



Comparison of measurement methods for partial discharge measurement in power cables

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April 2014

INTELLIGENT ELECTRICAL POWER GRIDS

Abstract

Nowadays it becomes more and more important to operate the electricity grid efficiently. To achieve this, condition based maintenance is a good way to reduce maintenance time and costs. For condition based maintenance partial discharge is an important tool to indicate insulation conditions.

This thesis focuses on partial discharge (PD) measurement in power cables. It focuses on ignition of PDs are triggered, what can be expected to measure, what kind of technologies are commercially available for PD measurement and it compares PD measurement according to IEC60270 (conventional) with PD measurement not according to this standard (unconventional).

During ageing of a defect in a power cables, different PD mechanisms can occur. Aged defects have lower generally inception voltage than virgin defects. PDs is measured by charge displacement in the cable to the defect, that is related to the energy dissipated during a discharge and the volume of the cavity.

During propagation of a PD pulse through a cable, high frequencies attenuate fast. Therefore their amplitude decreases. Because the charge of the PD pulse does not attenuate in that large amount, the pulse becomes wider. Furthermore the frequencies near DC attenuation more or less proportional to the charge.

There are several types of PD measurement devices on the market, offline as well as online, all using different voltage sources. Each voltage source has its advantages and disadvantages, depending on applied stress, continuous duty, size, weight and max applied voltage.

Location is determined with Time Domain Reflectometry (TDR) or double sides measurement.

PDs measurement can be performed according to the standard (conventional measurement) or not (unconventional measurement). There is a need for unconventional measurement because the time response of conventional measurement is too long. There could occur overlap of pulse responses and therefore it is not suitable for localization. This causes the need for unconventional measurement.

For conventional measurement there is a standard, for unconventional there is not. Therefore manufacturers have developed systems with different sensors, that are not calibrated according to a standard. Due to this, there can be differences in charge determination between systems.

Investigation of influence of the bandwidth of a system to the response of a PD, shows that filtering frequencies have influence on time length of the response, the sensitivity of the system and the charge determination.

Checking the accuracy of different charge determination methods for different sensors shows a wide dispersion in accuracy. Determining charge by taking the peak value of the frequency spectrum seems to be an accurate method for unconventional measurement. Depending on the pulses to be measured, this method could be used with a wide range of sensors. Furthermore, the extension of this method, that makes use of compensating the frequency spectrum of the measured PD, seems to be also an accurate method.

Because now there is also an accurate way to determine charge of PD pulses using different sensors, unconventional measurements of different systems can be compared. Next to this, unconventional measurement can be compared with conventional PD measurement.

Table of contents

Abstract	3
Table of contents	5
1 Introduction.....	8
2 Partial discharges occurrence	10
2.1 Introduction.....	10
2.2 PD mechanisms	10
2.2.1 Streamer	11
2.2.2 Townsend	11
2.2.3 Pitting	12
2.3 Types of PD.....	12
2.3.1 Internal discharges	12
2.3.2 Surface discharge	13
2.3.3 Corona	13
2.4 Properties of PDs that can be expected during PD measurement in cables.....	16
2.5 Initiation of PD activity	16
3 Partial discharges representation	17
4 Propagation properties of PD pulses in power cables	20
4.1 Introduction.....	20
4.2 Pulse propagation properties.....	20
4.2.1 The telegraph equations	21
4.2.2 Attenuation and dispersion.....	23
4.2.3 Characteristic impedance and reflection of PD pulses.....	26
4.2.4 Evaluation of a calibrator pulse through a MV cable	27
4.3 Conclusion	31
5 Commercial available PD cable testing technologies.....	32
5.1 Introduction.....	32
5.2 Off-line measurement	32
5.2.1 Introduction.....	32
5.2.2 Sources for energizing the power cable during PD measurement.....	33
5.2.3 Resonant systems.....	35
5.2.4 Damped AC voltage	40
5.2.5 Sensors for offline measurement.....	44
5.3 Localization of PD origin	45

5.4	On-line measurements	47
5.4.1	Introduction.....	47
5.4.2	Principle.....	48
5.4.3	Equipment	49
5.5	Summary and conclusions.....	51
6	Partial discharge measurements, conventional and unconventional.....	53
6.1	Introduction.....	53
6.2	Conventional measurement.....	53
6.2.1	Introduction.....	53
6.2.2	Standard	53
6.2.3	Description conventional PD measurement	54
6.2.4	Prescriptions of the IEC60270 standard for measuring PD	55
6.2.5	Limits of the conventional measuring method	57
6.2.6	Feasibility conventional measurement method for PD measurement in MV cables ...	63
6.2.7	Conclusion	64
6.3	Unconventional measurements	64
6.3.1	Introduction.....	64
6.3.2	Influence of the sensor on the PD pulse response.....	65
6.3.3	Conclusion	71
6.4	Comparison of PD measurement methods.....	72
6.4.1	Introduction.....	72
6.4.2	Methods used for charge determination of PD pulses	73
6.4.3	Simulations	75
6.4.4	Conclusion	82
7	Influence of the measuring circuit on the measurements.....	83
7.1	Introduction.....	83
7.2	Influence of different measuring components on the gain of the system	83
7.3	Measurements	84
7.3.1	Coupling capacitor combined with measuring impedance.....	84
7.3.2	High frequency current transformer	87
7.4	Conclusion	88
8	Gain compensation of the measurement system	89
8.1	Introduction.....	89
8.2	The method	89

8.2.1	Determination of the frequency response of the system	90
8.2.2	PD signal compensation	90
8.2.3	Charge determination	91
8.3	Gain compensation in practice.....	91
8.3.1	Gain determination	93
8.3.2	Gain compensation.....	96
8.3.3	Applying gain compensation method to a high frequency current transformer	99
8.3.4	Comparison of gain compensation method with determining charge by means of taking the peak value of the frequency spectrum	102
8.4	Conclusion	103
9	Summary and conclusions.....	104
9.1	Conclusions and summary.....	104
9.2	Recommendations.....	106
A	Appendix	107
B	Appendix	110
C	Appendix.....	112
	Acknowledgements	113
	Bibliography.....	114

1 Introduction

Nowadays it becomes more and more important to operate the electricity grid efficiently, because stakeholders, regulators and customers have high expectations of the electricity grid. Next to this, all the assets deal with ageing. Transport and distribution service operators are trying to achieve a high performance of the grid, in combination with a high reliability and a minimum of maintenance costs. [23]

Possible maintenance methodologies to apply are:

- No maintenance until breakdown (corrective maintenance)
- Apply maintenance after constant periods of time (time based preventive maintenance)
- Apply maintenance when the condition of the component is that bad that it will fail within a short time (condition based preventive maintenance)

Breakdown of a cable without redundancy, leads to outage of the grid. This is not desirable; corrective maintenance should better not be applied. It has shown that condition based maintenance has advantages above time based maintenance, with its reduction in maintenance costs.[22] The failure rate of assets behave like a the 'bathtub curve'. The failure rate of an asset population in the beginning of the lifetime is high because of manufacturing faults, during a long life time constant, and at the end of the lifetime increased because of ageing.[14] To prevent failure of assets, it is important to know the condition of the asset. After the component is installed in the grid, and after ageing when the asset is in the last phase of its lifetime.

Through the years, it has been recognized that PD indicates danger to the life of insulation [14]. PD measurement is one of the most important instruments to indicate insulation conditions.[3]

Nowadays there are several systems of different manufacturers to measure PD on the market. The technical difference between systems can be found in the difference of the energizing sources, the different sensors used, whether measured according to IEC60270, location determination and charge determination. There are also practical considerations to choose a system; this has to do with weight, size and duration of installation.

PD measurement can be performed according to the standard IEC60270, but this has some limitations, especially for PD measurement in power cables. To overcome these shortcomings, alternative systems have been developed: so called "unconventional systems". For these systems, there are no standards, what has lead to a wide range of varieties in systems.

1 Introduction

PD measurement according to the standard, performs charge determination of PD pulses with low uncertainty. For unconventional measurement there is no standard to be sure the charge is measured correctly.

Because of the diversity in PD measurement systems with different sensors, there are a lot of factors to consider when selecting a specific system. For example there could be made differences in charge indication.

Before a power cable leaves the factory and after installing, the cable is tested for PD. When measuring with different systems, it is important the measurements can be compared with each other to get an unambiguous indication of the PD activity in the cable. This is also important in case measuring a cable near the end of its life with different systems at different life times each, in order to make an accurate PD activity evaluation in time.

The purpose of this Master thesis is to create the possibility to compare measurement results of different PD measurement systems that are used for PD measurement in power cables.

The research objectives are:

- Comparing different PD measurement techniques available on the market
- Comparing conventional and unconventional measurement methods and show their applicability to MV cable tests
- Investigate different techniques for charge determination of PDs
- Study the influence of the measuring circuit on PD measurement

This thesis gives in **chapter 2** some information about different stages in ageing of insulation materials. **Chapter 3** gives a model of a cable with a defect, to give a practical idea of what happens when a PD occurs. **Chapter 4** gives some information about propagation of a PD pulse through a cable and what can be expected to measure at the end of the cable.

Furthermore a comparison is made of different PD measurement systems available on the market in **chapter 5**. **Chapter 6** compares conventional and unconventional measurement with respect to PD measurement in power cable. The opportunities and limitations are investigated to come to a conclusion about their applicability. **Chapter 7** treats the influence of the measuring circuit on the PD measurement. In **chapter 8** is investigated a universal method to determine charge in an accurate way using unconventional measurement.

2 Partial discharges occurrence

2.1 Introduction

The definition of a partial discharge according to IEC60270 is:

Localized electrical discharge that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor.

Partial discharges are in general a consequence of local electrical stress concentrations in the insulation or on the surface of the insulation. Generally, such discharges appear as pulses having a duration of much less than 1 μ s. More continuous forms can, however, occur, such as the so-called pulse-less discharges in gaseous dielectrics. This kind of discharge will normally not be detected by the measurement methods described in this standard.

Partial discharges are often accompanied by emission of sound, light, heat, and chemical reactions.

A PD causes a PD pulse. This is a current or a voltage pulse that results from the PD, caused by the displacement of charge.

PDs occur most likely in gas, vapour or in low density regions in oil. They are indicators for defects in the insulation materials. They degrade the insulation material as well as the electrode, and sooner or later the insulation will break down.

There are three conditions for the generation of PDs:

- 1 A starting electron must be available
 - 2 An avalanche is created by ionization
 - 3 A feedback mechanism has to be present
- [12]

Before a PD can take place, a starting electron must be present. This electron can be released from the electrode or from the gas in which the discharge will take place. Furthermore the field strength must be sufficiently high for the electron to gain enough kinetic energy to cause an avalanche by ionization. This created avalanche has to maintain itself, therefore a feedback mechanism has to be present.

2.2 PD mechanisms

Three common PD mechanisms that can cause a partial discharge are:

- 1 Streamer mechanism
- 2 Townsend mechanism
- 3 Pitting

2 Partial discharges occurrence

During the ageing process they occur in the above ranked way.

2.2.1 Streamer

A streamer is formed when an avalanche reaches the critical number of 10^8 charge carriers. At this value there is generated extra ionization. This extra ionization and thereby the generation of extra photons take care for the feedback mechanism, let the avalanche further grow and make new avalanches that grow to each other. Therefore the avalanche can maintain itself and a streamer is formed.

The breakdown channels of a streamer are narrow and the discharge time is relative short (about 1-10ns) [14]. During streamer discharge, only small part of the surface participates to a discharge, other small parts discharge individually. This can occur very fast and the pulses tend to overlap [12].

2.2.2 Townsend

Townsend occurs only in cavities where the condition of the size of the cavity and the pressure in the cavity exceed the Paschen's curve (see figure 2.1). This curve gives the condition for the voltage and the pressure * size of the cavity to initiate a discharge in the cavity. Townsend in general works until (pressure * distance) is 5bar*mm.

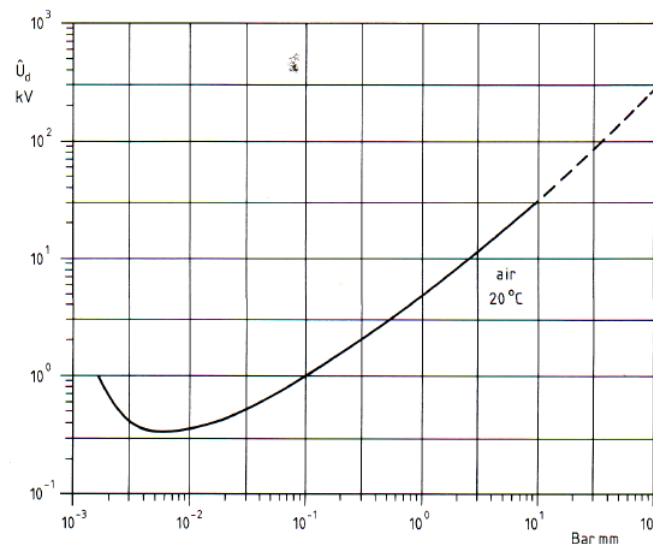


Figure 2.1: Paschen's curve [13]

When the conditions for the Townsend mechanism are fulfilled, a starting electron can create an avalanche by ionization. Some photons and the formed ions move to the cathode. When they hit the cathode, there is a probability that a new starting electron is initiated, which causes a new avalanche. This is how the feedback mechanism of Townsend works. So the feedback for the Townsend mechanism depends on the cathode material. The discharge process is shown in figure 2.2. The Townsend mechanism causes a diffuse discharge, a large area of the cavity surface participates within the discharge. For cavity depths of 0.1 to 1mm the discharge duration takes respectively about 80ns – 0.8μs [14]. This is caused by the slowly moving ions that can create new starting electrons when they reach the cathod. Because the charge displacement is the same as in the streamer stage but the discharge time is longer, the pulse has lower amplitude.

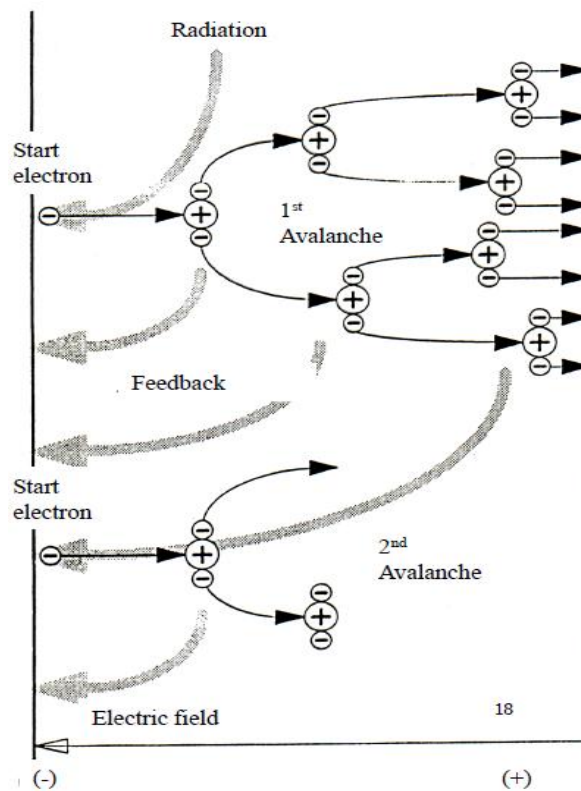


Figure 2.2: Townsend discharge process

2.2.3 Pitting

As a cause of ageing of the cavity wall by repetitively discharges in the cavity, pitting may occur under AC voltage. During discharging, by-products are produced. After a long time of discharging, the concentration of by-products is so large that there is going to form a conductive layer of crystals at the cavity wall. When the crystals are formed, there is generated field enhancement at the sharp edges of the crystals. At these edges, discharges occur far earlier than in the other stages of the material. The discharges take place in smaller space and have a low magnitude in combination with a relative high repetition rate. Due to the low magnitude (0.2pC) and the high repetition rate Pitting is much harder to measure.

2.3 Types of PD

PD's can be harmful for the dielectric of cables.[14].

There are three types of partial discharges:

- Internal discharges
- Surface discharges
- Corona discharges

2.3.1 Internal discharges

Internal discharges can occur in cavities that are present in solid insulation. They are also formed by the electrical treeing process, that wears out a cavity in the insulation. There can be made a distinction between cavities that are electrode bounded or totally enclosed by insulation material.

2 Partial discharges occurrence

Causes of PD's in solid dielectrics are shown in figure 2.3

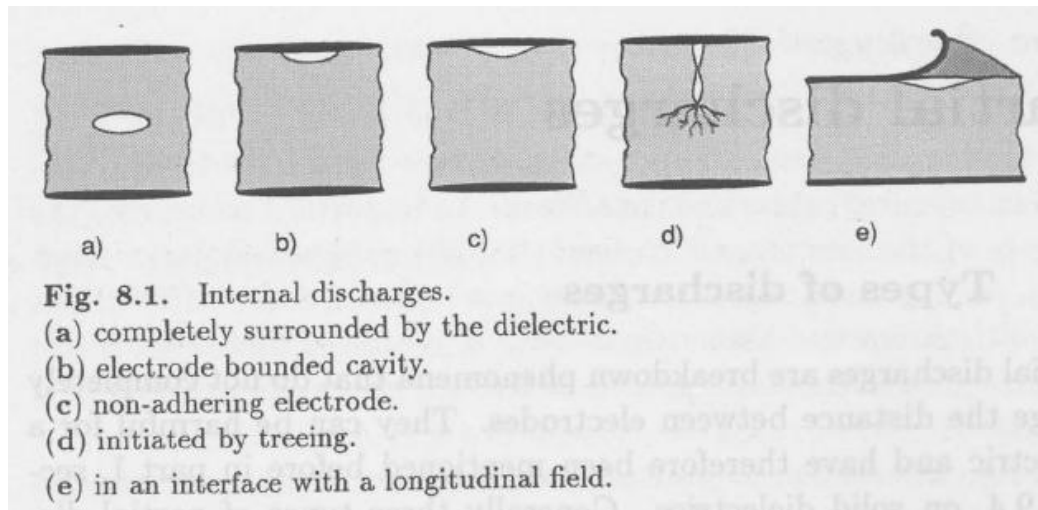


Figure 2.3: Internal discharges in solid dielectrics [14]

Ageing process

Virgin cavities

Unaged cavities, totally enclosed by dielectric material, do not have a conductive cavity wall. Therefore Townsend is not possible to occur in the so called 'virgin cavities'. In that case the voltage must increase to about 5% higher than required following the Paschen's curve for creating the required condition of streamers.

Aged cavity

After some time streamer discharges occurrence, there is formed a conductive layer on the cavity's surface. This is caused by chemical changes of the surface, formed during the discharges. Now the surface of the cavity is conductive, the Townsend mechanism can take place.

During the latest stage large discharges that start from the edge of the cavity occurs that appears in intermittent way. They seem to have a relation to breakdown and are a sign of progressive ageing.

2.3.2 Surface discharge

Surface discharges are streamer discharges that could initiate at a high tangential field strength along the interface. When PDs are detected near their inception voltage, it shows no difference between surface and internal PD. In case the voltage applied is raised, the discharge occurs along a longer surface. Thereby the surface discharge increases in length and magnitude. In this way surface discharge is easily to distinguish from internal discharges.

2.3.3 Corona

Corona occurs around sharp points in a high electric field. During PD measurement in cables, sharp edges at the end terminations can cause corona and could be covered with metallic round caps to bring the surrounding of the sharp point at equal potential. Corona can mask detection of other discharges during PD measurement. There are two types of corona: positive and negative corona.

Negative corona

Negative corona occurs at negative voltage. Figure 2.4 shows a point at negative voltage, in the vicinity of a cathode. Townsend discharges take place and the formed electrons of the ionization are at larger distance attached to an electronegative gas (Oxygen in Air). In this way heavy negative ions are formed. These ions are too heavy and slow to participate in the creation of avalanches and form a cloud in front of the negative electrode. Because presence of a cloud of negative heavy ions, the field strength is decreased and the discharges are stopped. When the space charge cloud of heavy ions has moved away, the discharge are initiated again. The electronegative gas is required for this recurrent appearing discharges. Negative corona occurs in case the voltage is sufficient to release electron out of the electrode, discharge peaks are measured symmetrical around the negative voltage peak of the sinusoidal AC voltage waveform. The magnitude of the discharges is constant, but the repetition rate increases with the voltage.

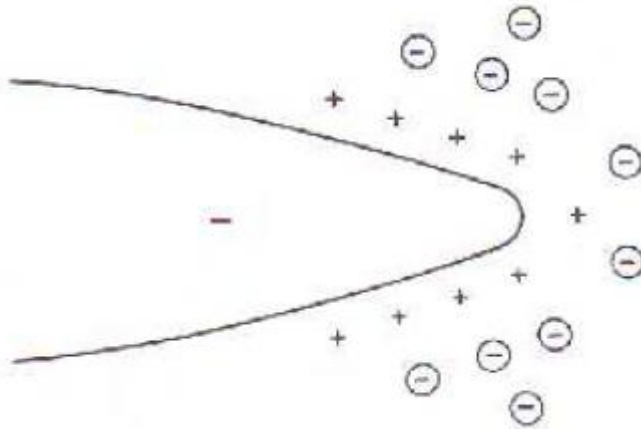


Figure 2.4 : Negative corona [13]

Positive corona

Positive corona has a higher inception voltage than negative corona. During positive corona, there is absence of a cathode at the high field strength. Streamers are formed in the gas, near the sharp point with high field strength, and cause the presence of positive ions in front of the sharp point (see figure 2.5). These positive ions form a positive space charge and let the field strength at the electrode decrease. At a certain field strength, the generation of streamers extinguishes. After the space charge of heavy ions is drifted away, generation of streamers is initiated again. The pattern of positive corona is not as regular as with negative corona and at higher voltages, large streamers can be generated.

Figure 2.6 shows the occurrence of PD along the phase angle of the applied voltage. It also shows that negative corona has a lower inception voltage than positive corona.

2 Partial discharges occurrence

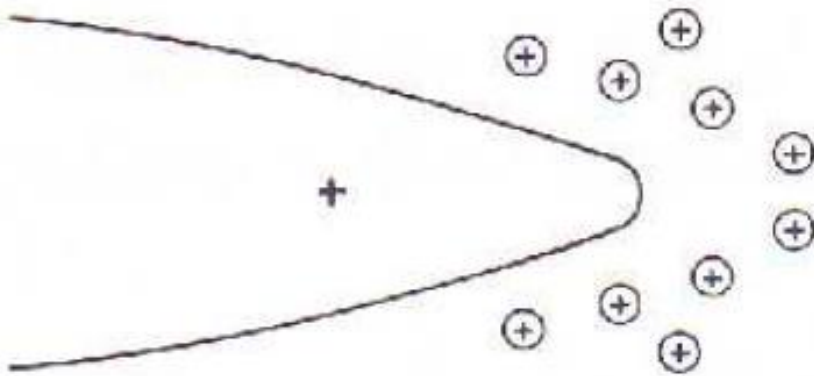


Figure 2.5 : Positive corona [13]

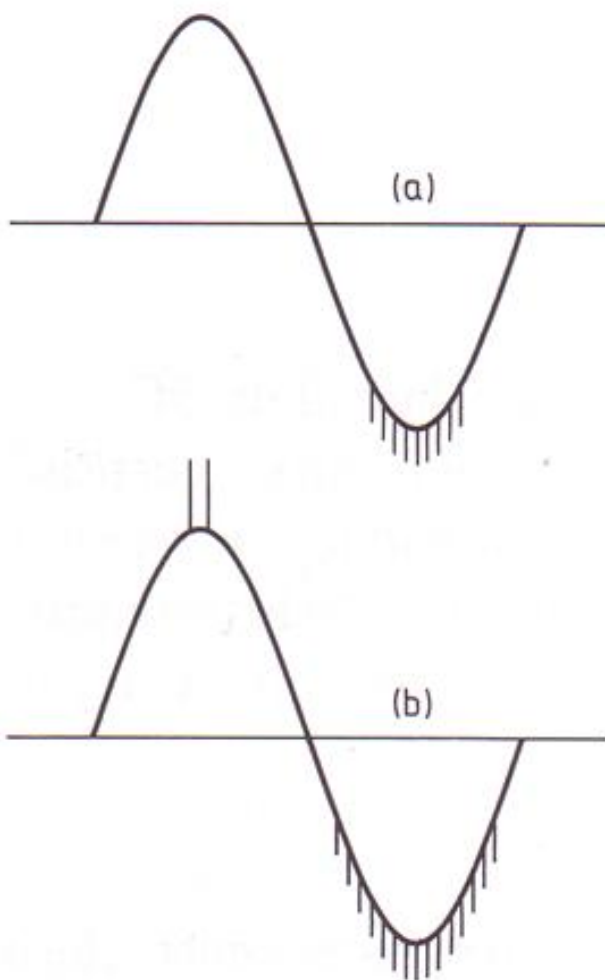


Figure 2.6: a) Negative corona after voltage rise b) Positive and negative corona after voltage rise [13]

2.4 Properties of PDs that can be expected during PD measurement in cables

The shape of a PD pulse depends on the propagation path of the pulse before it is measured. PDs with origin at or near the point of measuring have almost their original shape. In MV cables, the high frequency content of a pulse attenuates very fast. The longer the propagation path of the pulse, the more high frequency content is lost and the wider the pulse. Chapter 4 goes more in detail into this process.

