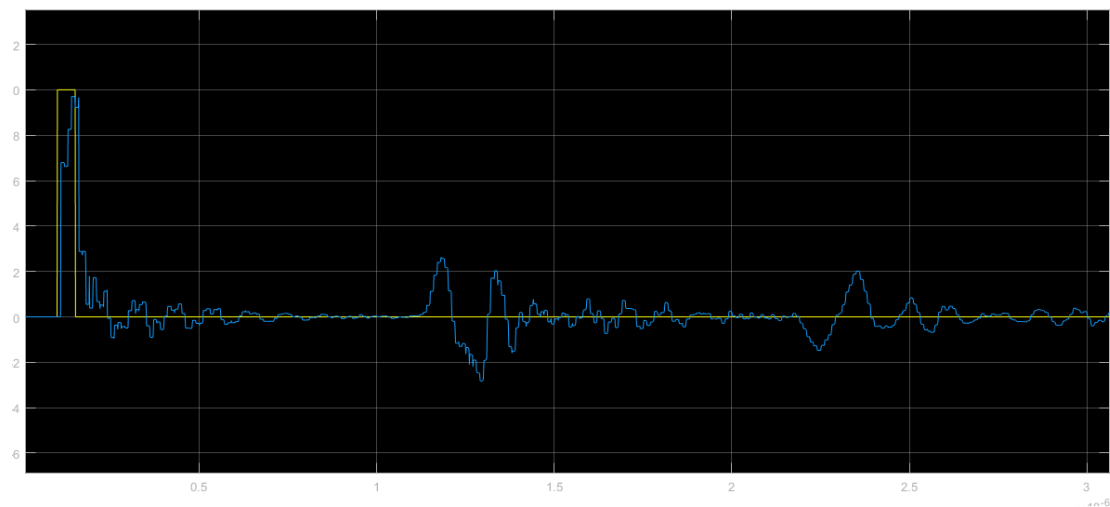

Figure 28 Simulation of the second set of random numbers put as impedance change in sequence

The last three sets of random numbers were also simulated but did not differ enough from the simulations shown in Figure 27 and Figure 28 to give more clarity, they are found in Appendix 3.

Despite relatively large impedance changes the reflection is still easily recognized, although it has decreased in size. This shows that very large impedance changes could cause the reflected signal to become unrecognizably small which is very likely the case for the experiments done for the boundary wire. There is also the ringing effect (Wilson, 2017) to consider when applying TDR in cables with no known characteristic impedance. The ringing effect could cause the reflection to be unrecognizable even if the reflection voltage is relatively high.

5.2 Method discussion

Research question 1

The method used to answer the first research question was to conduct a literature study. This choice of method was the only reasonable way to gather enough knowledge and perspective on the range of methods used to locate faults in electrical wires to answer this question.

The strength of reliability of a literature study is that it is easy to replicate the study by using the same search words and filters that was used in this study. It is also a good way to encounter the same possible solutions and comparing them in a similar way due to the benefits and limitations mentioned in both the articles and in Chapter 2.

A weakness of reliability in conducting a literature study is that researchers performing the study possesses different levels of prior knowledge and there is an element of interpretation to what is relevant to the study and what is not.

The first research question was answered by describing the most commonly used methods to locate faults in electrical wires in Chapter 2. From these methods a large number of optimized methods and combinations of methods have been developed to fit the industry in which it is used, but since no previous research in this area was found the conventional methods were investigated.

Research question 2

By using Design Science Research (DSR) to answer the second research question the authors of this thesis were allowed to create a work process that seemed most suitable to answer the research question.

A strength of DSR is the possibility to iterate through the work process when required and experiments can be conducted early on in the iteration. Once you arrive at the second step (Solution design) it is possible to go through several iterations in short time to gather data.

As mentioned in Chapter 3 (Method and implementation), DSR was well suited for this thesis since there were stakeholder requirements and the social context to consider, although this thesis only focused on investigating the accuracy of the selected method when applied to the autonomous lawn mower industry.

A weakness in DSR is that the first step of the iteration (Problem investigation) is very time consuming which could limit the number of iterations you can go through if the work has a time limit.

The second research question was answered for the TDR method when applied to a coaxial cable (RG58) and a boundary wire used for autonomous lawn mowers of <40m in length.

Fulfilling of the purpose

The purpose of this thesis was to identify a useful solution to find the location of a broken boundary wire. This purpose was not fully fulfilled as described in Result discussion (Chapter 5.1) since the investigated method was not confirmed as useful when applied to a boundary wire.

Also, the hypothesis saying that "an investigated method is applicable for all underground wires "(Chapter 1.3) was refuted since the results from a RG58 coaxial cable and the boundary wire did not relate.

6   Conclusions and further research

6.1   Conclusions

This study presented a few methods that could be used to locate faults in boundary wire and measured the accuracy of one of them. The presented methods were already existing and used in other contexts but not within the autonomous lawn mower industry. The study did not deliver a useful method to be used to locate faults in boundary wires. However, it was able to test and exclude the Time Domain Reflectometry technology because of the insignificant reflected signals in boundary wire, and to derive that the Frequency Domain Reflectometry technology can be excluded for the same reason. The third technology presented in the literature research was excluded earlier in the study because of the implementation difficulties and the difference between earth and battery ground reference.