2.5 Initiation of PD activity

PDs are initiated at a certain voltage, the extinction voltage V_i . The definition according to IEC60270 is: applied voltage at which repetitive partial discharges are first observed in the test object, when the voltage applied to the object is gradually increased from a lower value at which no partial discharges are observed. In practice, the inception voltage V_i , is the lowest applied voltage at which the magnitude of a PD pulse quantity becomes equal to or exceeds a specified low value.[9]

When a PD is initiated, it usually continues at this voltage, but usually also when the voltage is decreased a bit. The PD activity extinguishes at a certain voltage level, equal or below the inception voltage. This is called the extinction voltage. IEC60270 describes it as: applied voltage at which repetitive partial discharges cease to occur in the test object, when the voltage applied to the object is gradually decreased from a higher value at which PD pulse quantities are observed. In practice, the extinction voltage V_e is the lowest applied voltage at which the magnitude of a chosen PD pulse quantity becomes equal to, or less than, a specified low value.[9]

Defects with V_i smaller than the operating voltage, produce PD when the cable is energized. This PD activity will continue during operation. Because the PD damages continuously the cable insulation, it brings a high risk on failure of the cable.

Another situation is $V_i > \text{operating voltage}$, but $V_e < \text{operating voltage}$. In this case, the PD is triggered by a peak voltage caused by for example lightning or switching. When the PD activity is initiated, there is a chance the PD activity maintains during operation. It can also disappear for some time and show up after a while, or the activity can extinguish in total. This kind of defects will be found during PD measurement when a higher voltage than the operating voltage is applied. In case of online measurement, only when already a surge has caused the PD initiation.

The last case is $V_i > \text{operating voltage}$ and $V_e > \text{operating voltage}$. During operation these PDs can be initiated when transient overvoltages occur and extinguish fast after couple of cycles of the operating frequency. Commonly these PDs are not harmful, but there is a probability that this PD activity can cause a tree in the insulation material that could maintain below operating voltage because of high electric field at the tips of trees. [11]

3 Partial discharges representation

Due to the fact that partial discharges are related to ageing of a cable, charge measurement of PDs is usefull. When a cable sample has an internal defect or a surface defect, a practical scheme can give a representation of the situation, like depicted in figure 3.1

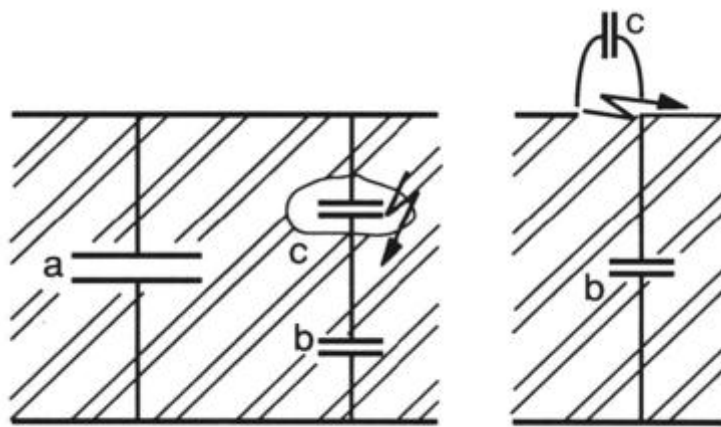


Figure 3.1: equivalent circuit for internal and surface discharges [14]

- a) Represents the sound part of insulation
- b) Represents dielectric in series with the gaseous capacitance c
- c) Represents a cavity or part of the surface that flashes over

Because there cannot be measured over the defect itself, we have to measure the charge displacement in the conductors to the sample. This is often done by putting a measuring impedance into the electric circuit to the sample. The measured charge is not the real charge displacement, the external charge displacement is measured.

$$q = b\Delta V \quad (3.1)$$

The real charge displacement in the defect is:

$$q_1 = c\Delta V \quad (3.2)$$

Where ΔV is the ΔV of figure 3.2.

Because in general capacitance $b \ll$ capacitance c , the PD pulse magnitude measured is far smaller than the real magnitude. The relation between the measured magnitude and the real magnitude is unknown, but there are two reasons why this method is used.

3 Partial discharges representation

The first reason is that the measured discharge magnitude in combination with the inception voltage can be related with a reasonable approximation to the energy dissipated during a discharge. For the derivation of this relation we use the model of figure 3.2.

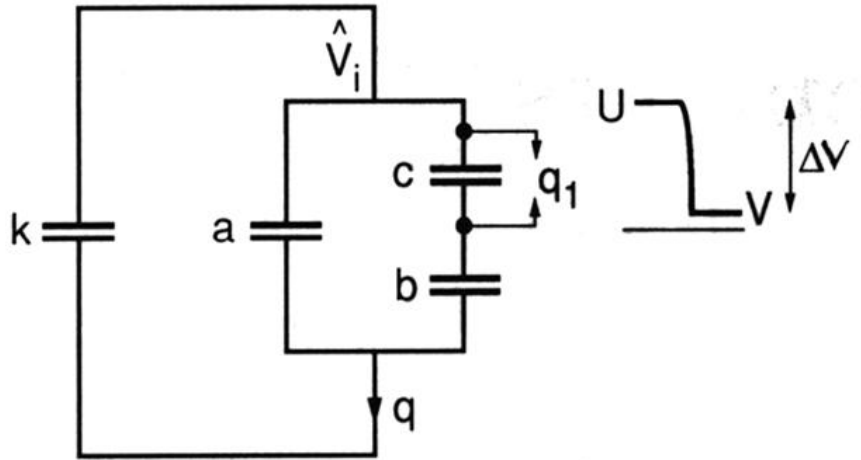


Figure 3.2: Model with components playing a role in charge displacement during PD [14]

a Represents the sound part of insulation

b Represents dielectric in series with the gaseous capacitance c

c Represents a cavity or part of the surface that flashes over

Vi Represents the instantaneous PD inception voltage of the cavity

U Represents the voltage across the cavity before a discharge of c

ΔV Represents the voltage drop over c caused by a discharge

When PD occurs, some charge is displaced from capacitor c to b. The following points give information over the voltage over b and c and the displaced charge.

- When a discharge occurs, the voltage across c drops with ΔV
- Due to that, the voltage across b increases with ΔV and the voltage over c becomes V
- The charge displacement to b is given by $q = b\Delta V$

The energy dissipated during a discharge can be related to the charge in the following way:

- Before discharge, the energy stored at c is $\frac{1}{2}cU^2$
- After discharge, the energy stored at c is $\frac{1}{2}cV^2$

The dissipated energy becomes

$$p = \frac{1}{2}cU^2 - \frac{1}{2}cV^2 = \frac{1}{2}c(U^2 - V^2) = \frac{1}{2}c(U - V)(U + V) = \frac{1}{2}c\Delta V(U + V) \quad (3.3)$$

Now we are making an error in order of 10% by taking $(U + V) = U$

Because usually $b \ll c$

$$U = \frac{b}{b+c}Vi \approx \frac{b}{c}Vi \quad (3.4)$$

3 Partial discharges representation

Making the assumption $b \ll c$ compensates more or less the error of $(U+V)=U$.

The dissipated energy becomes:

$$p \approx \frac{1}{2} b \Delta V V_i = \frac{1}{2} q V_i$$

Cables with the same nominal voltage have about the same inception voltage and the same discharge magnitudes are comparable. [14]

The measured charge is also related to the volume of the discharge. Figure 3.3 gives a representation of dimension parameters of a piece insulation material with a discharging cavity. Now we use figure 3.3 and derive the relationship between the volume of the discharge area and the measured charge displacement q .

$$q = b \Delta V$$
$$b \approx \epsilon_0 \epsilon_r \frac{S}{d}$$
$$q \approx \epsilon_0 \epsilon_r \frac{S \Delta V}{d}$$

When ΔV increases with L , and q increases with $S \Delta V$, q rises with the volume of the discharge.

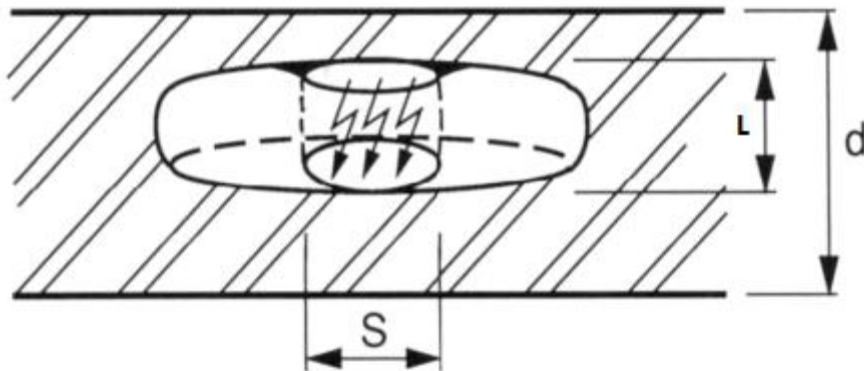


Figure 3.3: Dimension parameters of a piece insulation material with a discharging cavity [14]

Because q is related to the energy dissipated during a discharge and the volume of the discharge area, it is a good measure for PD.

4 Propagation properties of PD pulses in power cables

4.1 Introduction

When a PD pulse propagates through a coaxial MV cable, the PD pulse changes of shape, caused by attenuation and dispersion. Non destructive electrical PD measurements in cables is always performed at the end of the cable. PD pulses in MV cables often have to travel a significant distance before arriving at the measuring system. For PD measurement in cables, it is useful to have an idea what happens with a PD pulse that propagates through the cable. Therefore this chapter gives an insight about what happens with the PD signal during propagation through the cable and what happens with the pulse at the end of the cable.

4.2 Pulse propagation properties

A cable can be modelled by a circuit of many sections of inductors in series, with between each inductor section a capacitance in parallel. A model is shown in figure 4.1

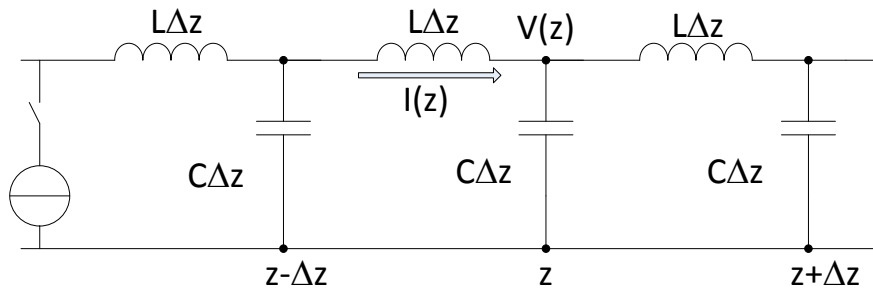


Figure 4.1: A simple model of an MV cable

After closing the switch in figure 4.1 it takes a while before the voltage arrives at the other side of the cable. The applied voltage causes a current through the first inductor and this current charges the first capacitance. When the capacitances get charged, the voltage rises and causes a current through the next inductor that charges the next capacitance. This process takes some time.

The current through the cable is equal to the differential of the charge with respect to the time:

$$i = \frac{dq}{dt} = \lim_{\Delta t \rightarrow 0} Cu \frac{\Delta z}{\Delta t} = Cu \frac{dz}{dt} = Cuv \quad (4.1)$$

The voltage induced between the conductor and earth screen at t_0 and x_0 is:

$$emf = \frac{d\phi}{dt} = \lim_{\Delta t \rightarrow 0} Li \frac{\Delta z}{\Delta t} = Li \frac{dz}{dt} = LCuv^2 \quad (4.2)$$

4 Propagation properties of PD pulses in power cables

We know that the induced voltage at t_0 and x_0 equals the source voltage. Therefore the travelling speed has to be equal to:

$$v = \frac{1}{\sqrt{LC}} \quad (4.3)$$

So when a PD pulse is injected in a cable, the travelling velocity of the pulse is equal to equation 4.3. Equations that describe propagation of electrical signals through the coaxial cable are the telegraph equations. These are treated in chapter 4.2.1.

4.2.1 The telegraph equations

The propagation of pulses through a cable is described by the telegraph equations. To get a more realistic model of a MV cable, the model of figure 4.1 is modified. During propagating through a cable, attenuation of the pulse signal arises, caused by the resistivity of the conductor and by leakage between the two conductors. Figure 4.2 gives a model for this. The ohmic losses dissipated in the conductor are represented by resistor R [Ωm] and the leakage current is caused by conductance G [$S m$]. The figure gives a representation an infinitely small lines section Δz .

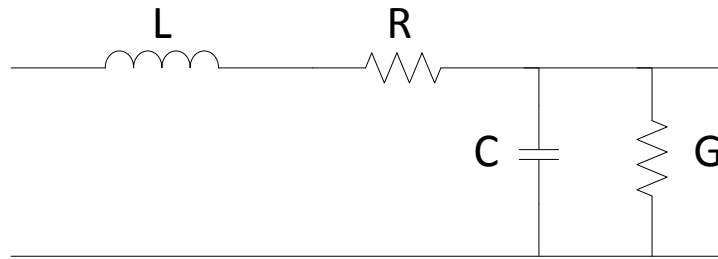


Figure 4.2: Model of a MV cable section with loss factors

Now we are going to have a look at the Telegraph equations to get insight of the behaviour of the pulse during propagation. For deriving the telegraph equations, Kirchhoff's laws are used in combination with the model of figure 4.2.

$$I(z, t) = -C\Delta z \frac{\partial V(z, t)}{\partial t} - G\Delta z V(z, t) - I(z + \Delta z, t) \quad (4.4)$$

$$I(z, t) + I(z + \Delta z, t) = -C\Delta z \frac{\partial V(z, t)}{\partial t} - G\Delta z V(z, t) \quad (4.5)$$

Taking $\lim_{\Delta z \rightarrow 0}$ gives:

$$\frac{\partial I(z, t)}{\partial z} = -C \frac{\partial V(z, t)}{\partial t} - GV(z, t) \quad (4.6)$$

$$V(z, t) = -L\Delta z \frac{\partial I(z, t)}{\partial t} - R\Delta z I(z, t) - V(z + \Delta z, t) \quad (4.7)$$

$$V(z, t) + V(z + \Delta z, t) = -L\Delta z \frac{\partial I(z, t)}{\partial t} - R\Delta z I(z, t) \quad (4.8)$$

4 Propagation properties of PD pulses in power cables

Taking $\lim_{\Delta z \rightarrow 0}$ gives:

$$\frac{\partial V(z,t)}{\partial z} = -L \frac{\partial I(z,t)}{\partial t} - RI(z,t) \quad (4.9)$$

Where

L [H/m]

R [Ω /m]

C [F/m]

G [Siemens/m]

The minus sign for decreasing of $i(z,t)$ and $u(z,t)$ during propagation in positive direction. To solve these equations 4.6 and 4.9, Laplace is needed. We go from the time domain to the frequency domain and we take $\frac{\partial}{\partial t} = p$.

$$- \frac{\partial V(z,p)}{\partial z} = (R + pL)i(z,p) \quad (4.10)$$

$$- \frac{\partial I(z,p)}{\partial z} = (G + pC)V(z,p) \quad (4.11)$$

$$- \frac{\partial^2 V(z,p)}{\partial z^2} = (R + pL) \frac{\partial I(z,p)}{\partial z} = (R + pL)(G + pC)V(z,p) = Z'Y'V(z,p) = \gamma^2 V(z,p) \quad (4.12)$$

$$- \frac{\partial^2 I(z,p)}{\partial z^2} = (G + pC) \frac{\partial V(z,p)}{\partial z} = (G + pC)(R + pL)I(z,p) = Y'Z'I(z,p) = \gamma^2 I(z,p) \quad (4.13)$$

$$V(z,t) = e^{\gamma z} f_1(t) + e^{-\gamma z} f_2(t) \quad (4.14)$$

$$I(z,t) = \frac{1}{Z_c} (e^{\gamma z} f_1(t) - e^{-\gamma z} f_2(t)) \quad (4.15)$$

$$\gamma = \sqrt{(R + pL)(G + pC)} \quad (4.16)$$

When taking for $p = j\omega$, propagation coefficient γ becomes like equation 4.17.

$$\gamma = \alpha + j\beta = \sqrt{(j\omega L)(j\omega C)} \sqrt{\left(1 + \frac{R}{j\omega L}\right) \left(1 + \frac{G}{j\omega C}\right)} \quad (4.17)$$

When the losses are small γ can be approximated by equation 4.16.

$$\gamma = j\omega\sqrt{LC} \left(1 - j \left(\frac{R}{2\omega L} + \frac{G}{2\omega C}\right)\right) \quad (4.18)$$

$$\alpha = \omega\sqrt{LC} \left(\frac{R}{2\omega L} + \frac{G}{2\omega C}\right) = \frac{1}{2}\sqrt{LC} \left(\frac{R}{L} + \frac{G}{C}\right) \quad (4.19)$$

$$\beta = j\omega\sqrt{LC} \quad (4.20)$$

And the velocity of the pulse is equal to equation 4.21.

$$v = \frac{\omega}{\beta} = \frac{1}{\sqrt{LC}} \quad (4.21)$$

Equation 4.19 shows that the attenuation constant α is independent of frequency. The same is displayed in equation 4.21 for the phase velocity. This means that the signal shape does not change during propagation and that the cable is distortionless.

In real, the attenuation constant for PD pulses in a cable is not independent of frequency. Some frequencies will attenuate more during propagation than others; especially high frequencies face large attenuation in MV cables. Next to attenuation, there occurs dispersion. In the next subchapter there is treated attenuation and dispersion using the model of figure 4.5 and there is shown some information about frequency related attenuation and dispersion.

4.2.2 Attenuation and dispersion

As already discussed in the previous chapter, during propagation of a pulse through a cable, there occurs attenuation and distortion. Distortion causes change in pulse shape, but also attenuation causes this. Figure 4.3 shows measured reflections of a calibrator pulse travelling through a MV cable. The pulse is reflected against very large characteristic impedance, therefore it is fully reflected at the ends of the cable. It shows that the pulse shape changes a lot during propagation.

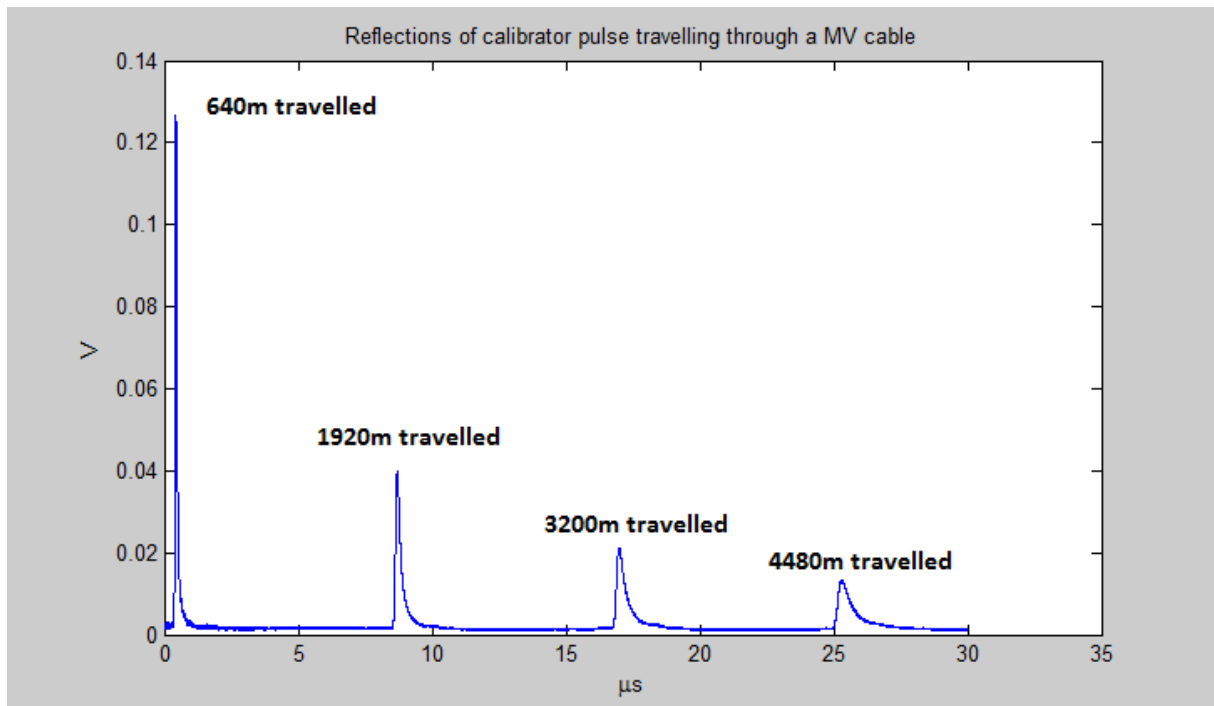


Figure 4.3: Reflections of a calibrator pulse travelling through a cable.

To analyse the cause of distortion and attenuation, we consider a little more advanced model than used before. Figure 4.4 shows the cross-section of a XLPE cable. From inside to outside there is depicted the aluminium conductor, the inner semiconductor the XLPE insulation, the outer semiconductor screen, the outer-outer semiconductor screen, the copper conductors and the PVC sheath. This cable is modelled by figure 4.5, where the semiconductor layers are shown as the conductor shield and ground shield. We take this model into account for further analysis.

4 Propagation properties of PD pulses in power cables

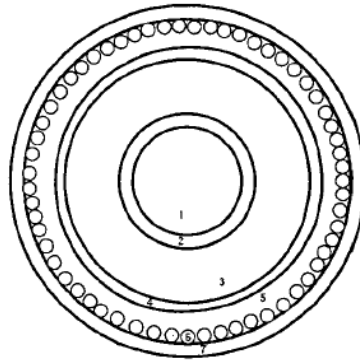


Figure 4.4: Cross-section of a MV cable

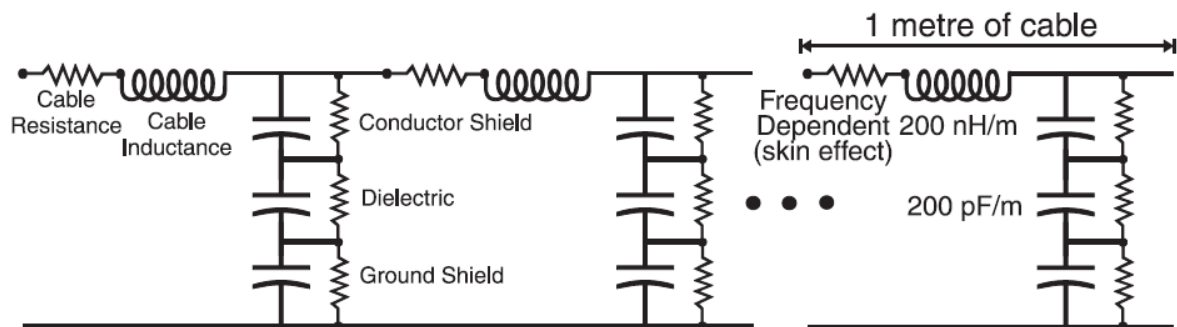


Figure 4.5: Model of a MV cable section depicted in figure 4.4 [27]

Attenuation of the PD pulse can be caused by conductor losses as skin effect, but also by losses in the insulation material

As we look at the total losses in a MV cable, models and measurements in [16] show that the frequencies above 100kHz are far more attenuated than below. These results are depicted in figure 4.6.

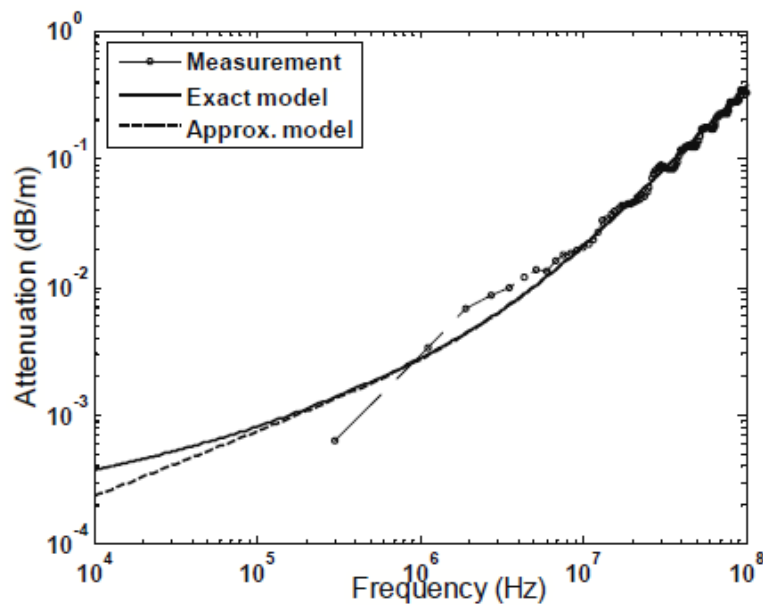


Figure 4.6: Attenuation of an XLPE cable [16]

References [16] shows that the attenuation in XLPE cables of the frequency range below 10MHz is mainly caused by losses in conductors as skin effect, figure 4.7. This attenuation rises with the square root of the frequency. The higher frequency attenuation is mainly caused by the dielectric system. Reference [27] shows that for PILC cables the attenuation of the frequency range below 1MHz is mainly caused by the skin effect. Paper insulated cables have a much larger $\tan\delta$ [14] than XLPE cables. Figure 4.7 shows the contributions of attenuation caused by conductor losses and dielectric losses of an XLPE cable.

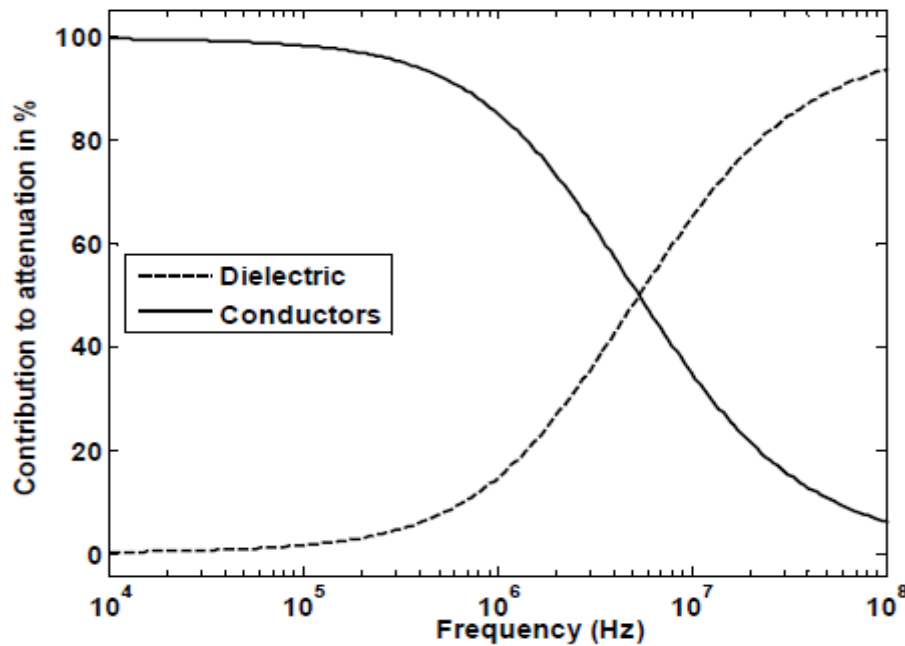


Figure 4.7: Attenuation contribution of dielectric and conductor of an XLPE cable [16]

Dispersion is caused by the difference between the group velocity of all the frequencies of the pulse and the phase velocity of each frequency. The propagation velocity is approximated by $\frac{1}{\sqrt{LC}}$. The variation of the capacitance between the conductor and the copper sheath takes care for almost the entire dispersion below 100MHz. The little inductance variation caused by the skin effect has only a small effect.[20] With increasing frequency, the semiconductor layers transform from ohmic to capacitive. This leads to a total capacitance between conductor and ground that is decreasing with frequency. As a consequence of this, the velocity for higher frequencies increases with frequency. This different velocities cause phase shift in the frequency spectrum during propagation. Therefore the pulse is distorted and the shape in the time domain is modified. [20]

When the electric and magnetic field distribution between the conductor and the neutral conductor are analysed, based on the semiconductor properties, it is shown that variation in velocity over the frequency spectrum occurs in the region the semi-conducting layers changes from resistive stage to the capacitive stage. Outside this region the velocity is nearly constant, but different in the high frequency region and in the low one. Therefore dispersion has only a significant influence in the regions of two decades of frequency with the centre frequency of equation 4.22

4 Propagation properties of PD pulses in power cables

$$\omega = \frac{\sigma(\omega)}{\varepsilon(\omega)} \quad (4.22)$$

With

$\sigma(\omega)$ The conductivity of the semiconducting layer as a function of frequency

$\varepsilon(\omega)$ The permittivity of the semiconducting layer as a function of frequency

In reference [19] there is given a realistic example of dispersion in an XLPE cable. It is shown that dispersion occurs in the MHz regions.

A question that rises is what happens in the time domain with a pulse that is influenced by attenuation and distortion and what is the amount of these two factors in practice.

Reference [20] shows that dispersion causes a shorter rise time than fall time of a PD pulse, the pulse is made more asymmetric. Attenuation causes the strong decrease in amplitude. Where dispersion causes more asymmetry in the pulse, attenuation of high frequencies cause a decrease in amplitude, and therefore a widening of the pulse.

This attenuation causes an increase of rise time that is larger than the fall time is increased by dispersion. The high frequency energy is spread in time as a result of dispersion [20], but this has not a significant influence on the amplitude of the pulse that is decreased by attenuation.

In short, the strong attenuation of high frequencies neglects the influence of dispersion on a PD pulse. Therefore the pulse becomes more symmetric. Measuring differences between arrival times by counting difference in peak times become less accurate. This has negative consequences for localization. [20]

In chapter 4.2.4 there is done an experiment to check how a calibrator pulse evolves over travelled distance. But first, the next chapter gives some basic information about the characteristic impedance that can be useful for measuring PD.

4.2.3 Characteristic impedance and reflection of PD pulses

The relation between voltage and current of a pulse, for every infinite small point of the cable is determined by the per section capacitance and inductance of the cable. This relationship between voltage and current at a single point in the cable is called the characteristic impedance.

When using the model of figure 4.1 and equation 4.1 and we substitute the velocity v by equation 4.3, equation 4.23 is obtained and gives the characteristic impedance.

$$Z_c = \frac{v}{I} = \sqrt{\frac{L}{C}} \quad (4.23)$$

This corresponds to a distortionless lossless line that is not a real case, but to explain the basics of pulse propagation, this model is very useful. For PD measurement in cables, it is important to know something about the characteristic impedance. During propagation of a PD pulse in a cable, it faces a constant environment, the characteristic impedance is constant. But in case the PD pulse reaches a joint, the propagation environment shows differences with the Z_c of the cable. The capacitance and inductance differ and therefore the relation between voltage and current will differ also. In case an end termination is reached, the characteristic impedance is even zero (in case of short circuited

termination) or infinite (open end termination). Short circuited terminations are not used in high voltage measurements.

When the PD pulse travels in forward direction and reaches a different medium, the characteristic impedance changes and the relation between voltage and current becomes different. A piece of the pulse is reflected into the backward direction and a piece is transmitted in the forward direction. The pulse is split in two parts. When two cables with different characteristic impedances are connected, voltage and current are continuous at the interface. Because there is reflected a part of the pulse, there can be made the conclusion that the reflected pulse plus the incoming pulse is equal to the transmitted pulse.

The voltage waves are described by:

$$Vi(x, t) + Vr(x, t) = Vt(x, t) \quad (4.24)$$

The current waves are described by:

$$\frac{Vi(x, t)}{Z1} - \frac{Vr(x, t)}{Z1} = \frac{Vt(x, t)}{Z2} \quad (4.25)$$

$$Vr(x, t) = \frac{Z2-Z1}{Z2+Z1} Vi(x, t) \quad (4.26)$$

$$Ir(x, t) = \frac{Z1-Z2}{Z2+Z1} Ii(x, t) \quad (4.27)$$

When a PD pulse arrives at the open end of a cable, $Z2$ is infinite. When measurement is performed at the end of the cable, $Vr(x, t) = Vi(x, t)$ and there is measured the incoming and reflected voltage at the end termination. Therefore the measured voltage is twice the incoming voltage.

After generation of a PD, half of the charge travels to one half of the cable and the other half travels to the other side. Half of the pulse charge is arriving at the end of the cable, but there is measured the correct signal because of the voltage doubling at the very high measuring impedance at the end of the cable.

In case calibrating at the measurement side, the first pulse is measured at correct amplitude. When system calibration is performed at the opposite open end of the cable, the injected pulse travels to the measuring system with a very high impedance and there is measured twice the original incoming signal. This has to be taken into account.

Furthermore when a cable is measured with one or more joints, there can be measured reflections of PD signals that are reflected against joints.

4.2.4 Evaluation of a calibrator pulse through a MV cable

Now we are going to evaluate the frequency spectrum of a calibrator pulse propagating through a cable, the pulse sequence 506 of appendix C. The pulse is injected at one side of the MV cable. At the opposite side, the reflections are measured. There are measured 4 reflections, with travelled distances starting at 640m and with an addition of 1280m for every reflection.

4 Propagation properties of PD pulses in power cables

The time domain records and the cumulative charge are plotted in figure 4.8. It is shown that the amplitude of the pulse decreases fast, while the charge is not decreasing that fast. The pulse becomes wider, therefore the charge, that is proportional to the area beneath the pulse, is not attenuating as much as the amplitude.

By evaluation of the frequency spectrum of the pulse that propagates through the cable, the cause of the rapidly decrease of the pulse amplitude can be discovered. The frequency spectrum of the recorded pulses is calculated by the FFT function in Matlab, the results are shown in figure 4.9.

Figure 4.9 shows that the high frequencies attenuate very fast. This causes the fast decrease in amplitude of the time signal of the pulse. When making a link to PD measurement, it can

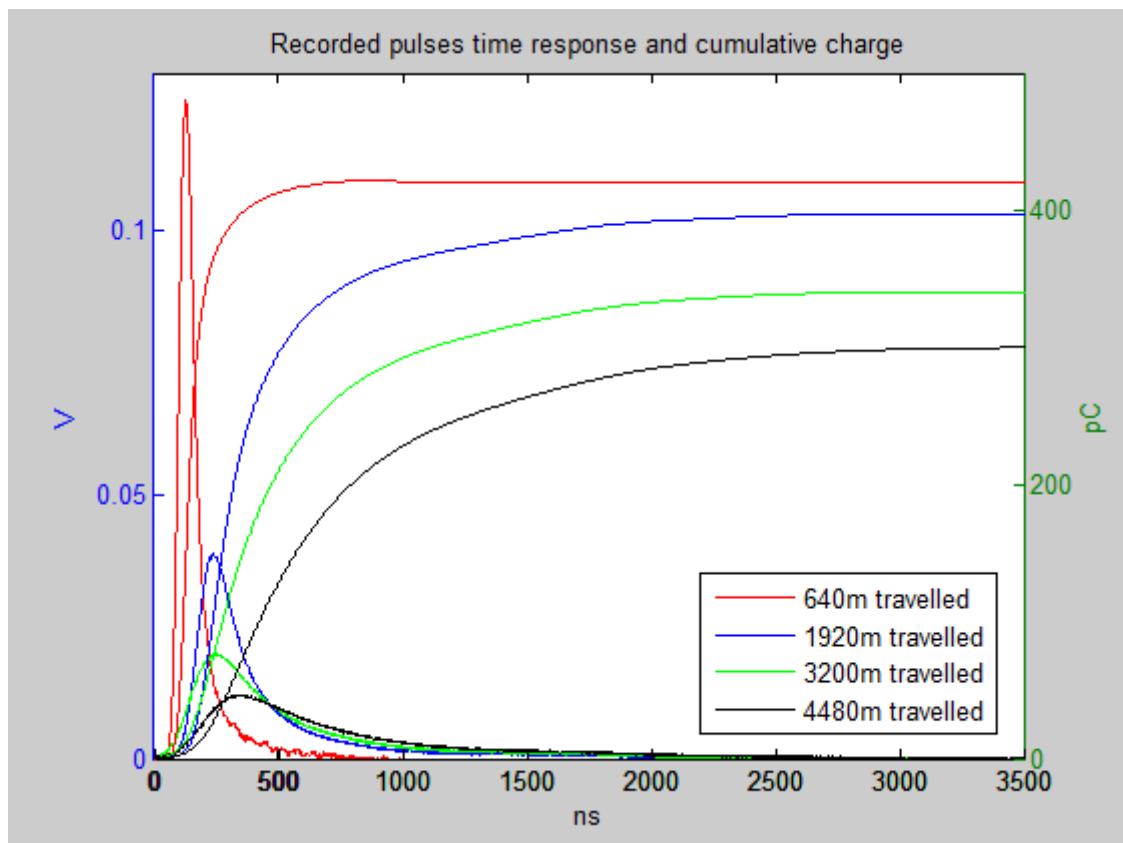


Figure 4.8: Measured different reflections of calibrator pulse and their integral

be said that using a band pass filter with a low high cutoff frequency, loses sensitivity. This is the case especially for smaller pulses that have left a significant high frequency content. In chapter 6 it is investigated the influence of the cutoff frequencies on the pulse in time domain.

For measurement of PD pulses that have travelled some km through a cable, it is probably less useful to use a system with a high low cutoff frequency of some hundreds of kHz, because there is probably filtered away a lot of information.

This chapter gives an insight of the properties of a PD pulse after travelling through a cable. It gives an idea of the frequency range that can be measured. More information about the influence of filters on the PD pulse is shown in chapter 6.

4 Propagation properties of PD pulses in power cables

Figure 4.9 shows that the high frequency content is attenuated much more than the frequencies of about below 100kHz. When zoomed in a little more, the cable seems to behave like a low pass filter. It displays that the frequency spectrum below about 40kHz is staying flat, these frequencies seem to attenuate with the same factor during propagation of the pulse through the cable.

Because the charge is not attenuated as much as the amplitude of the pulse and the fact that the low frequency regions attenuate also not that much during propagation, rises some interest in investigation whether there is a relation between the charge and the low frequencies of the pulse.

The charge of the pulse obtained with the measured voltage signal is:

$$q = \frac{1}{2} \frac{T}{Z_c} \sum_{n=1}^N x[n] \quad (4.27)$$

Where

$X[n]$ = a sample with index n of the measured voltage signal

T = time between two samples = $1/\text{sample rate}$

Z_c is the characteristic impedance of the cable

When calculating the frequency spectrum of the measured signal, the discrete the Fast Fourier Transform is used. This frequency spectrum will be:

$$X[k] = \sum_{n=0}^N x[n] e^{-\frac{j2\pi(k-1)(n-1)}{N}} \quad 1 \leq k \leq N \quad (4.28)$$

The calculation of the frequency spectrum value for $\omega=0$, corresponds always to the first calculated value of the spectrum. In this case it corresponds to $X[1]$ in equation 4.28. When calculating this value, equation 4.29 results.

$$X[1] = \sum_{n=1}^N x[n] \quad (4.29)$$

When scaling this by the factor $\frac{1}{2} \frac{T}{Z_c}$, equation 4.30 is obtained.

$$X[1] = \frac{1}{2} \frac{T}{Z_c} \sum_{n=1}^N x[n] \quad (4.30)$$

This is the same as equation 4.27 and therefore, the charge is obtained with the DC value of the frequency spectrum.

Figure 4.10 shows the frequency responses, scaled by factor $\frac{1}{2} \frac{T}{Z_c}$, and the cumulative charge of pulse set 506 of appendix C. As displayed, the DC value of the frequency spectrum equals the highest value of the cumulative charge. Also the lower frequencies, close to the DC value have about the same magnitude. Therefore it can be said that they attenuate more or less with the charge. In chapter 6.4 there is written more about this topic.

4 Propagation properties of PD pulses in power cables

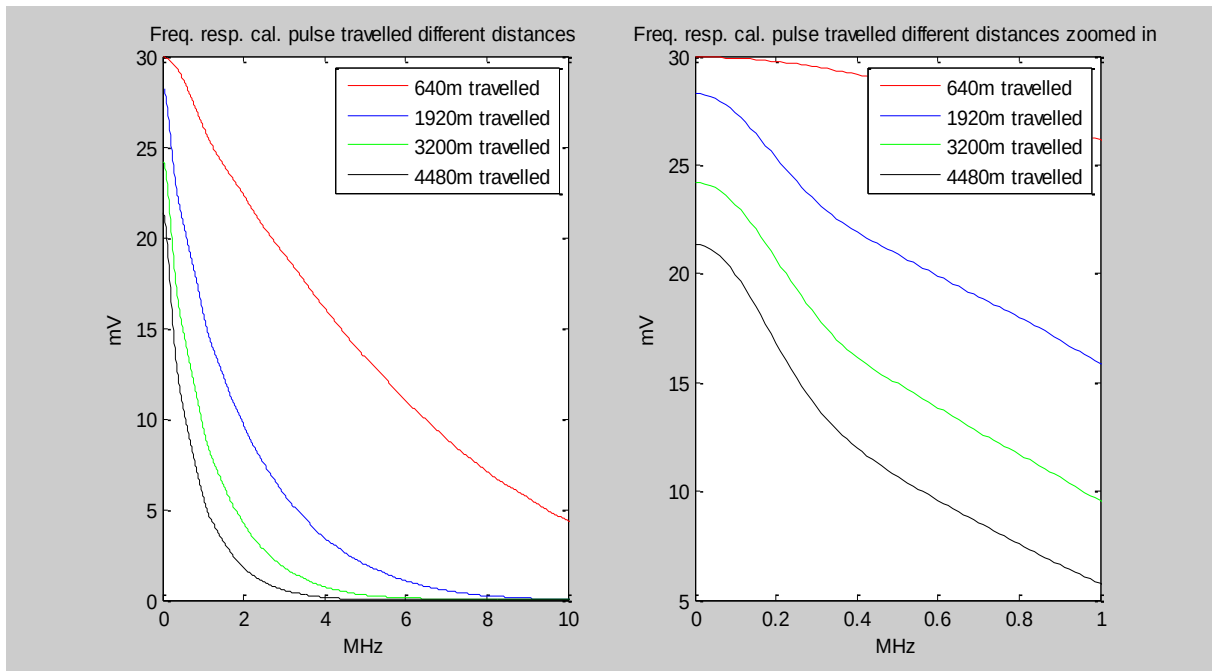


Figure 4.9: Frequency spectrum of recorded pulses of figure 4.7

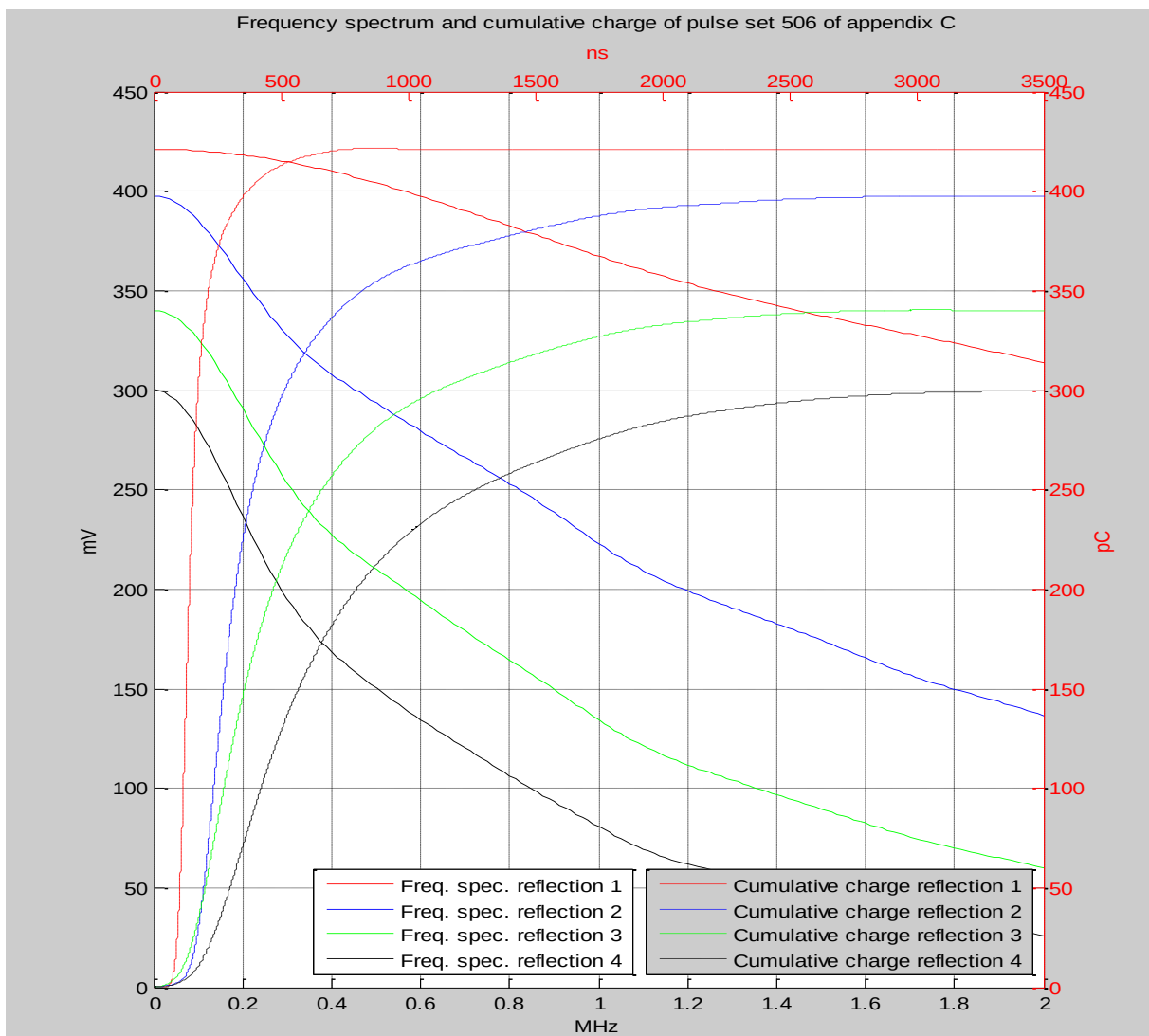


Figure 4.10: Frequency spectrum and cumulative charge of pulse set 506 of appendix C

4.3 Conclusion

During propagation the shape and the amplitude of a PD pulse change. Knowledge about these changing properties, this could help to select a useful sensor for a PD measuring system.

When a PD pulse travels through a MV cable, attenuation and dispersion occur. Attenuation causes a decrease of the amplitude of the pulse. Dispersion causes an asymmetry in the shape of the pulse. This causes the smaller rise time than fall time.

Dispersion occurs in the MHz regions. In practice, the high frequency content of a PD pulse travelling through a MV cable is attenuated relatively fast. Next to the rapidly decreasing amplitude, the pulse becomes wider in time. Because the MHz frequency regions attenuate rapidly, dispersion plays only a very little role in the shape change of the pulse.

During an experiment with a calibrator pulse in a real MV cable, it turned out that indeed the high frequencies attenuate very fast. This causes a fast decrease in amplitude of the pulse. Therefore measuring, especially steep PD pulses, with a band pass sensor with a low high cutoff frequency decreases the sensitivity a lot.

Usage of a system with a high low cutoff frequency causes measurement losses of useful information about the PD pulse. Therefore these systems are not recommended.

When looking at frequency spectrum of a PD pulse travelling through a MV cable, the lower frequencies of tens of kHz attenuate much less than the higher frequencies. The cable seems to act like a low pass filter. The lower frequencies seem to attenuate proportional with the integral of an UWB pulse, so proportional to the charge. The value proportional to the charge of a pulse can be derived from the DC value of the frequency spectrum. Frequencies close to the DC frequency, have about the same magnitude as the frequency spectrum magnitude at DC. Therefore it can be said that the lower frequencies attenuated more or less proportional to the charge.

5 Commercial available PD cable testing technologies

5.1 Introduction

In this chapter available PD testing technologies are presented and studied. For the measurement of partial discharges there is a standard specified, IEC60270. So measurements can be performed according to this standard (conventional measurement) or not (unconventional measurement). Next to this, the distinction can be made between PD measurement when the cable is in operation (online measurement) and PD measurement when the cable is offline (offline measurement). Also there are different sources to energize the test object. Finally a distinction between used sensors and PD localization methods is made. First offline measurement is considered and afterwards online measurement.