6.1.1   Practical implications

The result of this study shows that reflectometry methods does not work in todays boundary wires. To locate faults in this area requires some other method or a different wire with characteristics more similar to a coaxial cable.

6.1.2   Scientific implication

The result from this study excludes the methods explored in the literature research from consideration as applicable methods to locate faults in boundary wires.

This study produced an accuracy measurement for TDR on a coaxial cable for both open-end and shorted circuits.

6.2   Further research

In this study, TDR technology was tested in two iterations, at least one more iteration could be done by designing circuits to study the behavior of incident signals with higher voltage and shorter rise time.

Further research could explore the possibility of using a twin core cable as a boundary wire, where one of the cores is used as ground reference during the fault locating process.

Further research could also explore and investigate other technologies that are not depending on impedance or reflection.

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8 Appendices

Random number script

```
r = randi([25,75],1,10)
```

MATLAB Script for simulating voltage loss according to formula (1).

```
impedance = 50
impedanceAtPoint = 50
impedanceChange = 2
incidentSignal = 10
reflectedSignal = 0
reflectionCoefficient = 0
result = zeros(1,100)
meters = zeros(1,100)


for i = 1:100
    if mod(i,2) == 0
        impedanceAtPoint = impedanceAtPoint + impedanceChange
    else
        impedanceAtPoint = impedanceAtPoint - impedanceChange
    end


    reflectionCoefficient = (impedanceAtPoint - impedance) /
(impedanceAtPoint + impedance)
    reflectedSignal = incidentSignal * reflectionCoefficient
    if reflectedSignal > 0
        incidentSignal = incidentSignal - reflectedSignal
    else
        incidentSignal = incidentSignal + reflectedSignal
    end


    impedance = impedanceAtPoint
    result(i) = incidentSignal
    meters(i) = i
end
signalAtEnd = incidentSignal
```