5.2 Off-line measurement

5.2.1 Introduction

Offline measurement of PDs requires an uncoupled and de-energized power cable, an external power supply and a measuring circuit. Several kinds of voltage signals can be applied to energize the cable. The selection of a source depends on several parameters. It makes a real difference if you are measuring in the field or in the laboratory. While measuring in a laboratory has almost no restrictions, measuring in the field is more complex. In the field power requirements play a large role. Also weight, size and time to install of the measurement system play a role.

Cables' capacitance increase with the length of the cable. When 50Hz voltage is applied to energize a long cable, the large capacitance of the cable requires a large reactive power at operating voltage. In case there is used only a 50Hz power supply to energize the cable, a very big power supply is required. Therefore other methods are developed to energize the cable.

Next to the different developed sources there are systems with different sensors, with different bandwidths on the market.

In these chapters we will compare different kind of PD measurement systems that are available on the market. There are given answers to questions like:

- Are these measuring methods accepted in the IEC60270 standard?
- Does this method cause the same stress in the cable as under operating voltage?
- What is the maximum load I can energize?
- How long will it take to make the setup ready?
- Which volume and weight takes the measurement system and is it easy to transport?

5.2.2 Sources for energizing the power cable during PD measurement

Applied voltage sources should initiate PD in defects of the cable that should also occur during normal operation. It is important that the applied voltage is not larger than necessary to avoid extra damage to the cable. Therefore the source should be able to supply a variable voltage.

When we look at the practical side of the source, it is preferable that the source is transportable to make measuring at different sites possible.

In this chapter we treat next to normal operation frequency, three other commonly used methods:

- VLF (Very low frequency)
- Resonant systems (with variable inductance or variable frequency)
- DAC (Damped AC systems)

Normal operation frequency

Application of 50Hz voltage brings the advantage that these PD measurements are directly comparable with PDs that occur during operation and PD initiated during a routine test.

VLF (Very low frequency)

The reactive power demand of a cable is linear proportional to the frequency. To avoid the need for a large power supply, VLF uses a very low frequency. VLF technique applies an AC signal with a frequency of 0.01Hz – 1Hz with a voltage between one and two times the rated cable voltage for a time less than 10minutes. There 0,1Hz is the most commonly used frequency.[10]

VLF systems are available on the market in complete measurement systems, but there are also units available with only a power source. During measurement with a complete system, all the information such as magnitude, phase and location of the recorded PDs are saved in a folder on the measuring device.

The measured magnitude and the PD pattern can be comparable or totally different from measurements at 50Hz voltage. Testing cables with VLF may, depending on the defect, requires a higher voltage to get the same PD level as at operating frequency. With lower frequencies, the charge at the cavity wall has a longer time to leak away. Therefore the contribution of the deposited charge on the surface of a cavity wall is less, and there is needed a higher inception voltage.[11] The decay time of charge deposited at the surface of a cavity is highly dependent on the conductivity of the surface of the cavity. The difference in decay time of deposited charge between virgin cavities and aged cavities can vary from 1ms – 1000s. This wide time range causes the difference in PD behaviour.

Reference [10] shows that the development of electrical trees that show PD activity is larger at VLF than at operation frequency. When the tree is initiated at VLF, there is a higher probability on failure. There is no evidence that VLF has a lower initiation voltage for trees.

Practical usage of the VLF equipment

There are different types of VLF equipment. There are complete measuring systems, but only VLF sources are also available.

Sources are available from 28kV – 200kV [30]. The longer the cable the more powerful the source has to be. Figure 5.1 shows VLF devices of different voltage classes and table 5.1 shows some properties of different orders of VLF devices.

Table 5.1: Properties of Different VLF voltage sources [30]

VLF systems			
Peak voltage	28kV	50kV	200kV
Load capacitance	0.4 μ F	5 μ F	0.75 μ F
Frequency	0.1Hz	0.1Hz	0.1Hz
Weight	34kg	9kg + 73kg + 98kg In case 352kg	About 2000kg
Size	Wxdxh = 38x29x56cm	Wxdxh = 43x280x24cm +51x36x69cm +38x46x56cm On wheels76x152x130	155cm w x 93 cm d x220cm h + 61 x 65 x 180
Duty	continuous	Continuous	continuous
Power supply	230V 50/60Hz	230V 50/60Hz	230V single phase
Transported by	By hand	On wheels	Car trailer



Figure 5.1: Different sizes VLF systems [30]

Advantages and disadvantages of VLF technique

Advantages:

- VLF is easy to install
- VLF for MV cables is easy to transport because of size and weight
- VLF can power long cables
- VLF can power continuously
- There can be measured up to high voltages (200kV)

Disadvantages:

- Partial discharge test data may not be directly comparable with power frequency data.
- Growth rate of electrical trees can be higher than at operating frequency

5.2.3 Resonant systems

Resonant power supply systems make resonance circuits in combination with the test object and the rest of the capacitances and inductances in the circuit. Figure 5.2 shows that the system consist of a power supply, an exciter transformer to regulate the voltage, an inductance, a capacitive voltage divider to measure PD's and the test object (cable, represented as capacitance). Resonance is created when the sum of the reactive impedances in the network is zero, but in practice it is not always possible to reach total resonance. In this case the inductance is only partially compensating the capacitance of the cable. When equation 5.1 is satisfied, there is created total resonance and equation 5.2 shows the resonance frequency.

$$X_L = j\omega L = X_C = \frac{1}{j\omega C} \quad (5.1)$$

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (5.2)$$

During resonance condition, the power supply has to supply only power according to the losses of the circuit. These are losses in the wire of the inductor, the $\tan\delta$ losses and the iron losses in the inductor. It depends on the cable and system components, but the losses are around 0.5 – 2%.

To implement a resonance power supply system there are two options:

- Making use of a variable inductance
- Making use of a variable voltage frequency

[4]

Creating resonance with a variable inductance is an inductance tuned resonance system (ACRL). This option influences the inductive impedance of the circuit in such a way that when equation 5.1 is satisfied, resonance is formed. Because of the variability of the inductance value, the operating voltage frequency can be fixed. This has a big advantage when measurement is performed in the lab. There is no variable frequency power supply required and the 50Hz grid voltage can be applied. The load range that can be energized is calculated with equation 5.3.

$$\frac{C_{max}}{C_{min}} = \left(\frac{L_{max}}{L_{min}} \right)^2 \quad (5.3)$$

5 Commercial available PD cable testing technologies

Applying a fixed inductance is the other option. To satisfy equation 5.1 with a fixed inductance, the frequency have to be changed. This frequency tuned circuit is also called an ACRF. In figure 5.2, a schematic diagram of an ACRF system is shown.

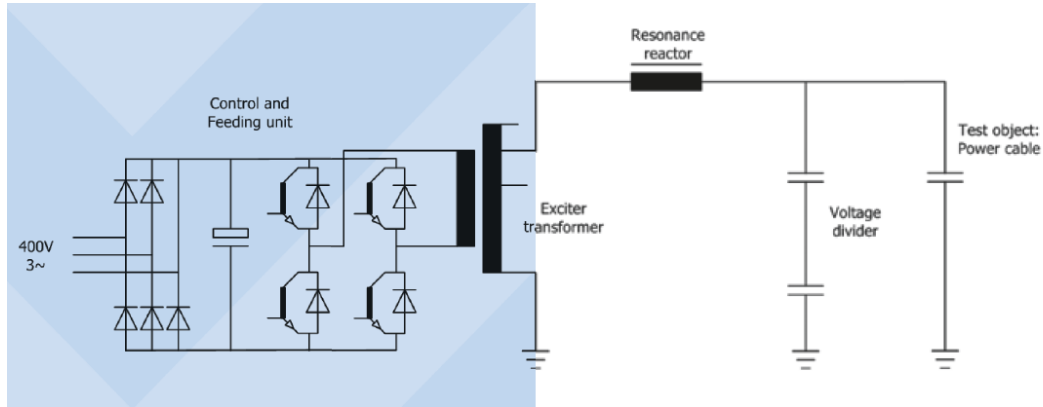


Figure 5.2: Scheme of an ACRF system [33]

For testing very long cables and for testing in the field, ACRF is more suitable than ACRL. Equation 5.4 determines the minimum and maximum frequency that can be measured with ACRF:

$$\frac{C_{max}}{C_{min}} = \left(\frac{f_{max}}{f_{min}} \right)^2 \quad (5.4)$$

Frequencies that are recommended to be applied lie between the 20Hz – 300Hz IEC60270=> (IEC60060-1). Furthermore, the resonant system causes about the 50Hz stress when it operates in the frequency range of 20Hz-300Hz. A system is desired as light as possible. Therefore the source transformer and the inductor have to be as light as possible.

The power supplied by the source that feeds the test circuit is

$$P = 2\pi f_{min} C U^2 \quad (5.5)$$

Equation 5.5 shows, that the source frequency is proportional to the supplied power. Therefore a low supply frequency, causes a low supplied power and requirement of a small source. But in case of low frequency appliance, the iron circuit of the inductance has to be bigger than at higher frequencies, to avoid saturation.

As already mentioned, there is a bandwidth commonly accepted for PDs measurement with a resonance system: 20-300Hz. The upper frequency of 300Hz is determined by, the increasing hysteresis losses and skin effect losses in the inductor and transformer when the frequency is raised further. Therefore it is disadvantageous to apply a higher frequency than 300Hz. [21]

The minimum frequency is determined by the max weight to power ratio, the ratio between the weight (m) of a system and the equivalent test power (P50).

$$r = \frac{m}{P_{50}} \quad (5.6)$$

The maximum power that is required for a specific test at a specific frequency is determined by

$$P_{max} = 2\pi f_{min} C_{max} U^2 \quad (5.7)$$

5 Commercial available PD cable testing technologies

The equivalent power becomes

$$P_{50} = \frac{50\text{Hz}}{f_{min}} P_{max} \quad (5.8)$$

The surface of the iron circuit of the transformer and inductance has to be enlarged to avoid saturation if a low frequency voltage is applied. According to P_{max} , if the frequency decreases, P_{max} decreases also. In contradiction to this, the weight of the system goes up. Applying frequencies below 20Hz, the increase of weight is no longer compensated by the reduction of power and the weight to power ratio increases. Therefore, there should not be applied a frequency lower than 20Hz.

When comparing the ACRF with an ACRL system, the weight to power ratio of an ACRL is about three to five times higher than of an ACRF system.

The power quality of the system is also an important value for selection of parameters of the resonance system. The power quality is the ratio between the test power and the required power to cover the ohmic losses in the circuit, and depends on the frequency.[21] Usage of a fixed inductor generates lower losses than usage of a variable inductance. From this point of view it is recommended to use a fixed inductor. The fixed inductor has a Q factor that is more than twice of Q factor of a variable inductance. A disadvantage using a variable frequency is the generation of noise by the frequency converter.

$$Q = \frac{P_{test}}{\text{Ohmic losses}} \quad (5.9)$$

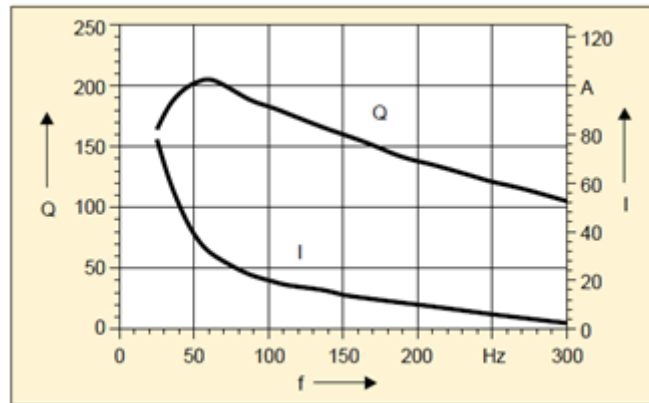


Figure 5.3: Quality factors and load current depending on test frequency [21]

Figure 5.3 shows that for lower frequencies the current, and so the power, decreases, but the power factor stays sufficiently. In this case, to generate 100MVA test power with a feeding power of 100kVA.

Usage of resonant systems for PD measurement brings the advantage that the PD level measured, is well comparable with measurements at 50Hz frequency. PD level measured above 200Hz is slightly lower than measured at power frequency at the same voltage.[3]

Table 5.2 gives an overview of the difference between ACRL and ACRF.

Table 5.2: Comparison of ACRL and ACRF systems [15]

Resonant circuit	ACRL (inductance-tuned)	ACRF (frequency-tuned)
Frequency	50 Hz	20..300Hz
Max test power	$S_{Lmax} = 2\pi fCU^2$	$S_{fmax} = 2.5 * S_{Lmax}$
Quality factor	$q = 40..60$	$q = 80..>120$
Load range	$C_{max}/C_{min} = L_{min}/L_{max} = 20$	$C_{max}/C_{min} = (f_{max}/f_{min})^2 = 225$
Feeding power	$P_{eL} = (2\pi fCU^2) q$	$P_{ef} = P_{eL} * (f_f / f_L) * (q_L / q_f)$
Power supply	Single or two phase	Three phase
Weigth to power ratio	3..8 kg/kVA	0.8 ... 1.5 kg/kVA
Components with moving parts	Tuneable reactor regulator transformer	None
Noise of the source	None	Yes

Practical usage of a resonant system

With a resonance system, very long cables can be energized at high voltages. For long cables, there can be put more units into parallel. A disadvantage of a resonance system in comparison to other methods is the large, heavy and very less easy to transport equipment. For measurement of a 150kV cable, the equipment has a weight of about 30 tons.[21] A truck is needed for transport, see figure 5.5. The equipment can also be fitted in a container; therefore it is possible to ship it easily. For medium voltage equipment a heavy van can fulfil, but the equipment cannot be moved by hand out of the van toward the test object because it is still very heavy (see figure 5.4). To get an idea of the performances of the systems table 5.3 shows some properties of resonant systems of different classes.



Figure 5.4: Small resonance test system [15]

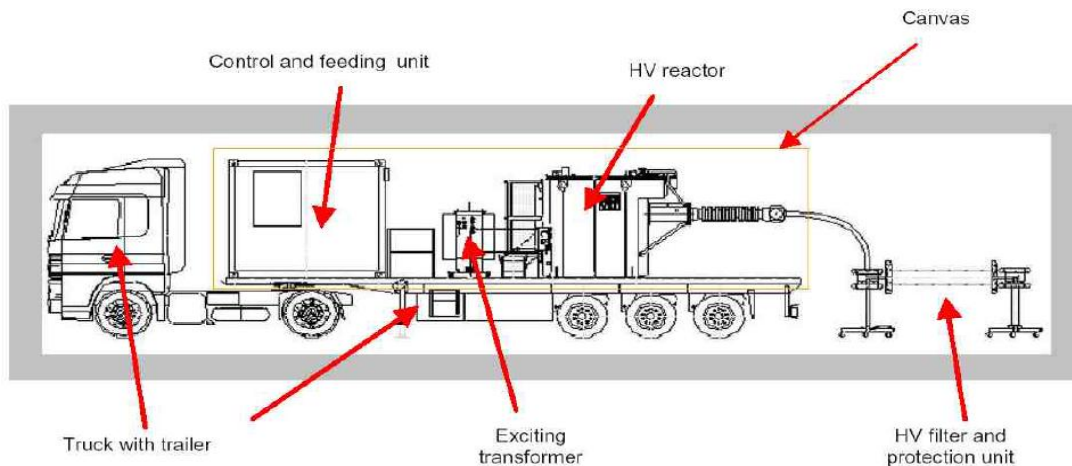


Figure 5.5: ACRF test system for HV and EHV cable system testing on a trailer [15]

Table 5.3: Properties of resonant test systems [33]

Resonant systems			
Peak voltage	55kV	100kV	220kV/400kV
Load capacitance	1.5 μ F	At 25kV: 25Hz:15 μ F 300Hz:1 μ F At 100kV: 25Hz: 0.93 μ F 300Hz: 0.006 μ F	At 220kV: 25Hz:4.6 μ F 200Hz:0.09 μ F At 400kV: 25Hz: 1.1 μ F 200Hz: 0.02 μ F
Frequency	50Hz (fixed)	25Hz – 300 Hz	25Hz - 200Hz
Weight	Heavy	Heavy	Really heavy
Transported by	Small truck / container truck	Small truck / container truck	Big truck

Sometimes it is not possible with the heavy load to get in the direct vicinity of the test object. The high voltage wire, supported by insulator posts, has to bridge some tens of meters. Therefore the line must be secured by a safety loop with warning lamps and emergency switches, or there can be used special flexible emergency cables. [21]

For operation of an ACRF system it includes a control unit with a PLC and with an operator display that shows the measured values for voltage, current and frequency. Next to this, a laptop and software can be connected to the system to give more comfort to the control. With this software more important parameters, like test voltage, test current, frequency, inverter pulse width and temperature of the inductor, can be displayed than on the operating screen. At the same moment software can store all these parameters in time base of every second.

With high voltage filters as a blocking impedance, a measuring capacitance and a coupling capacitance, a sensitivity of <10pC can be reached.[21] However, the sensitivity is also depending on the environmental noise.

Advantages and disadvantages of resonant system technique

Advantages:

- Compared with 50Hz/60Hz the method uses less power
- Measured PD level is comparable with measurements at power frequency
- Resonant systems can energize long cables
- Resonant systems can power up to 400kV

Disadvantages:

- The equipment is very heavy compared with other systems
- For transport of HV equipment a truck is needed or for MV a heavy van

5.2.4 Damped AC voltage

Principal

A damped AC voltage source is also especially developed for energizing power cables in the field. Energizing power cables for PD measurement with DAC, can be done with a low power source. Figure 5.7 gives a schematic diagram of an OWTS system. Figure 5.7 shows that DAC systems require an HVDC source, a fixed inductance with air core and low losses, a semiconductor switch with a very short closing time and a cable as test object.

The cable is energized by a ramp DC voltage source, in few seconds to normal operating voltage (see figure 5.6). In this way, the HVDC source can energize the cable slowly with a low current. The charge time depends on the load and the maximum applied voltage, see equation 5.10. When the peak voltage is reached, the switch is closed and the test object is discharged into the inductor, see figure 5.7. There is formed a network that consists of the inductance L, the capacitance of the cable and the resistance of the circuit that generates a damped oscillating voltage. The frequency of the oscillation is determined by the resonance frequency of the circuit, equation 5.10.

$$t_{charge} = V_{max} * \frac{C_{cable}}{I_{load}} \quad (5.10)$$

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (5.11)$$

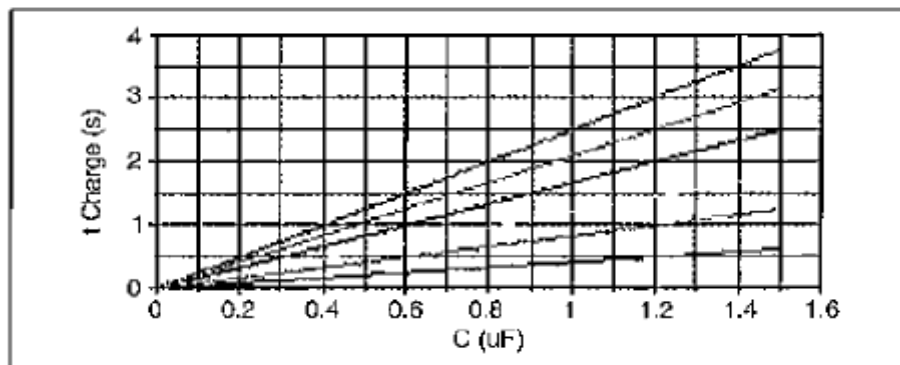


Figure 5.6: Charging of test object by DAC system [7]

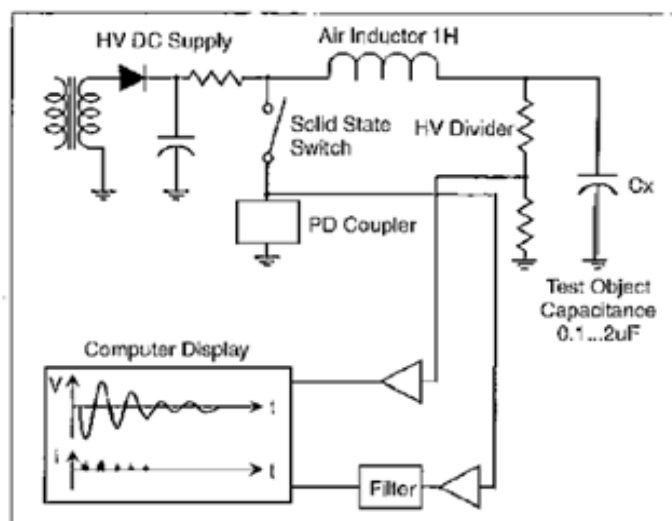


Figure 5.7: Schematic OWTS system [7]

The damping is determined by the losses in the circuit. In case there are low losses in the circuit, the damping is low.

As mentioned earlier, an advantage of DAC is the reduction of the power source. In comparison with resonant systems and 50Hz appliance, the DAC method uses hardly energy.

$$Uc(t) = U(1 - e^{-\frac{t}{\tau}}) \quad (5.12)$$

$$Ic(t) = \frac{U}{R_{total}} e^{-\frac{t}{\tau}} \quad (5.13) \quad \text{with } \tau = R_{total} * C$$

The energy that is used is:

Energy of dissipated on Resistor + energy stored in capacitor

$$= \int_0^t R_{total} * i^2(t) dt + \frac{CU^2}{2} \quad (5.14)$$

$$= \frac{CU^2}{2} + \frac{CU^2}{2} = CU^2 \quad (5.15)$$

For the charging time of the capacitor we take 3τ

When we take for $U = 12\text{kV}$ and for $C = 0.5\mu\text{F}$ (2km XLPE cable)

$$E = CU^2 = 0.5 * 10^{-6} * 12^2 * 10^3 = 72\text{W} \quad (5.16)$$

And when we take a high ohmic source of $2\text{M}\Omega$

$$\tau = 2 * 10^6 * 0.5 * 10^{-6} = 1\text{s} \quad (5.17)$$

The power for producing a DAC signal becomes:

$$P = \frac{E}{3\tau} = \frac{72}{3 * 1} = 24\text{W} \quad (5.18)$$

In case of applying 50Hz voltage to the sample, S becomes:

$$S = \omega C U^2 \quad (5.19)$$

$$= 2\pi 50 * 12000^2 * 0.5 * 10^{-6} = 23\text{kVA} \quad (5.20)$$

It can be seen that this makes a huge difference in power source.

DAC systems are available in types that have different frequency ranges. Ranges from 50Hz – 800Hz are used, but some devices can only measure in the range 20Hz – 350Hz.[33]. IEC60270 only considers AC voltages up to 400Hz, therefore measurement according to the standard should be performed within this frequency range. Furthermore reference[3] says that voltage frequencies above 200Hz generate a PD level that is slightly decreased compared with 50Hz measurements. This has to do with the starting electron mechanism. For creating an avalanche, there must be a starting electron. Virgin cavities have a much larger initiation delay time than aged cavities, because there is

less charge stored at cavity surface and the starting electron has to come from the gas in the cavity. Because of the delay time in initiation, the probability to initiate a PD in a virgin cavity at higher frequencies is less than at 50Hz. For aged cavities surface generation is active and at sufficient voltage, the delay time decreases exponentially. But when a too low voltage is applied delay time could be relative long. These facts lead in general to a lower PD magnitude at higher frequencies for dielectric bounded cavities.

A high frequency with a high damping coefficient causes a short time which fulfils the inception criteria, this is related to the number of shots needed.

Nevertheless, reference[6] asserts that DAC between 20Hz and 500Hz, combined with PD measurement is an effective way of on-site testing of all kinds of power cable systems, because similarity in PD occurrence measuring with DAC and at operation frequency.

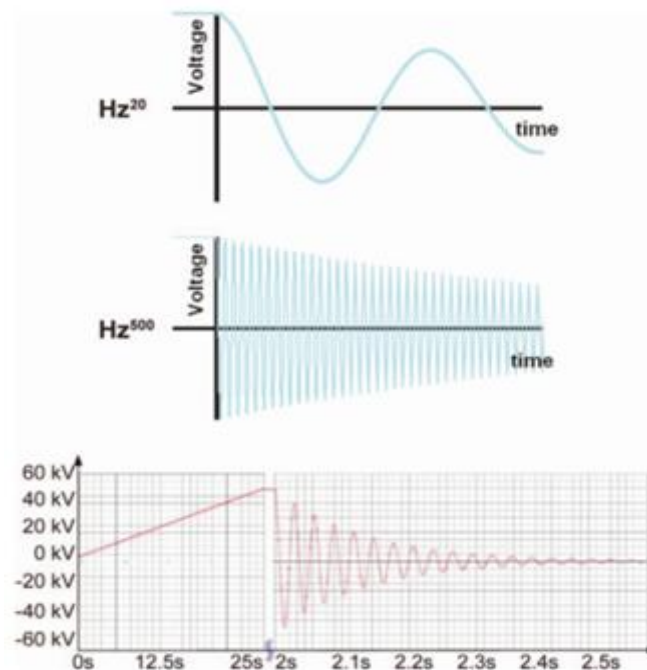


Figure 5.8: Decaying AC voltage produced by charging with a DC ramp voltage and discharging through an inductance [8]

Practical usage of the DAC equipment

Figure 5.9 shows that a DAC measuring unit is relative small. It consists of two units: one containing the inductance, the switch, the measuring capacitance and the measurement device; the other consists of the HVDC power supply and a computer with software to display and store the measurement results.

In comparison to the resonance system, that needs a truck for it, it is relatively light. These features make this measurement method very suitable for field testing. When the cable is disconnected and de-energized, preparing a PD test takes just a couple of minutes. With an OWTS (a DAC system), it is also possible to determine the location of the PD generating defects. In chapter 4.1.7 there is more about this. Figures 5.9 and 5.10 show DAC systems for different voltage classes and table 5.4 shows properties of different orders of DAC systems.

Table 5.4: Properties of DAC systems

DAC systems			
Peak voltage	28kV	60kV	250kV
Load capacitance	50Hz: 0.05 μ F 800Hz: 4 μ F	50Hz: 0.025 μ F 800Hz: 4 μ F	20Hz: 0.035 μ F 350Hz: 8 μ F
Frequency	50Hz – 800Hz	50Hz – 800Hz	20Hz – 350Hz
Weight	55kg	80kg	950kg
Size	Diameter: 60cm Height: 65cm	Diameter: 65cm Height: 97cm See figure 5.9	See figure 5.10
Duty	In shots	In shots	In shots
Power supply	110 – 240Vac 50-60Hz	110 – 240Vac 50-60Hz	
Transported by	Car, contains small wheels	a van	Heavy van / small truck



Figure 5.9: DAC system for 60kV peak [33]



Figure 5.10: DAC system for 250kV peak

Advantages and disadvantages of DAC technique

Advantages:

- Compared with 50Hz/60Hz the method uses almost no power
- Measured PD level is comparable with measurements at power frequency
- DAC systems can power up to 250kV
- The equipment can be transported easily

Disadvantages:

- Voltage appliance is not continuous

5.2.5 Sensors for offline measurement

To detect a PD signal, there are capacitive and inductive sensors. Each have their advantages and disadvantages.

Capacitive sensors consist of a coupling capacitor and measuring impedance (or coupling device). Figure 5.11 shows a typical setup for PD measurement with a capacitive sensor. For PD measurement in power cables the coupling capacitor in combination with the measuring impedance are tuned to create a band pass filter with a characteristic impedance very large compared with the characteristic impedance of the cable. Therefore the signal is reflected in total and there is measured twice the signal. This increases the sensitivity. For PD measurement according to the standard, the band pass is created according to IEC60270. Therefore their Bandwidths start at some tens of kHz and end at some MHz.

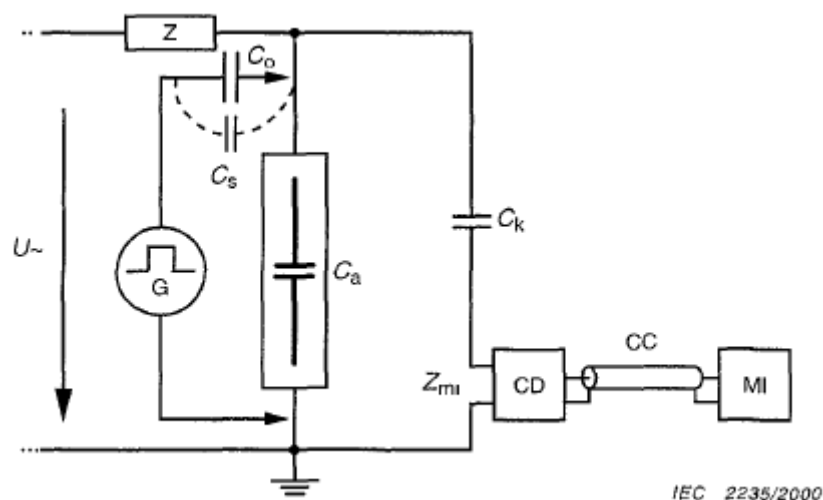


Figure 5.11: Basic scheme for discharge measurements [9]

For unconventional measurement can be tuned to other bandwidths. By filtering the lower frequencies out of the signal, the high voltage stands over the capacitor and the PDs are measured with the measuring impedance. An example of a measuring impedance is a little high frequency transformer or an L//C//R impedance. Capacitive sensors have high sensitivity compared with inductive sensors, but are not galvanic isolated from the test circuit.

Inductive sensors are galvanic isolated from the circuit and the risk for damage on the measuring equipment is lower than with capacitive sensors. The inductive sensor can be places around the

earth wire, in series with the measuring impedance. Measurement of a single cable for PD, inductive sensors are not usable at their own, because they measure current and at an open end there is no current flowing.

Inductive PD measuring sensors are high frequency current transformers. Figure 5.12 shows a high frequency current transformer. It shows that it is applied easily, the only thing that has to be done is to put the earth wire through the transformer.

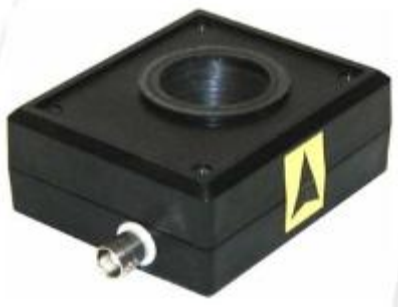


Figure 5.12: High frequency current transformer [34]

There are high frequency current transformers that can be used for measuring according to the standard with a bandwidth from 100kHz – 12MHz. The problem is that an inductive sensor with a low lower cutoff frequency, gives automatically a lower gain than HFCT's with a higher cutoff frequency [18]. More about this is described in Appendix B.

For unconventional measurement there are used different bandwidths by different manufacturers. This causes different responses. Therefore the results are not always well comparable with each other. Low cutoff frequencies used are in the range between 100kHz and 1MHz. High cutoff frequencies used reach into tens of MHz. More about bandwidths is described in chapter 6.3.

5.3 Localization of PD origin

If there are PDs measured which form a potential risk for the cable, it is very desirable to know the position of the PDs in the cable. When the location is known, the cable can be dug up at right location and can be repaired. For determining the location, we consider two methods:

- Time Domain Reflectometry
- Double-sided measurement

Time Domain Reflectometry

In case PD activity is generated in a power cable, two current pulses result. One travels to the beginning of the cable, the other to the end, each with half the magnitude. The length of the pulse depends on the discharge duration and the velocity of the pulse along the cable. The velocity of the pulse is determined by

5 Commercial available PD cable testing technologies

$$v = \frac{1}{\sqrt{LC}} \quad (5.21)$$

To get an idea of the pulse length, a pulse with a duration of 100ns and a velocity of 160m/ μ s (approach of common velocity in a MV cable) is 16 meters long.

At the end of the cable an impedance is placed to detect the PD. The first pulse travels directly to the measuring device and arrives at t_1 , the second reflects with coefficient 1 because of the open end of the cable and arrives some time later at t_2 (see figure 5.13). The position of the defect can be calculated with equations 5.22 – 5.24.

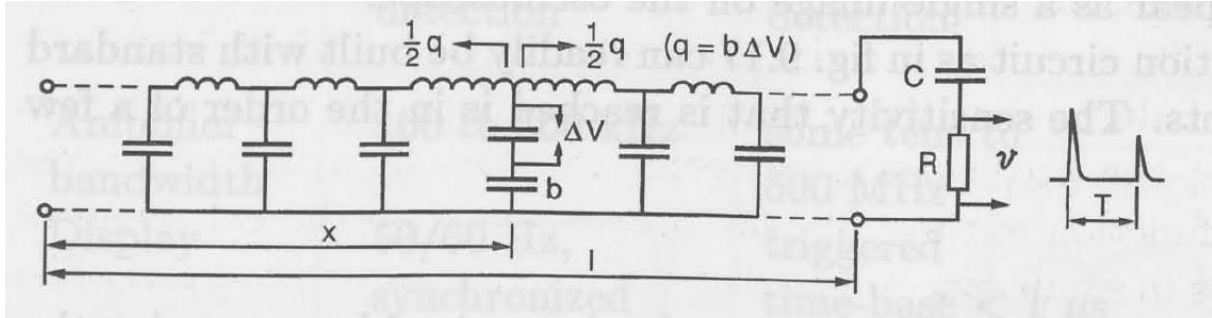


Figure 5.13: Localisation of PD origin by travelling waves [14]

$$t_1 = \frac{l-x}{v} \quad (5.22)$$

$$t_2 = \frac{l+x}{v} \quad (5.23)$$

With the difference in arrival times T , x becomes:

$$x = \frac{vT}{2} \quad (5.24)$$

The property that measurements can be taken at a single side of the cable, makes this method very suitable for determining location of PD's. When applying TDR it has to be taken into account that for longer cables than about 4km, depending on the noise, the attenuation is too large to detect PDs with low magnitude. During propagation along distances, high frequency components are attenuated. That cause a decrease in amplitude of the PD and the pulse becomes wider. Therefore, the arrival times are less precisely determined and the accuracy of the localisation of PD's decrease.

Double-sided measurement

At both ends of the cable PD pulses are measured. With this method the double cable length can be measured, about 8km. The principle of reflection at the open end of the cable is not used anymore, but synchronization of the measured signal has to be done. Because the reflection signals are not used, both pulses only have to travel from its origin to the end of the cable. There takes place a reduction of the travelling path. One pulse arrives at t_1 at cable end 1, the other arrives at t_2 at cable end 2.

To calculate the difference between the arrival times, the time base of the two measuring devices at the two ends must be very accurate aligned. An accuracy of 10-20m is preferable in practice. With a

common speed of about $160\text{m}/\mu\text{s}$ in cable, the time difference to reach an accuracy of 16m is 100ns. The alignment of the time base can be done in different ways:

- GPS
- Pulse injection

GPS

Satellites of the GPS system send information about place and time to earth. The time between the arrival times of information coming from different satellites, can be used for determining the position of the receiver on earth. It takes at least four satellites to determine the three location coordinates and the time, but more satellites increase the accuracy. A disadvantage is that the satellites have to be visible for the receiver, large buildings can distort the signal. Also there can be some small errors in the determination of the arrival times of the signals from different satellites. This lead to an error in the time and location. Furthermore the signal of the satellite travel through variations in atmosphere that also brings errors in arrival time.

Nevertheless in practice the accuracy is still high and is behind the limit of 100ns. To gain more accuracy, DGPS can be used. This makes use of a reference receiver at a known place. Because the known position of the reference receiver, the time errors can be calculated. DGPS has an accuracy of 5-20ns (about 1-5m)

Pulse injection principle

For pulse injection pulse sensor / injections units (SIU) are needed. When a pulse is injected at one side of the cable, it can be measured at the other side of the cable. When the other SIU receives the pulse, it immediately sends a pulse back. [25]. The travelling time of the pulse through the cable can be gained out of the arrival time of the pulse at end 1 and injection time. When the travel time of the pulse is known, the time bases of the two units can be aligned. The cable is used for transmission of the information, in this way the system is not influenced by factors from outside. Furthermore the accuracy is even higher than GPS and the used equipment is less expensive.

5.4 On-line measurements

5.4.1 Introduction

Online PD measurement is a very useful tool for condition based maintenance. The first advantage is, that in theory, the cable doesn't have to go offline. The cable is measured during operation, so loads can stay connected and the energy transport through the cable can continue during measurements. This has a great advantage in case redundancy is not available. In practice it is not allowed to place a sensor at some position around a conductor or earth wire when the cable is still in service, but installing the sensor takes a very short time.

Because the cable is measured online, the measurement is sort of continuous. In comparison with offline measurement there is made a 'movie' instead of a snapshot of the PD activity. Because online PD measurement systems can measure full time for days [31], developing of the PD activity in time can be measured, and trend watching is possible. In this way condition based maintenance can be applied more accurate.

During online PD measurement only PD is measured initiated by the operating voltage. This brings the same stress as during operation. This has advantages and disadvantages. When the cable is taken offline for installation of the sensor, PDs that have initiation voltage above operating voltage will not initiate before a transient overvoltage has reached the cable. On the other side, PDs with initiation voltage and extinction voltage both above the operating voltage are not triggered and these defects will not develop.

Because online PD measurement doesn't require an external source, equipment is small and handsome.

5.4.2 Principle

Online PD measurement systems can measure at one single point or at both ends of a cable.

Single point measurement

Measurement systems that measure at a single point makes use of TDR to locate the origin of the PD in the cable. This method of localization is described in chapter 5.3. For long cables, or cables with high PD signal attenuation, there could be used a transponder. This transponder is placed at the remote end of the cable. When the pulse half of the that is travelling to the remote end arrives at the transponder, the transponder injects a large pulse that is travelling to the beginning of the cable. In this way, the time difference between the otherwise small reflected pulse is measured properly.

Double side measurement

In case there is measured at two sides of the cable, the system makes use of two measurement units, each at an end of the cable. Thereby the time bases are aligned by GPS time signal or by the pulse injection method (see chapter 5.3). Figure 5.14 shows a simplified scheme of system that measures at two sides of the cable. Because online measurement systems can be placed in a substation or in a ring main unit (RMU), they are exposed to lots of noise and interference signals, often with amplitudes larger than the PD signals. Therefore the triggering of the measuring hardware cannot be implemented simply. During monitoring not every PD has to be measured. The target is to give a representative view of the cable condition. When real time monitoring is applied, huge data processing capacity is needed. To give a representative view of the PD's in the cable and to reduce the amount of data, only cycles of 30ms are measured. The measuring units get a trigger signal from GPS or a synchronisation pulse from the cable that is higher than the rest of the signals. The time of recording data depends on the power frequency of the cable. The 50Hz grid has a period of 20ms; therefore time to record data is 30ms including the trigger pulse and the analysed data block.

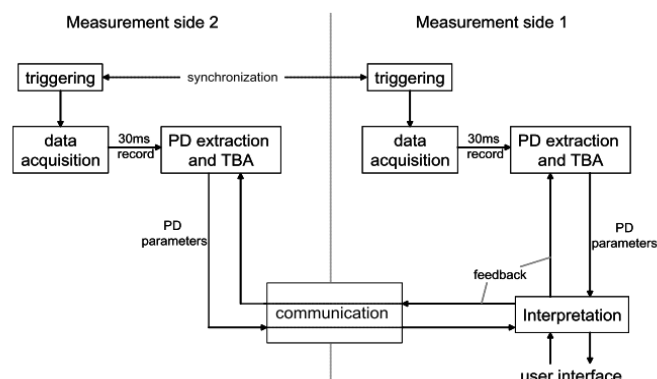


Figure 5.14: Simplified scheme of an online PD measurement system [26]

5 Commercial available PD cable testing technologies

PDs are filtered out of the data blocks, to reduce the data stream to the interpretation unit. A communication via TCP/IP link is set up between the data acquisition devices and an interpretation unit. The results are combined, interpreted and it is done some PD analysis. Invalid PD's are rejected and the valid PD's are kept. The results are stored and displayed at a computer with a user interface.

5.4.3 Equipment

Hardware

The equipment of a single point measurement system can be simpler than equipment of a multiple point measurement system. This is because there doesn't have to be synchronization between two measurement units. Equipment could consist of a high current transformer, and an advanced oscilloscope with a large bandwidth of some hundreds of MHz and specially made PD measurement software.

Figure 5.15 shows a scheme of hardware components of a measurement device that measures at two sides of the cable. The sensors are high frequency current transformers, clamped around earth wire or insulated cable in a RMU or substation. From the sensor, the measured values are amplified and go to a data acquisition card in the computer. The PC in the control unit does some analysis of the data. Further the system has a GPS receiver for synchronization of time bases and a pulse generator to align time bases.

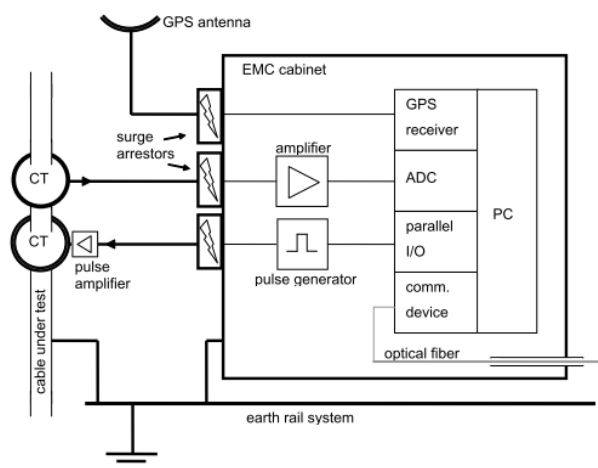


Figure 5.15: Hardware of one measurement setup [26]

Sensors and filters

For PD measurement at two sides of the cable, there are required two devices to measure PDs, one at each side of the cable. Each of these two measurement units makes use of a sensor/injection unit (SIU). The unit can measure PD pulses as well as inject a pulse into the cable. The sensors are high frequency current transformers and injection coils, that can be clamped easily around the earth wire or around the insulated conductor. In this way the system can stay online while assembling the setup. Next to this practical advantage, safety has also to be considered. There is no galvanic connection between sensor and conductor; therefore it is very difficult for high voltage to reach the control equipment.

Used split core current transformers have bandwidths that start around 100kHz and end at tens of MHz. The filter in the control unit strongly filters the 50Hz power frequency out of the signal.

For PD measurement at a single location, HFCTs can also be used. Commercial systems also use HFCTs with bandwidths starting at about 100kHz until about 25MHz. Next to these filters, there can be added extra filters in noisy environments. There are high pass filters with a low cutoff frequency of 100kHz and low pass filters with a cutoff frequency of 70MHz. There can also be applied filters in the software.

PD analysis

When the waveform of the PDs is known, matched filtering can be applied. It causes a maximum SNR. To determine the desired transfer function of the filter, the frequency spectrum of the PD signal and the frequency spectrum of the noise have to be determined. The signal first meets a whitening filter that determines the noise spectrum out of present and previous data. Also a notch filter is applied to filter narrow band radio broadcast signals. For the determination of the PD spectrum, the transfer function of the sensor is needed and the load impedance of the RMU. After spectrum determination, a matched filter bank can be applied. Any other filter than the matched filter gives a lower output signal.

To analyse the data of the records, the time bases have to be aligned to compare the data with each other. As already mentioned synchronization of the time bases of the two measurement devices can be done by GPS, or by pulse injection. The pulse generator and injection coil inject pulses with very a very high accuracy to 30ms in between. If we combine the pulse propagation time with the arrival times of the accurate synchronization pulses, the time bases of the two can be aligned. Of the interval between two reference pulses, a 50Hz period is used for PD extraction. A central computer downloads the data from the measuring units and combines this data by finding pairs of pulses that satisfy the condition:

$$|t_{arrival\ end2} - t_{arrival\ end1}| < t_{travelling} \quad (5.25)$$

In this way signals from outside are skipped.

Also the polarity of the measured pulse can be used to determine whether the pulse is from inside or outside the cable.

For single point measurement, distinction between measured polarity cannot be used to determine where the pulse is coming from.

The polarity of the PD pulse can cause a positive or negative measured pulse at the HFCT. Next to that, also the direction the pulse is coming from can cause a different measured polarity. Because only current is measured, determination of the direction of the energy flow by use of the poynting vector cannot be used. Pulses that have their origin inside a substation, have commonly other shapes than a pulse that has travelled through a cable. This property is used to determine whether the pulse is coming from the cable or not.

Practical usage of the online measuring system

Online PD measurement devices just have the size of a modern oscilloscope and weights less than 10kg, so it is very easy to handle. It requires a supply voltage of 90-264V AC. Online PD measurement is used successfully from 3.3kV up to 750kV [31]. To assemble a measuring setup, it takes about 5-10 minutes.

5.5 Summary and conclusions

Now we have considered online and offline measurement methods. Their principles, equipment and their practical usage. An overview of the most important parameters of the energizing sources are shown in table 5. Every system has its advantages and/or disadvantage at different subjects.

For measuring, capacitive and inductive sensors are used. Capacitive sensors have a higher sensitivity, but inductive sensors are galvanic separated of the test object. Furthermore inductive sensors with a low lower cutoff frequency have a lower gain within their bandwidths than HFCTs with a higher low cutoff frequency.

For localization of the defect in a cable, TDR can be used. Also measurement at double side of the cable can be applied. This doubles the maximum length that can be measured, but the method requires synchronization of the measured signals.

When comparing online with offline measurement, a significant difference is the possibility of trend watching of PD activity. With online measurement it is not possible to detect all the defects in the test object. Therefore use of online and offline methods could be useful when it is desired to create a complete picture of the defects in the cable.

5 Commercial available PD cable testing technologies

Table 5.5: Global comparison of PD measurement voltage sources

Properties of Cable energizing methods	Stress compared with service stress	Most important difference with 50Hz/60Hz	Voltage range used	Load capacitance	Duty	IEC60270 compatible	Weight and volume	transportability	Suitability field measurement
50/60Hz AC	Identical	No difference	MV and HV	small compared with other sources	continuous	Yes	Large and heavy comparing with the other methods	No transport possible	Not suitable
VLF	Different	Very low frequency, higher inception voltage. Deposited charge at cavity walls has more time to leak away	28kV – 200kV peak	Several km	continuous	Yes	Small	Even HV units can be transported in a van	Very handy
Damped AC with OWTS	Very similar	Damped voltage. Energizing shots, large amount of shots needed. Because short duration of shots, virgin cavities are probably not detected, but also not activated	28kV – 250kV peak	Several km	In shots with damping of the signal	Yes, in case frequency < 400Hz	Small	Even HV units can be transported in a van	Very handy
Resonant system	Close to 50Hz	When frequency is kept below 200Hz, there is no big difference	55kV – 400kV	Several km	continuous	Yes	Large and heavy comparing with the other methods	For MV a heavy van is needed to transport, for HV a truck	More difficult to transport and to position next to object, so less suitable
Online	Identical	Only transient overvoltages can initiate PD with V_i above operating voltage. PD with V_i and V_e above operating voltage are probably not initiated	3.3kV -750kV cables	As long as the cable is	continuous	Yes	Small	Non applicable	Very easy to install

6 Partial discharge measurements, conventional and unconventional

6.1 Introduction

When comparing different PD measurement methods, it can be remarked that there are systems that measure according to the IEC60270 (conventional way of measuring), but that there are also systems that do not measure according to the standard. In this chapter we explain conventional and unconventional measurements and we investigate why measuring according to the IEC standard is not always suitable for PD measurement in cables. An explanation is given why unconventional measurement is needed. We can make a distinction between two types of PD measurements.

- Conventional (this is according to the standard for partial discharges IEC60270)
- Unconventional (not following the IEC60270 standard)

6.2 Conventional measurement

6.2.1 Introduction

This chapter describes how conventional PD measurement works. Next to this, it gives insight into conditions for measuring according to the standard, compares different settings within the prescribed margins of the standard and shows the limits of this method for measurement of PD in MV cables.

6.2.2 Standard

The IEC 60270 standard is an international standard for measuring Partial Discharges. PD's that occur in electrical components, devices or systems when tested with alternating voltages up to 400 Hz or with direct voltage.

This standard

- defines the terms used;
- defines the quantities to be measured;
- describes test and measuring circuits which may be used;
- defines analogue and digital measuring methods required for common applications;
- specifies methods for calibration and requirements of instruments used for calibration;
- gives guidance on test procedures;
- gives some assistance concerning the discrimination of partial discharges from external interference.

The terminology, definitions, basic test circuits and procedures often also apply to tests with other frequencies, but special test procedures and measuring system characteristics, which are not considered in this standard, may also be required.[9]

6.2.3 Description conventional PD measurement

The procedure of conventional PD measurement is shown in figure 6.1. A typical measurement setup is shown in figure 5.11. From right to left there is shown the high voltage supply with blocking inductance (filter) to block discharges of the supply into the measurement system. The High voltage source with filter supplies voltage to the test object, depicted as a capacitor (for example a cable). Parallel to this, in series, is placed a filter consisting of a coupling capacitor and a measuring impedance. This filter takes care for filtering the power frequency and its harmonics. The sensor, or measuring impedance, measures the input PD current pulse and transforms it into an output voltage.

After measuring the PD pulse, the signal is filtered with specifications according to the IEC60270 standard. Figure 6.2 shows that a very small piece of the total frequency spectrum of a PD pulse passes the IEC filter. Therefore, the time response output signal of the filter has a totally different shape than the original PD pulse.