Impedance change simulations.
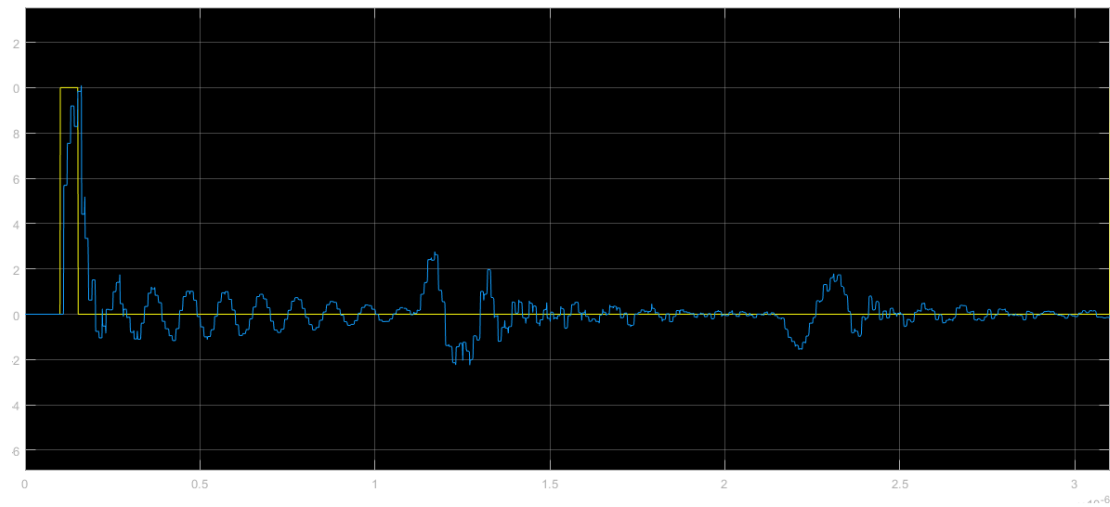
Figure 29 Simulation of the third set of random numbers put as impedance change in sequence
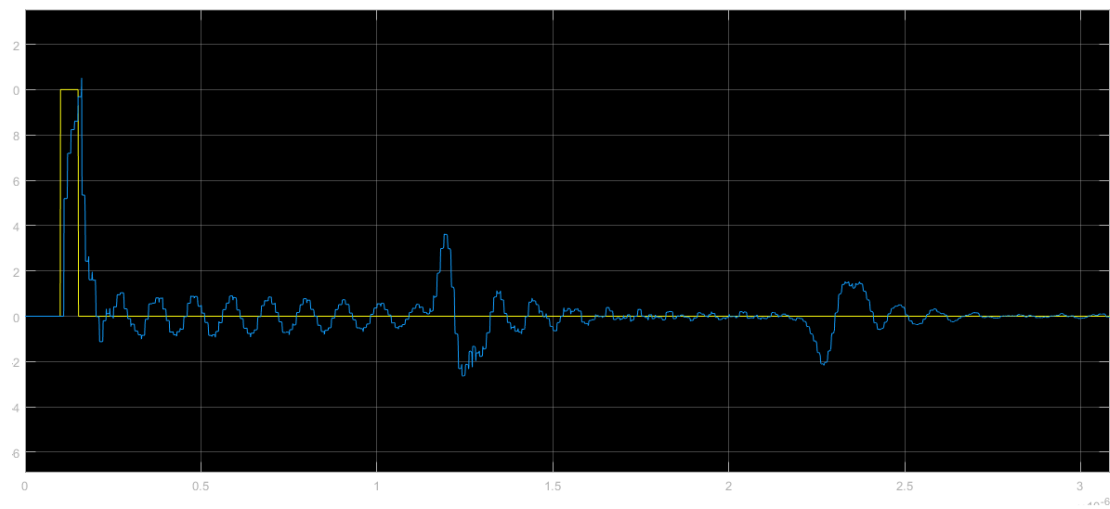
Figure 30 Simulation of the fourth set of random numbers put as impedance change in sequence
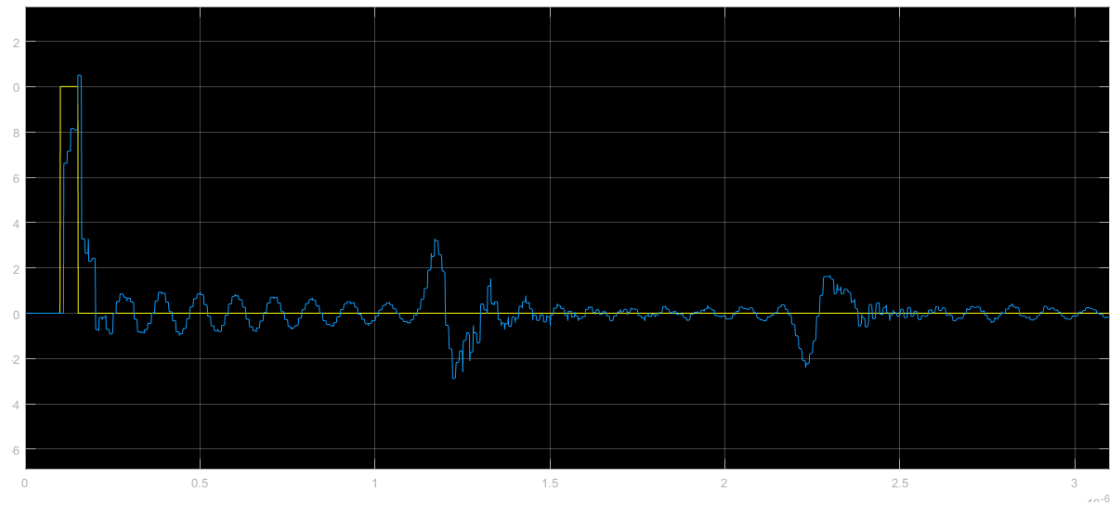
Figure 31 Simulation of the fifth set of random numbers put as impedance change in sequence

RG58 datasheet.

Data Sheet

HUBER+SUHNER

Flexible RF cable
RG_58_C/U   Item: 22510015

Description

RG: RG type RF cables

RG58, 50 Ohm, 1 GHz, 85°C, ø4.95 mm, PVC jacket

Technical Data

Construction

	Material	Detail	Diameter
Centre conductor	Copper, Tin plated	Strand-19	0.9 mm
Dielectric	PE (Polyethylene)		2.95 mm
Outer conductor	Copper, Tin plated	Braid, 96%	3.6 mm
Jacket	PVC II (low migration)	RAL 9005 - bk	4.95 mm +/- 0.15

Print: HUBER+SUHNER RG 58 C/U 50 Ohm (production order number)

Electrical Data

Impedance	50 Ω +/- 2
Operating Frequency	1 GHz
Capacitance	101 pF/m
Velocity of signal propagation	66 %
Signal delay	5.03 ns/m
Screening effectiveness	≥ 38 dB (up to 1 GHz)
Operating voltage	≤ 2.5 kV$_{rms}$ (at sea level)
Test voltage	5 kV$_{rms}$ (50 Hz/1 min)

Mechanical Data

Weight		3.7 kg/100 m
Min. bending radius	static	25 mm
		50 mm

Environmental Data

Temperature range	-25 °C ... +85 °C
Installation temperature	-20 °C... +60 °C
Halogen free	No
2011/65/EU (RoHS - including 2015/863 and 2017/2102)	compliant
1907/2006/EC (REACH)	compliant

Additional Information

MIL reference: M17/183-00001 (former reference: M17/28-RG058)

Remarks
(For details refer to the HUBER+SUHNER RF CABLES GENERAL CATALOGUE or contact your nearest HUBER+SUHNER partner)

Suitable Connectors

Cable group	U7 3 mm / 50 Ohm

Figures

Tables