The charge is determined by the fact that the peak value of the output signal is proportional to the charge. By means of a calibrator that injects a known charge, the system can be calibrated. After calibration, the system can be used for charge determination of PD pulses with different magnitudes.



Figure 6.1: Process of conventional PD measurement

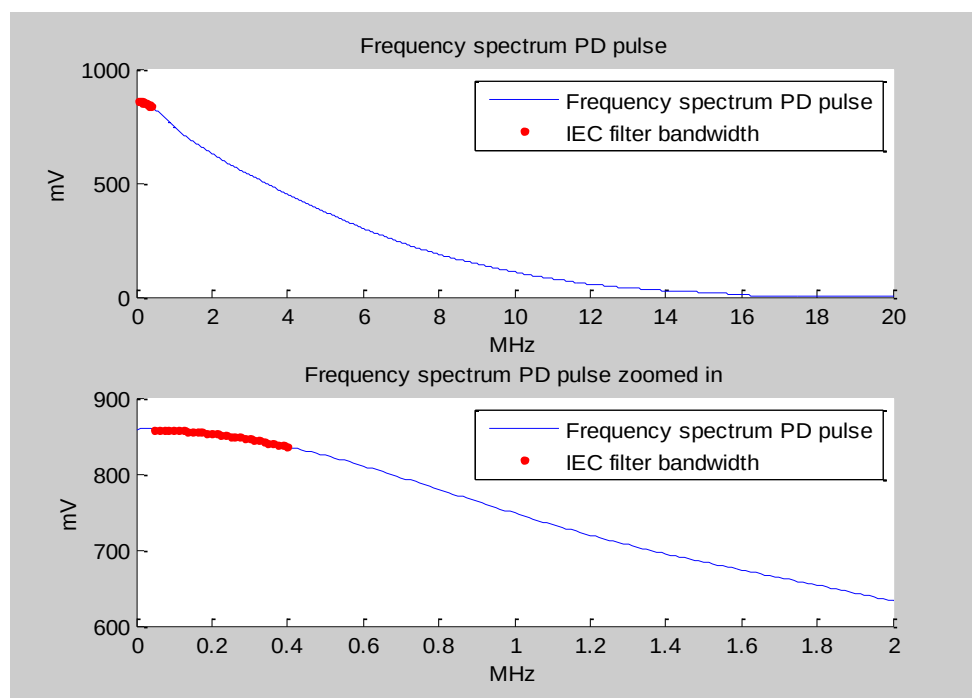


Figure 6.2: Frequency spectrum of a calibrator pulse and the IEC bandwidth 30kHz-400kHz

6.2.4 Prescriptions of the IEC60270 standard for measuring PD

This chapter handles the most important things that have to be fulfilled to measure PD according to the standard.

Coupling device

The measuring impedance, also known as coupling device, often forms one unit with a high voltage coupling capacitor (see figure 6.3). When a PD pulse arrives at the measurement location, it sees a different impedance. The combination of coupling capacitor has to fulfil:

- High impedance for the operating frequency.
- Only the low voltage PD signal should be measured with the measuring impedance

The combination of coupling capacitor and measuring impedance acts as a filter with as output the measuring impedance. The low cutoff frequency of this filter has to be tuned in a way that at least the power frequency signal and its harmonics are filtered out. Next to this, the measuring impedance only measures the high frequent signals.

Figure 6.3 is shows an example of a measuring coupling capacitance and measuring impedance. Together they must have a very large impedance at 50Hz to avoid large currents to be flown.

When assuming all operating voltage stands over the coupling capacitor, the current that is flowing through the combination of measuring impedance and coupling capacitor becomes:

$$I_{max} = U_{max} 2\pi f C_{coupling}$$

Where

- U_{max} = the maximum test voltage
- f = frequency of the test voltage
- C = coupling capacitance

When having a large characteristic impedance in comparison with the measured MV cable, the voltage reflection coefficient is approximated by 1. In that case there is a doubling of the voltage of pulses achieved at the measuring point. This is preferable to gain high sensitivity.

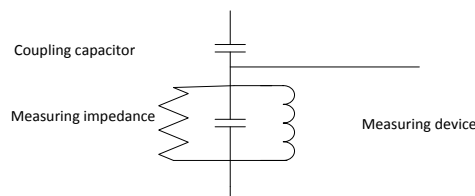


Figure 6.3: RLC measuring impedance with coupling capacitor

The standard prescribes that the coupling device should filter at least the test voltage and its harmonics for reaching the measuring equipment.

Measuring instrument

After measuring PD with a combination of coupling capacitor and measuring impedance, the signal arrives at the measuring instrument, see figure 5.11. At this point a filter, specified according to the standard, filters the signal. To achieve good results, it is important that the bandwidth of the measuring impedance in combination with the coupling capacitor lies within the IEC specified bandwidth. To avoid errors, a pulse train response should give a flat amplitude of frequency response within the bandwidth of the IEC filter. This bandwidth is shown in figure 6.4.



Figure 6.4: Correct bandwidth example for measuring PD in conventional way

When measuring PDs according to the standard, there are two kinds of bandwidths specified for the IEC filter. There can be measured with narrow band and with wide band. The bandwidths are specified as follows:

- Wide band
 - $30\text{kHz} \leq f_1 \leq 100\text{kHz}$
 - $f_2 \leq 500\text{kHz}$
 - $100\text{kHz} \leq \Delta f \leq 400\text{kHz}$

It is important that the bandwidth of the sensor is overlapping completely the bandwidth of the IEC filter, to get correct measurement values for the charge of PDs. In case no filter is used, the bandwidth of the sensor must fulfil the IEC bandwidth. The standard prescribes an adequate attenuation below f_1 and above f_2 , so there is a range left to implement this adequate attenuation. The effect of the order of filter, will be investigated later on.

The second type IEC filter is called narrow band filter. It uses a very narrow bandwidth compared to wide band. The specifications are described as:

- Narrow band
 - $9\text{kHz} \leq \Delta f \leq 30\text{kHz}$
 - $50\text{kHz} \leq f_m \leq 1\text{MHz}$

Where Δf stand for the width of the band and f_m is the centre frequency. It can be shown that the bandwidth can vary between 9 and 30 kHz. With the chosen bandwidth, the band can be shifted in the frequency spectrum where the amplitude of the frequency spectrum of the PD pulse is more or less constant (about between 50kHz and 1MHz, which depends on the pulse). Onwards it is not

recommended to use a sensor with a bandwidth that does not completely overlap the band of the filter.

Furthermore it is recommended that the transfer impedance at frequencies of $f_m \pm \Delta f$ should be 20dB below the peak pass-band value. [9].

A difference between the wide band and the narrow band method is the pulse resolution time. The pulse resolution time is the shortest time between two consecutive short pulses with the same shape, charge and polarity for which the peak value of the resulting response will not change more than 10% of that for a single pulse. In general the pulse resolution time is inversely proportional to Δf [9]. This means the wider the bandwidth of the system, the smaller the pulse resolution time. When the arrival time between PD's is shorter than the pulse resolution time, there has been made an error in the measurements. The pulse resolution times for the different bandwidths are:

- Wide band pulse resolution time
 - $5\mu s - 20\mu s$
 - In practice $< 10\mu s$
- Narrow band pulse resolution time
 - $> 80\mu s$

[9]

6.2.5 Limits of the conventional measuring method

In this chapter it is explained how to calibrate an IEC system and why, the influence of the order of the filter is determined and the limit of pulse width is treated.

Charge determination

When calibrating the IEC system for a certain value and pulse shape, all the measured pulse response peaks that the system is going to measure must be proportional to the calibrated value. A calibrated system with a pulse of 500pC must measure a PD with a charge of for example 100pC also correctly by measuring its proportionality to the calibration peak pulse response.

Because of the proportionality property of the system, pulses with different charge but with the same shape show linear related peak values in the time response. In case calibrating and checking if the system is proportional to different pulse shapes, using the same pulse shape but different charge, does not make sense.

Desired is to measure different kinds of pulse shapes with only a single calibration. Therefore the frequency spectrum of the calibrator pulse has to be approximately constant within the bandwidth of the IEC filter. To achieve this, the standard prescribes that the IEC system has to be calibrated by a calibrator pulse that has a rise time $< 60ns$. By pulses with longer rise time, decay of the frequency spectrum takes place at lower frequencies. This can be obtained of figure 6.5

In figure 6.5 the frequency spectrum of 4 real pulses, measured with a sensor that has a low cutoff frequency of 10kHz, are plotted. This is chosen because a combination of coupling capacitor and measuring impedance can reach such value of low cutoff frequency. Also the frequency responses of

6 Partial discharge measurements, conventional and unconventional

the filtered signals by different orders are plotted. The IEC bandwidth 30kHz – 400kHz is used. Table 6.1 shows the properties of the used pulses.

Table 6.1: Most important properties of the pulses used for described experiments

Used calibrator	q inj.	q at measuring point	Travelled distance through MV cable	Rise time	Decay time
3706	500pC	421,5pC	640m (first reflection)	41,2ns	108,8ns
3706	500pC	398,8pC	1920m (second reflection)	91,6ns	410,4ns
3706	500pC	340,5pC	3200m (third reflection)	140,4ns	699,2ns
3706	500pC	300,1pC	4480m (fourth reflection)	186ns	1165,6ns

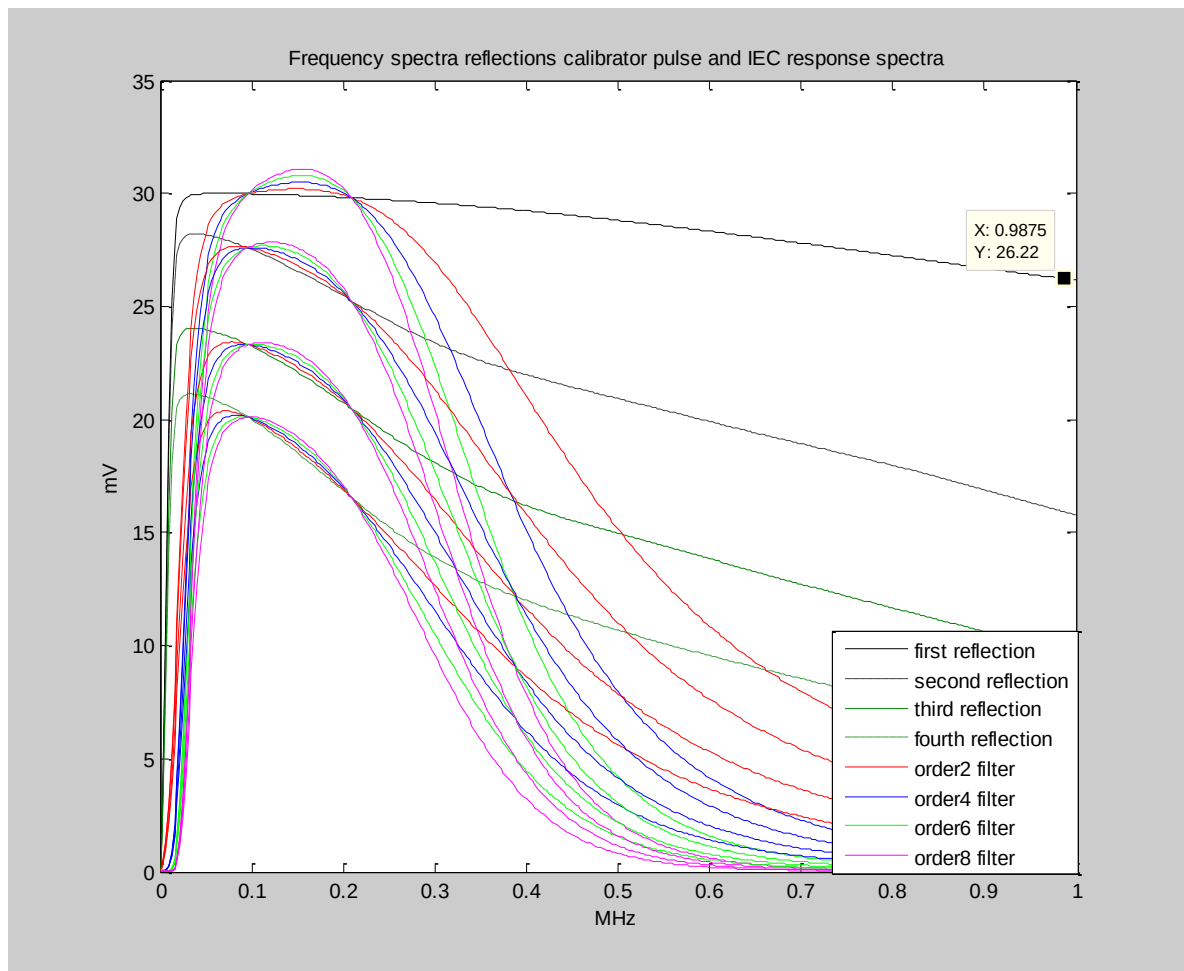


Figure 6.5: Frequency spectra of the measured calibrator pulse signals and of the IEC filtered signals

As displayed in figure 6.5 only the first reflection has a flat frequency response in the region of the IEC wide band bandwidth. Only this pulse can be used to calibrate the system. It can also be observed in table 6.1 that reflections 2,3 and 4 have a longer rise time than 60ns and therefore are not recommended for calibration. In figure 6.6 the peak of the IEC filter output against the real charge of the reflections 1,2,3 and 4 that is measured with UWB is plotted. The pulses and filter of figure 6.5 are used to plot these reflections. Next to the frequency responses, the proportionality line from the calibration pulse charge to the origin is plotted.

6 Partial discharge measurements, conventional and unconventional

It shows that a large error has been made in approaching the proportionality line by the measured peak values for the charges of the different pulse shapes. This is caused by the non flatness in the frequency spectrum of reflections 2, 3 and 4 of the pulses.

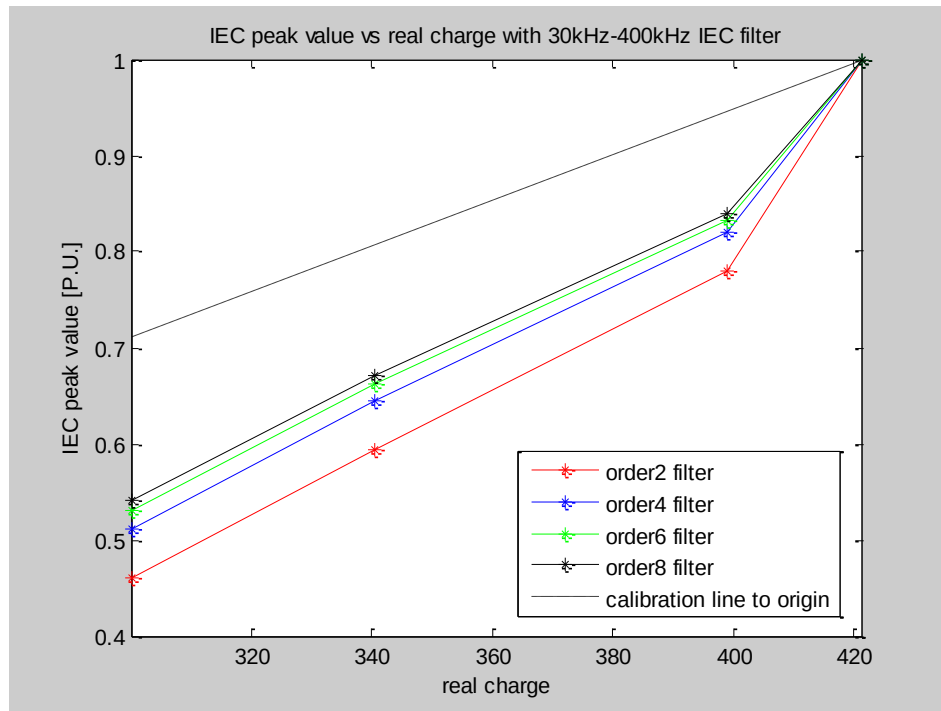


Figure 6.6: Peak value IEC filter vs. real charge of input pulse

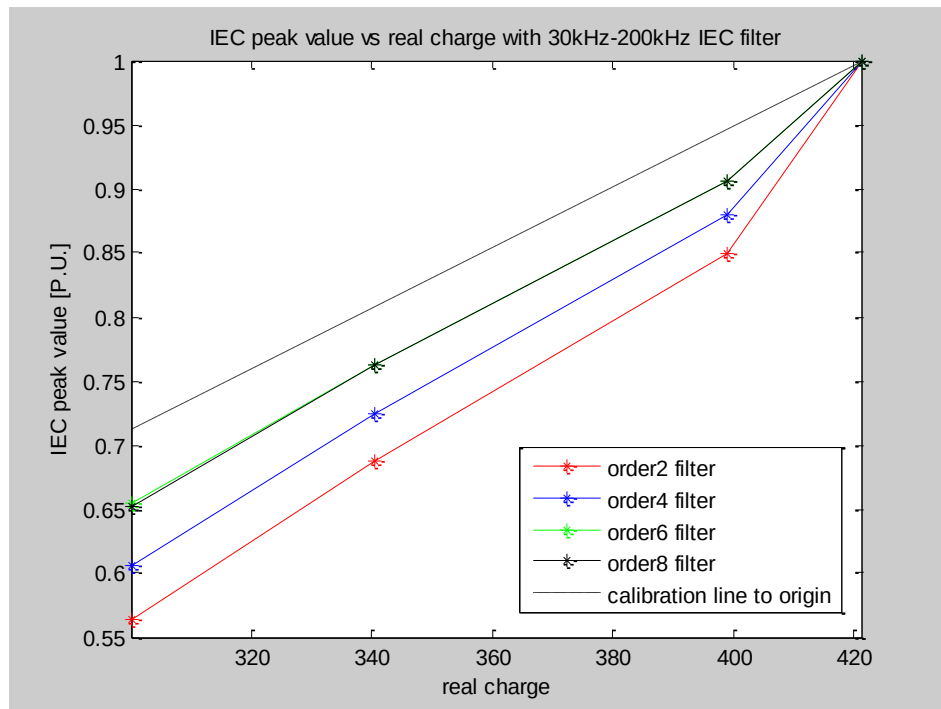


Figure 6.7: Peak value IEC filter vs. real charge of input pulse

To reduce the error in charge determination, the bandwidth can be narrow, while the low cutoff frequency is kept at the lowest value possible. In figure 6.7 a bandwidth of 30kHz-200kHz is used. It shows that the error has become smaller. This is due to the less differentiation in frequency spectra between the first reflection and the other three. A drawback is that the error made by measuring

pulses in the non flat region is related to the steepness of the decay of the frequency spectrum of a pulse.

In case there has to be dealt with wide pulses, the bandwidth of the IEC filter can be narrowed while keeping the low cutoff frequency the same. In this way, the filter bandwidth is moved to the area where the spectra are more flat. The second, third and fourth reflections of the sequence of pulses start with the decay of its high frequency content at about 80kHz. Because wide band prescribes a low cutoff frequency of 30kHz and a minimum bandwidth of 100kHz, puts the high cutoff frequency at 130kHz. The decay of the frequency spectra of the reflections 2, 3 and 4 lie within this bandwidth. Therefore measuring these pulses with wide band IEC filtering is less accurate.

The narrow band filter is suitable for measuring this width of pulses. Narrow band is also applied, using a bandwidth of 50kHz-80kHz. In this case the approach of the peak values to the proportionality line of calibration is relatively good, as figure 6.8 shows. This figure plots the relationship between IEC filter peak value and the real charge normalized to the peak value of the first reflection. With the order 8 filter the highest accuracy achieved.

When comparing the time responses of wide band 30kHz-400kHz and narrow band 50kHz-80kHz, the time response of the narrow band is, as mentioned before, indeed far longer. These time responses are expressed in figure 6.9. Another thing that can be remarked is that the polarity of the wide band time response is clearly recognizable by the first peak, but that is not the case with narrow band because the signal is very more oscillating. Therefore it is not possible to determine the polarity of the PD pulse with narrow band.

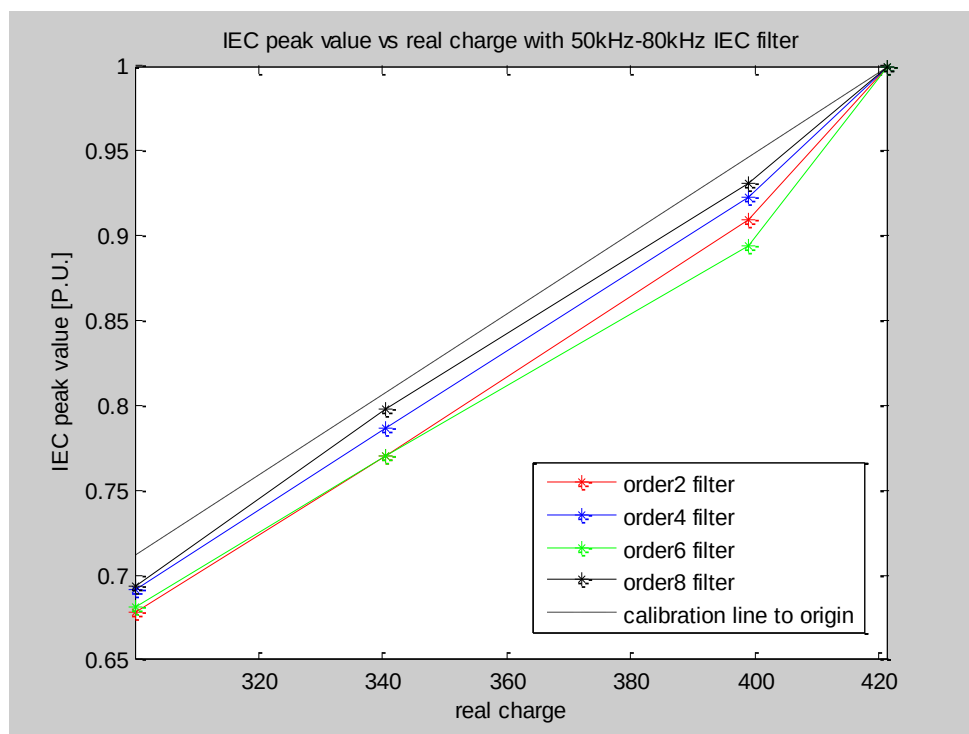


Figure 6.8: Peak value IEC filter vs. real charge of input pulse

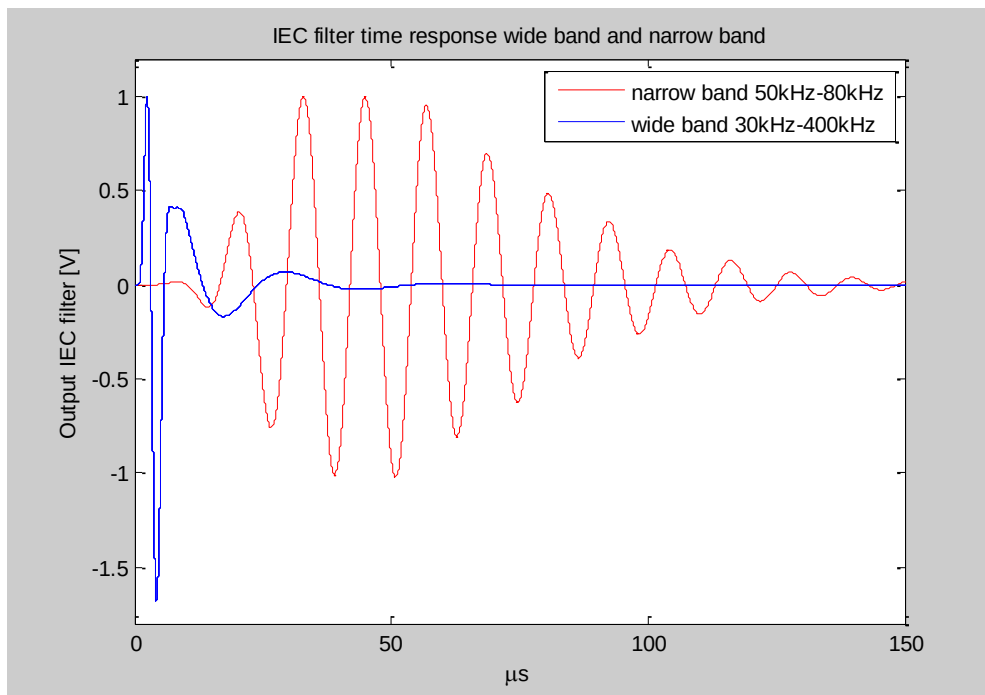


Figure 6.9: Time responses of calibrator pulse, wide band and narrow band filtered

Superimpositioning of consecutive pulses

This chapter will show the error that can be made in case two consecutive pulses separated by time that is less than the pulse resolution time.

As already mentioned, the response of an IEC filter to a very short pulse in a MV cable takes far more time than the original signal. We are going to determine the pulse resolution time of a MV cable.

There is a 1nC calibration pulse injected into the MV cable and recorded with an oscilloscope using a bandwidth from DC to 300MHz (Ultra Wide Band, UWB). The data is imported in Matlab and afterwards filtered. A signal of two consecutive pulses has been made. The distance between the pulses can be varied by adding a demanded number of zeroes between the pulses. The signal is put into an IEC filter and the time response is given in figure 6.10.

As already mentioned, to reach the pulse resolution time according to IEC60270, it is required that the response of the filter to two consecutive pulses does not differ more than 10% of the response value to one single pulse.

To create the shortest pulse resolution time, we take the 30kHz-430kHz bandwidth to filter the input signal of the two consecutive pulses. In figure 6.10 the response of the filter to the pulse in a MV cable is displayed. The superposition error is clearly visible.

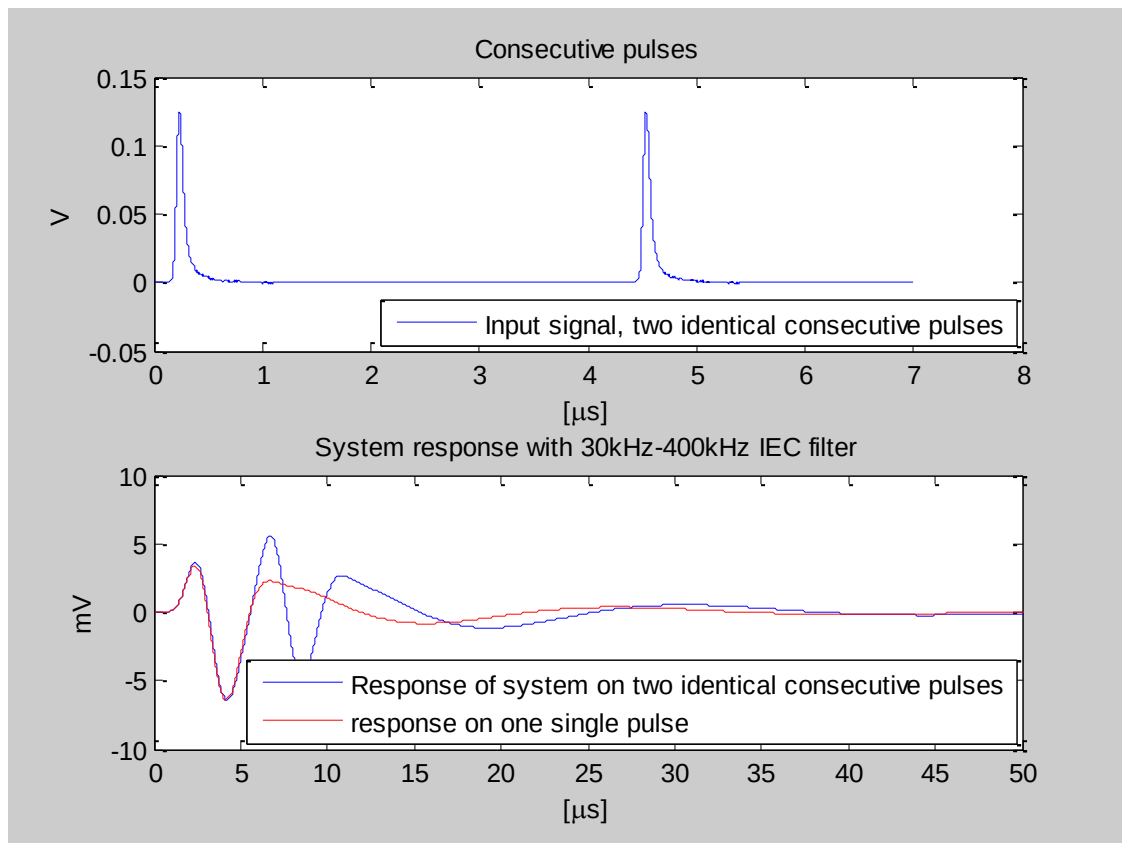


Figure 6.10: Two consecutive input pulses and their IEC filter output response

A summation of the advantages and disadvantages of conventional measuring method is made in table 6.2.

Table 6.2: Advantages and disadvantages of IEC wide band and narrow band PD measurement

	Wide band	Narrow band
Advantageous	- Compared with narrow band a relative short pulse resolution time (In general the pulse resolution time is inversely proportional to BW) - Polarity can be easily gained out of the response signal	Sensors with a relative high low cutoff frequency can be used
Disadvantageous	- Sensor with a relative low cutoff frequency needed - Cannot measure correctly pulses as long as the narrow band can measure.	- A long pulse resolution time - Polarity cannot be gained out of the output signal

6.2.6 Feasibility conventional measurement method for PD measurement in MV cables

This subchapter handles the feasibility of the IEC method for PD measurement in MV cables. Thereby the two topics discussed are:

- Charge determination
- Localization

First the suitability of conventional measurements method for measuring the charge of PD in MV cables is investigated, afterwards the suitability for localization has been researched.

During PD pulse propagation in the cable, the damping of the high frequency content of PD pulses is large. Therefore the flat region in the measured frequency spectrum begins at the lower cutoff frequency of the sensor and ends at a more and more lower frequency.

Therefore, the wide band measurement method becomes less suitable for measuring pulses that have to travel a distance through the cable that is too long. As shown in figures 6.6 and 6.7, measuring pulses with travel paths between 0 and 1.3 km give already an error. With narrow band, the charge of a sequence with short and wide pulses can be determined with a good accuracy, but the pulse resolution time is very large.

The pulse resolution time of the wide band method is approximately between $5\mu s$ and $20\mu s$, depending on the bandwidth of the filter. So to have no integration error caused by super positioning of the response of two consecutive pulses, there has to be $5\mu s$ - $20\mu s$ between arrival times of the pulses at the measuring location.

$$v = 160 \text{ m}/\mu s = 3200 \text{ m}/20\mu s = 800 \text{ m}/5\mu s \quad (6.1)$$

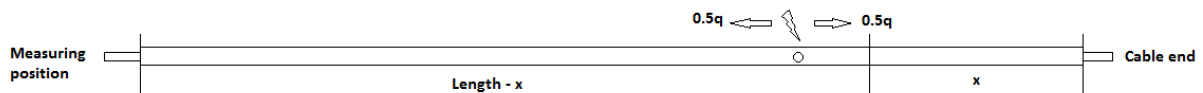


Figure 6.11: Model of a cable with a defect that produces PD

In case there is PD in cables, measured with the conventional method, superimposition of responses have to be taken into account, as mentioned before. The time between pulses has to be equal or larger than the pulse resolution time. Half of the PD pulse is travelling from the defect to the beginning of the cable and the other half to the end. It reflects there and travel to the beginning of the cable. Therefore it can occur that the differences in arrival times of the two half pulses are equal or more than the pulse resolution time. This is the case when a defect in a cable is x meters away from the cable end, as shown in figure 6.11. There is PD measured with an error in case the defect is in cable length x , because of superimposition of pulse responses. The distance one half of the PD pulse has to travel with velocity v through the cable to gain an extra travelling time that fulfils the pulse resolution time is equal to $2 \cdot x$.

When we use some practical values to get an idea of length of x we take:

$$\text{pulse resolution time} = 10\mu s \quad (6.2)$$

$$v = 160 \text{ m}/\mu s = 1600 \text{ m}/10\mu s \quad (6.3)$$

Therefore

$$2x = v * \text{pulse resolution time} \quad (6.4)$$

$$x = 800 \text{ m} \quad (5) \quad (6.5)$$

This is a long distance in comparison to the total cable lengths of 1-4km that are measured. Next to this, it cannot be recognized if superimposition of pulses is measured.

This in combination with determination of charge of wide PD pulses that travelled distances longer than 2km through a MV cable, gives the conclusion that conventional PD measurement could give an error in charge determination of PD in MV cables.

Because of superimposition of pulse responses, arrival times of pulses could not be determined. Therefore conventional measurement is not suitable for defect localization with TDR in power cables.

6.2.7 Conclusion

At the moment conventional measurement is the only measurement method that is described in a standard. The standard describes the conditions for this measurement and the calibration method. For calibration, only steep pulses can be used, with rise time < 60ns. It is also recommended that the frequency responses of the PD pulses that are predicted to measure are flat within the bandwidth of the IEC filter. Therefore with wide band can be measured accurate relatively small pulses, with travel distances in a MV cable of about 1km. With narrow band wider pulses until couple of km's can be measured with high accuracy. Because the time response is proportional to the inverse of the bandwidth, the smaller the IEC bandwidth, the longer pulse resolution time. Because of the long time response, the widest bandwidth has to be used, but therefore only steep pulses can be measured, hence pulses with short travelling distances. Because of the long time response, an error can be made in determination of charge, when PDs are measured of a defect that is within distance x from the end of the cable. The combination of the length of the time response and the width of the PD pulses that can be measured with high accuracy makes conventional measurement less suitable for measuring PD in cables.

6.3 Unconventional measurements

6.3.1 Introduction

As discussed in the previous chapter, for PD measurement in cables it is desirable to measure a short pulse response. This will reduce errors in charge determination and makes defect localization possible. Because of the long response time of the conventional method, unconventional measurements are needed. Due to the fact that there is no standard for unconventional

measurements, different systems are used with different sensors that measure different pulse responses.

To be sure the cable meets its prescribed quality, it is measured for PD at the factory. After shipping and placing, but before taking the cable into service, a commissioning PD test is taken. Often different kind of PD measurement systems are used. To be sure the placed cable still fulfils the prescribed quality which it had at the factory, the measurements of the sometimes different systems have to be comparable. Often, this is not the case.

In this chapter we investigate different kinds of methods that could make possible comparison between conventional and unconventional measurements and between unconventional measurements using different sensors.

First we investigate the influence of different sensors on the response of a PD pulse, secondly we compare different methods for determination of charge, measuring with different sensors simulated by digital filters. Afterwards PD pulses are measured with real sensors and the results are compared.

6.3.2 Influence of the sensor on the PD pulse response.

Because there is no standard for unconventional PD measurement, different PD measuring systems use different sensors that give different pulse responses. In this chapter we are investigating the influence of different sensors on the PD pulse response. The different sensors are simulated by a second order filter with different bandwidths.

To investigate the influence of the BW of the sensor on the pulse response there is used an UWB recorded pulse of 859pC, generated by injecting a 1000pC with the 3706 Haefely calibrator that has to travel 640m through a MV in order to reach the measurement point. First the pulse is filtered only with a high pass filter with different low cutoff frequencies. For low cutoff frequencies are used 0Hz (UWB), 10kHz, 50kHz, 100kHz, 200kHz, 500kHz and 1000kHz. Figure 6.12 shows the time response, their integral and the frequency spectra of the UWB signal and the filtered signals.

It shows that the higher the low cutoff frequency, the higher is the negative overshoot of the response and the shorter the length of the pulse. The short time response is useful to decrease the pulse resolution time. The integral of the pulse goes to zero. The higher the low cutoff frequency, the faster it reaches the value of zero. This is caused by the fact that the integral of the response of a high pass filter always goes to zero because the DC component is filtered out of the signal.

When we look at the time response, we see that the lower the low cutoff frequency, the more the highest peak looks like the original signal. Integration of this highest peak could approach the charge. The peak of the integral corresponds to the zero crossing of the signals. Figures 6.20-6.24 show that this is an accurate method for determination of charge for the first two reflections, if a sensor is used with a low cutoff frequency below 10kHz.

Now we are going to take the same test, but for the pulses measured after travelling 3200m. Figure 6.13 shows the results. We see that the high frequencies are strongly attenuated. We also see that the length of the time responses of the filtered signals are about the same as from the pulse that has travelled 640m, while the length of the original UWB pulses is much longer than the UWB pulse of figure 6.12. When comparing the shapes of the filtered signals and the UWB signal, there is more difference between them by the pulse that has travelled 3200m than 640m. Determination of charge

by integrating the first peak becomes worse. Figure 6.14 shows the first peaks of the two pulses. When comparing the amplitudes of the two UWB signals, it is expressed that the 3200m signal has very less amplitude than the 640m signal. This is caused by attenuation of the high frequencies during propagation of the pulse through the cable. When comparing the peaks of the time responses of the different filters (see figure 6.14), we see that sensitivity of the 3200m pulse decreases stronger than from the 640m pulse. The high frequency content of the 3200m pulse reaches until about 200kHz. It explains that measuring with a low cutoff frequency above 200kHz decreases the sensitivity strongly. It shows for these pulses, that measurement of pulses that have travelled through the cable for a long distance, measured with a system with a relative high lower cutoff compared with the frequency content has a relative low sensitivity.

Now the high cutoff frequency is investigated and a low pass filter is used to do so. For the high cutoff frequencies is taken: 10MHz, 2MHz, 1MHz, 800kHz, 400kHz. Figure 6.15 shows the results.

When the high frequencies are filtered, the sensitivity decreases strongly. Furthermore the pulse becomes wider, this is the same that happens during propagation through the cable. Next to this, the rise time decreases, by a lack of dispersion (see chapter 4). The integral of the signal is not influenced by filtering high frequencies, which 6.15 also shows. This is logical because the DC component is not filtered out.

6 Partial discharge measurements, conventional and unconventional

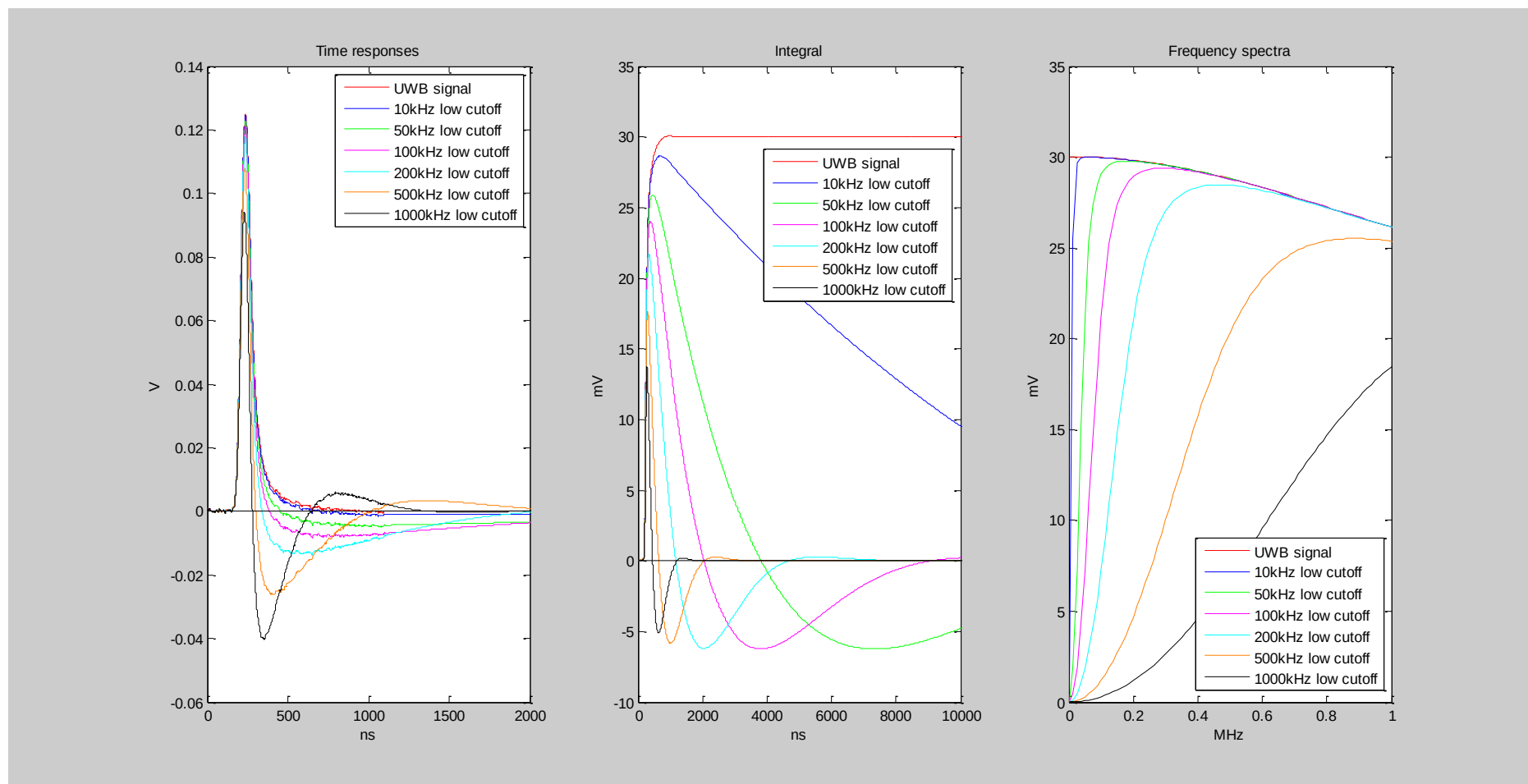


Figure 6.12: Time responses, integrals, frequency spectra of UWB signal and filtered UWB signal with different low cutoff frequencies for pulse that has travelled 640m through a MV cable

6 Partial discharge measurements, conventional and unconventional

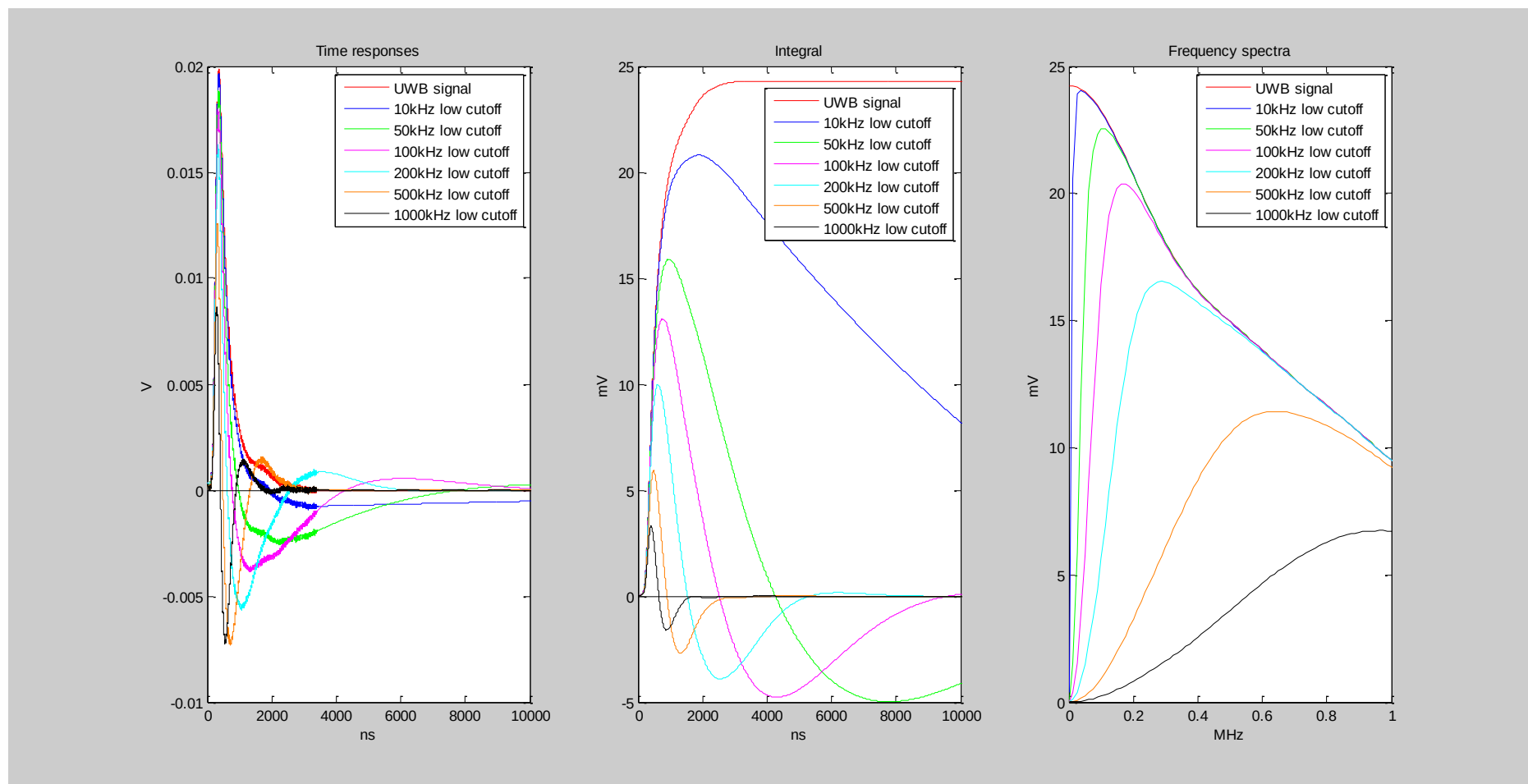


Figure 6.13: Time responses, integrals, frequency spectra of UWB signal and filtered UWB signal with different low cutoff frequencies for pulse that has travelled 3200m through a MV cable

6 Partial discharge measurements, conventional and unconventional

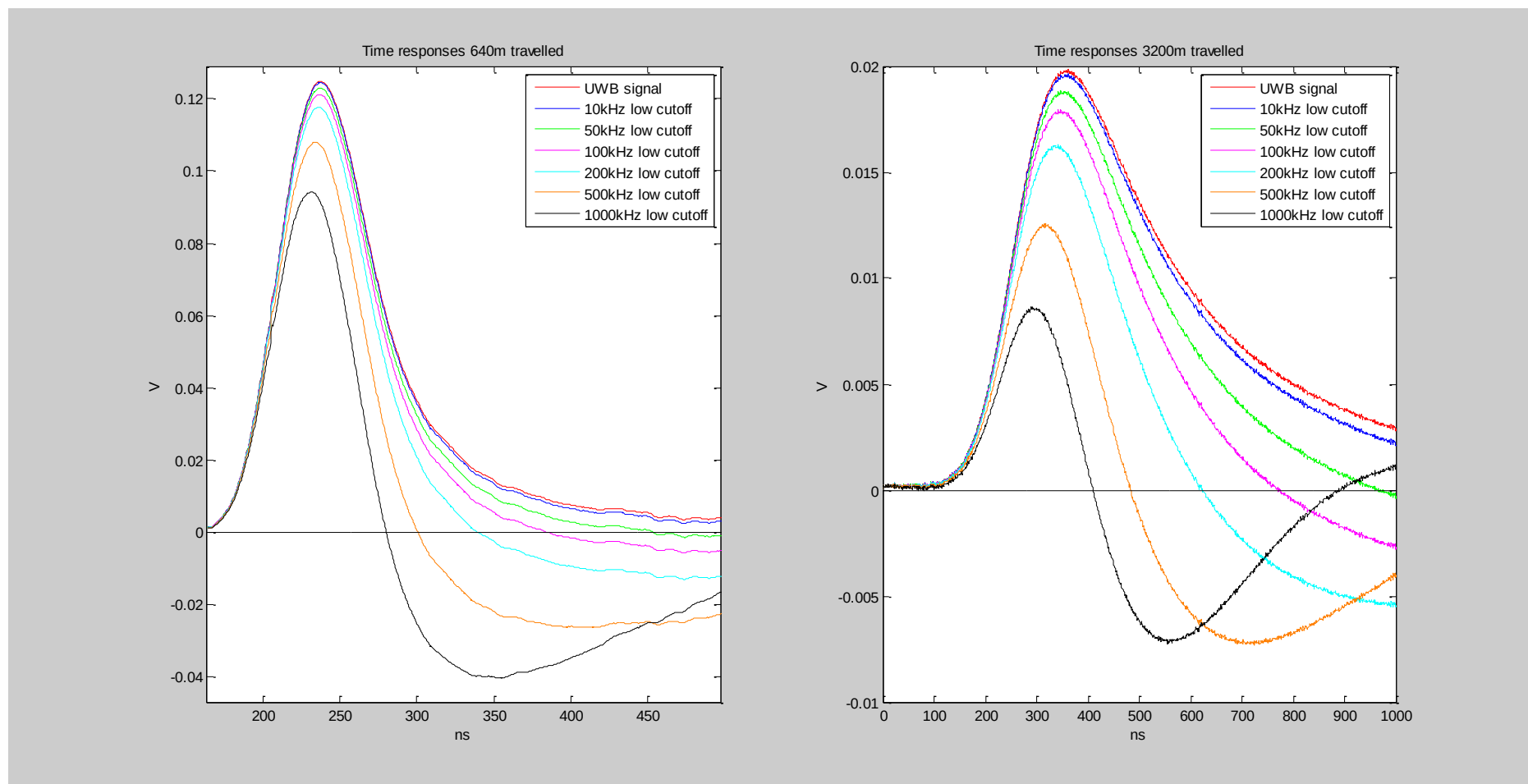


Figure 6.14: Zoom in first peak time response of figures 12 and 13 respectively

6 Partial discharge measurements, conventional and unconventional

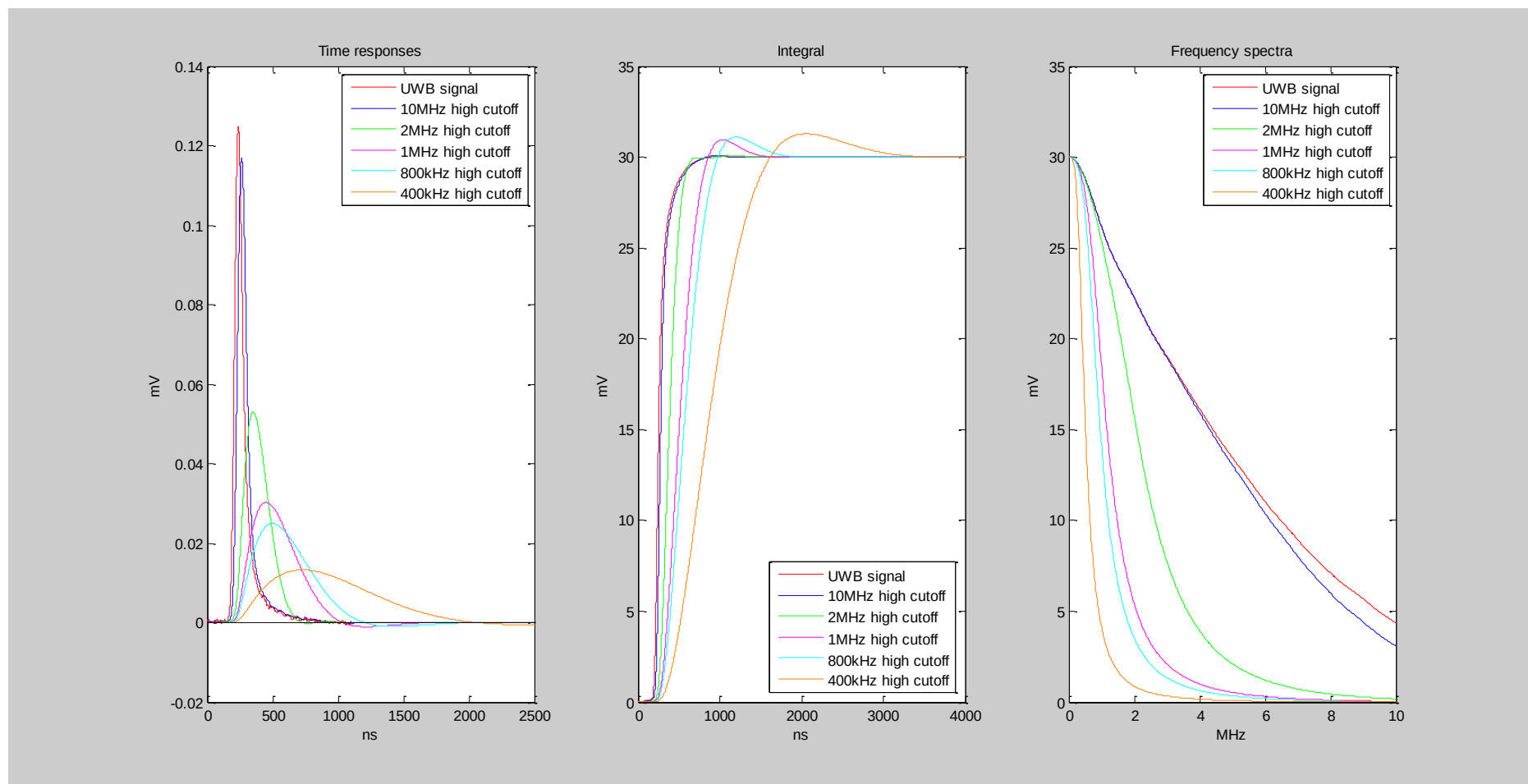


Figure 6.15: Time responses, integrals, frequency spectra of UWB signal and filtered UWB signal with different high cutoff frequencies for pulse that has travelled 640m through a MV cable

6.3.3 Conclusion

Now we will come to a conclusion about the influence of the bandwidth on the time response. Figures 6.16 and 6.17 illustrate how the bandwidth has been changed during the simulations.

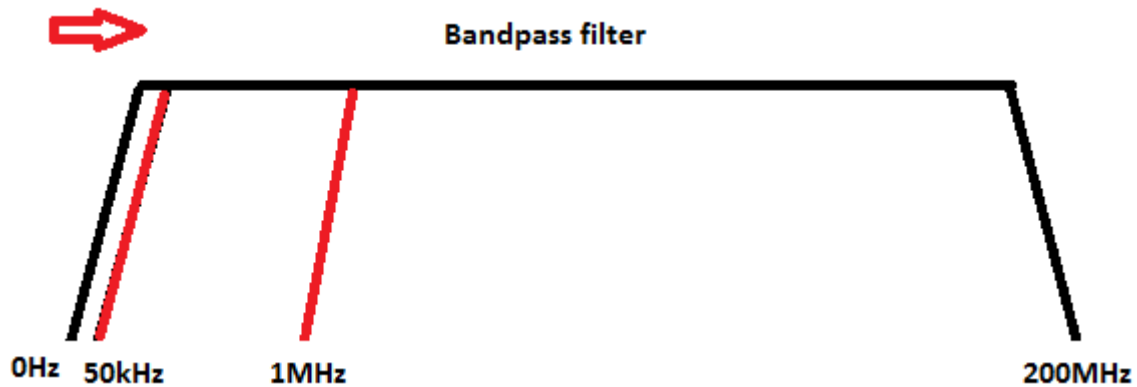


Figure 6.16: Change of low cutoff frequency

Low cutoff frequency 0Hz → 50kHz

- The first peak of the response looks like the UWB pulse
- Due to BPF has a very long negative area to make the integral of the signal zero
- Therefore the time response is very long.
- First peak integration gives an approach of the integral of the signal when filtering until 10kHz

Low cutoff frequency 0Hz → 1MHz

- Response has a very different shape than UWB pulse
- Integral goes fast to zero
- Therefore the response time is almost likely the UWB pulse and the pulse resolution time is decreased
- The sensitivity is strong decreased when measuring with a low cutoff frequency relatively high compared with the high frequency content of the pulses.

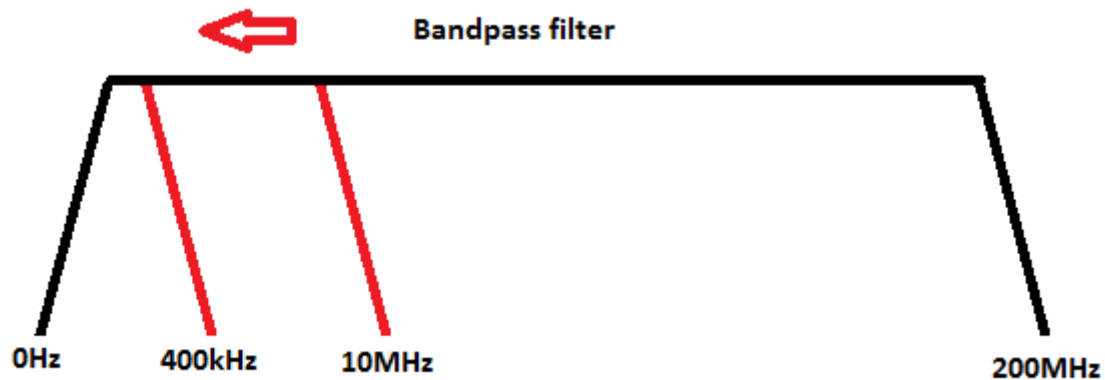


Figure 6.17: Change of high cutoff frequency

High cutoff frequency 10MHz → 400kHz

- Sensitivity is decreased
- Rise time of the time response becomes larger
- Pulse becomes wider
- Integral of signal is not influenced

For unconventional PD measurement in cables, frequencies above tens of MHz can be filtered without having a significant influence on the pulse response. This is because pulses in cables have a high frequency content reaching until tens of MHz. To avoid a decrease of the sensitivity of the measuring system, the higher frequencies of the pulse should not be filtered. This also due to the increase of the length of the pulse response.

Filtering low frequencies above flat area of the frequency spectrum of the pulse, leads to lower sensitivity. Furthermore, when filtering with a high lower cutoff frequency leads to a shorter time response. Therefore the integral of the pulse goes also fast to zero. Approaching the charge of the pulse by integrating the first peak of the signal gives an approach below about 10kHz.

For choosing a sensor bandwidth, the pulses expected to be measured, the charge determination method, sensitivity, and the length of the time response must be taken into account.

6.4 Comparison of PD measurement methods

6.4.1 Introduction

Now the influences of the bandwidths of the sensors on the system responses are known, orders of magnitude for parameters of usable sensors can be defined to use in comparison research for different charge determination methods.

This chapter first handles four different methods for determination of charge, afterwards the methods are tested and compared for a various sequence of pulses.

6.4.2 Methods used for charge determination of PD pulses

The methods that are compared are:

- Conventional measurement (according to IEC60270)
- Peak value calibration
- Integration of the highest peak of the system response
- Peak detection around low cutoff frequency in frequency spectrum

First the methods are described, afterwards the comparison is made. The description of the charge determination method according to IEC60270 is already explained in chapter 6.2, therefore only the three other methods are described now.

Peak value calibration

Peak value calibration is the simplest method to use. The peak value of the time response is taken as a value proportional to the charge. In this chapter it is investigated whether the method is that accurate to say something about the order charge of different PD pulse.

Integration of the highest peak value

Determining charge by taking the integral of the highest peak is a simple method that first determines the highest peak of the absolute pulse response. Afterwards the zero crossings of the signal that are found, give the boundaries of the integral. As last step the integral of the absolute signal is taken between the boundaries. This approach comes from the fact that charge is the integral of current with respect to time. If the UWB signal is integrated, the charge is achieved. But when a band pass filter (BPF) or a high pass filter is applied, the integral of the pulse response becomes zero (see figure 6.12). Therefore taking the integral of the whole signal is useless. We see that in case the low cutoff frequency is relative low, the first peak has more or less the same shape as the UWB signal. The higher the low cutoff frequency, the more difference between the shapes and the area below the first peak of the pulse response and the UWB signal.

In the chapter 6.4.3 there is investigated whether integration of the first peak can give a good approach for the charge. Therefore the limitations of this method are made visible.

Peak detection around the low cutoff frequency in the frequency spectrum

This method takes the peak value of the frequency spectrum near the low cutoff frequency of the measurement system. For this method we transform the recorded PD signal from the time domain into the frequency domain by means of the Fast Fourier Transform. Recording of the PD pulse happens in a digital way; the pulse is sampled with a constant sampling rate. When the sampling rate (S_r) is $n \cdot \text{samples/s}$ with a sequence length of N there is obtained a signal like equation 6.6 is obtained.

$$x[n] = \sum_{n=1}^N x(t) \delta\left(t - \frac{n-1}{S_r}\right) \quad (6.6)$$

Now we transform the signal from the time domain into the frequency domain. For every frequency, its contribution to the signal can be determined in this way. Discrete data can contain only

frequencies between zero and $0.5 \times \text{sampling rate}$. [23] Equation 6.7 presents the Discrete Fourier transform done by Matlab.

$$X[k] = \sum_{n=0}^N x[n] e^{-\frac{j2\pi(k-1)(n-1)}{N}} \quad 1 \leq k \leq N \quad (6.7)$$

The calculated frequency range reaches from DC to sample frequency/2 is divided over $(N/2)+1$ samples. Because $1 \leq k \leq N$, the relation of equation 6.8 is found:

$$f = (k - 1) * \frac{Sr}{N} \quad (6.8)$$

The resolution of the frequency spectrum depends on the sampling rate and the number of samples of the recorded signal. When a higher resolution is desired, zeros can be padded to the signal. In that case the number of samples N increases, but the frequency response does not change. When N becomes larger, the resolutions increases.

To reduce calculation time and to obtain the same result, the Fast Fourier Transform function is used in Matlab instead of the Discrete Fourier Transform directly (equation 6.7) [2]

Out of the frequency spectrum the charge can be determinate. If we start with $\omega=0$ (corresponds to index $k=1$ in Matlab), the exponential is equal to one and equation 6.9 is left.

$$X[1] = \sum_{n=0}^N x[n] \quad (6.9)$$

$X[k=1] = X(f=0)$ = the sum of all sample values of the signal, it is a value proportional to the integral of the discrete time signal. Because the integral of a PD pulse measured with UWB is proportional to the charge, the $X(f=0)$ is also proportional to the charge. This is also explained in chapter 4.2.4.

Figure 6.18 plots the frequency spectrum of an UWB pulse that is injected into a 640m MV cable and measured at the other end (first reflection). The frequency spectrum of the second reflection that has travelled 1280m further, is also plotted. The plot shows that the higher frequencies damp fast, compared with the lower frequencies. During propagation, the frequency spectrum becomes significantly smaller. Figure 6.18 shows that the first part of the spectra is flat and has about the same value as $X(f=0)$ and approaches proportionality to the charge of the pulse.

There is also made use of filtered signals. The UWB pulses are filtered with low cutoff frequencies of 50kHz and 500kHz. The frequency responses are also plotted in figure 6.18.

When comparing the frequency spectra of UWB and a filtered pulse, we see that the $X(f=0)$ value of the HFCT spectrum is very small and approaches zero. This is logical, because the integral of a band pass filter filtered signal goes to zero. When the peak value of the frequency spectrum is investigated, it shows that for a relative low lower cutoff frequency and a small pulse (large content of high frequencies), the peak of the frequency spectrum is a relative good approach for the value proportional to the charge (see figure 6.18). In case the pulse travels for a longer distance through

the cable, this approach becomes less accurate when measuring with the same filter. The same thing will happen when a filter with a higher low cutoff frequency is applied, see figure 6.18.

In chapter 6.4.3 we will investigate the influence of filters on this methods for charge determination, using different pulses.

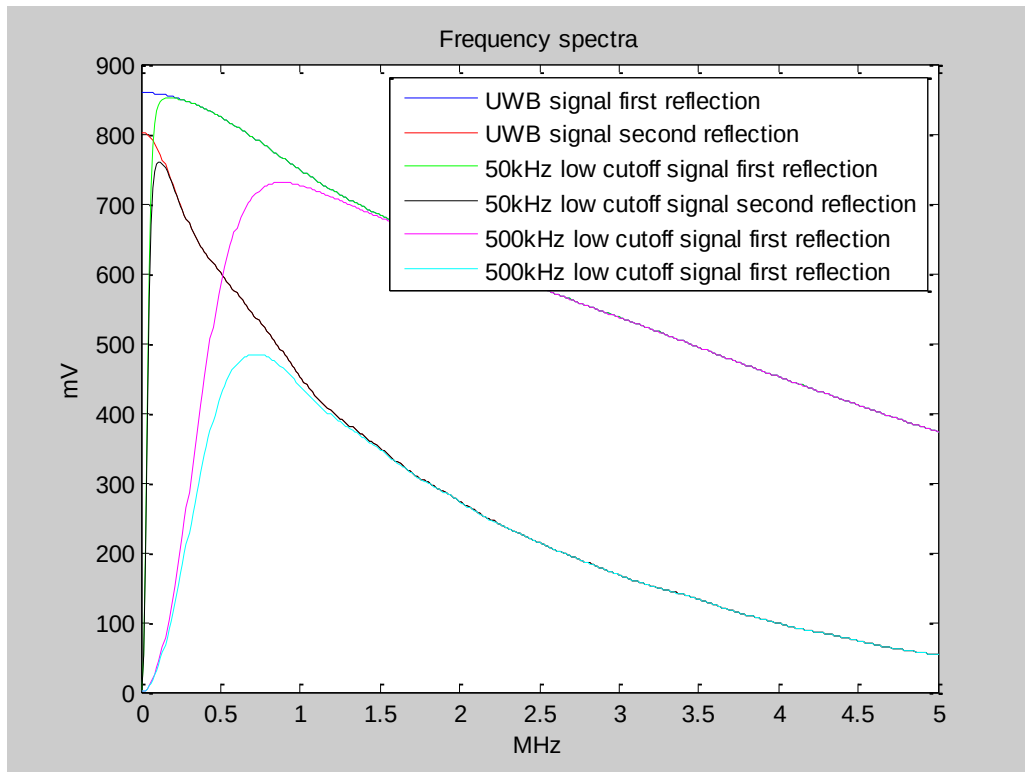


Figure 6.18: Frequency responses of UWB reflections and filtered reflections

6.4.3 Simulations

To check the charge determination methods, there must be specified some sensors with different bandwidths and there must be specified a sequence of UWB pulses for which the charge determination methods are tested.

The selection of pulses is caused by the combination of different charges, different initial pulse widths corresponding to different defects and the usual length between two accessible measuring points in a MV cables network where the cables can be decoupled from the network. We use two different initial pulses:

Small pulses

- Short pulse length: rise time < 50ns

Wider pulses:

- Longer pulse length: rise time until 100ns

The defects can have different charges in real. For this comparison there is made the choice for:

- 1000pC
- 500pC

The pulse properties are shown in table C1 of appendix C.

The calibrator pulses are measured after they have travelled through the cable. Because pulses are injected into a cable that is wound on a drum and the two cable ends are close to each other, there is measured some little noise signal coming from the calibrator at the time of injecting, that travels through the air. This noise travels with the speed of light and arrives almost directly at the measuring probe. Because the measured signal should be triggered at the first injected pulse, there is chosen for 500pC. The first pulse triggers the signal as desired for pulse of calibrators 3706 and 3709.

The experiments in this chapter are performed with the injected pulses of table C.1, injected with calibrator 3706, containing a charge of 1000pC at the place of injection. The pulse properties are also shown in table 3.

The bandwidths used for the filters are determined by the time response of the filters and the gain of real sensors. Appendix B explains that the gain for HFCT's with a lower low cutoff frequency is very low. HFCT's with higher low cutoff frequency have a higher gain, but due to the difference in time response, it could become more inaccurate to determine charge of the pulse. When a very high low cutoff frequency of 1MHz is taken, as described in chapter 6.3.2, the time response is about as short as the UWB pulse itself. Next to this, in practice, different PD measurement systems measure with HFCT's with a low cutoff frequency that lie in the range of about 100kHz-1MHz

Because it is desired to have an accurate charge determination and a fast response, the chosen low cutoff frequencies are: 10kHz, 50kHz, 100kHz, 200kHz, 500kHz, 1000kHz.

Table 3: Pulses that are used for simulations

Used calibrator	q inj.	q at measuring point	Travelled distance	Rise time	Tail time
3706	1000pC	858,9pC	640m	42,8ns	112ns
3706	1000pC	802,7pC	1920m	92,4ns	414ns
3706	1000pC	687,7pC	3200m	140ns	704,4ns
3706	1000pC	607,8pC	4480m	188,4ns	1191,6ns

The determined parameters are used for the simulations. With the simulations, there are determined some errors. The error of the highest peak integral and the peak of the frequency spectrum method are determined by equation 6.10

$$Error = \frac{q_{real} - q_{determined}}{q_{real}} \quad (6.10)$$

The charges are distilled out of the measured voltage signal by equations 6.11 and 6.12.

$$q_{real} = \sum_{i=1}^{i=n} \frac{0.5 * T * 10^{12}}{Z_c} V(i) [pC] \quad (6.11)$$

$$q_{determined} = \frac{0.5 * T * 10^{12}}{Z_c} * \text{determined charge value} [pC] \quad (6.12)$$

- The factor 0.5 is used because of total reflection of the signal is measured twice its amplitude
- T = time between samples
- Z_c = characteristic impedance of the cable
- $V(i)$ = measured UWB signal
- n = length sample sequence

When using the frequency spectrum peak method, the 'determined charge value' of equation 6.12 is equal to $kcal * \max \text{value frequency spectrum}$. Therefore kcal has to be determined.

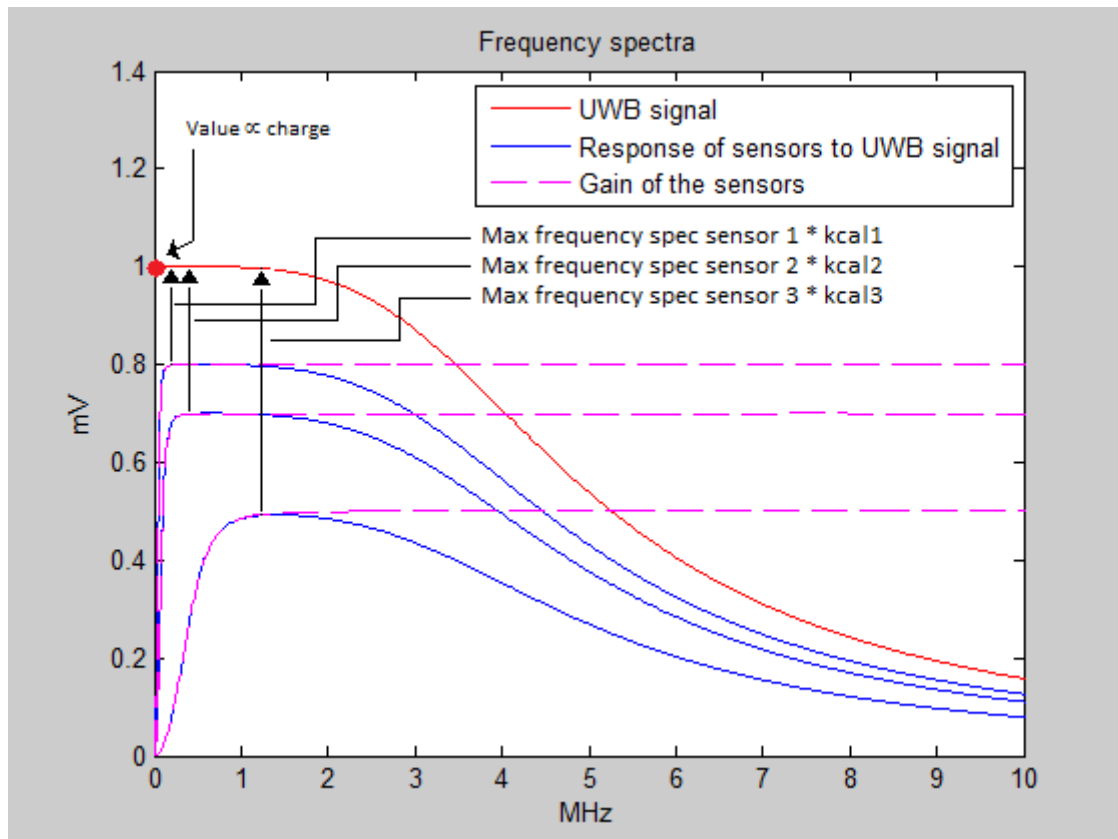


Figure 6.19: Frequency spectrum of UWB pulse, gain of sensors (sensors with low cutoff frequencies: 10kHz, 100kHz, 500kHz) and the frequency response to the UWB pulse measured by the different sensors

The value of kcal should be determined by measuring a steep pulse that contains a large high frequency content. The flat area of the frequency spectrum of the pulse should reach until a frequency value at which the gain of the sensor has reached about its maximum. The first maximum point of the gain of the sensor is displayed in figure 6.19, at the location where the black arrows point from the purple and blue lines to the red line. In figure 6.19, the flat piece of the frequency content of the UWB signal reaches indeed the frequency where the sensor with highest low cutoff frequency reaches maximum gain. In that case, for all the three sensors the calibration constant can be determined. When the UWB pulse is measured with one of the sensors, the calibration constant, kcal, times the maximum frequency spectrum value (the value at the begin of the black arrows of figure 6.19) results in the value plotted with the red dot in figure 6.19. This value is proportional to the charge. When kcal is determined, the charge can be determined by equation 6.12. For the

simulations in this chapter, there is used a filter in Matlab to simulate different sensors. For each simulated sensor, different low cutoff filters are used, but the gain of the sensors is kept for all at 1.

The error of the IEC and the peak value method is determined by equation 6.13

$$Error = \frac{kcal_{max} - kcal_{min}}{kcal_{min}} \quad (6.13)$$

$$kcal = \frac{q_{real}}{measured\ value} \quad (6.14)$$

Thereby kcal is a sequence of calibration constants for the different pulse shapes that are measured with a system with a specific bandwidth. For the highest peak value method there are defined different systems by using different low cutoff frequencies. The same is done for the IEC method, but in this case the signal is filtered afterwards by an IEC filter, see figures 6.20 and 6.21.

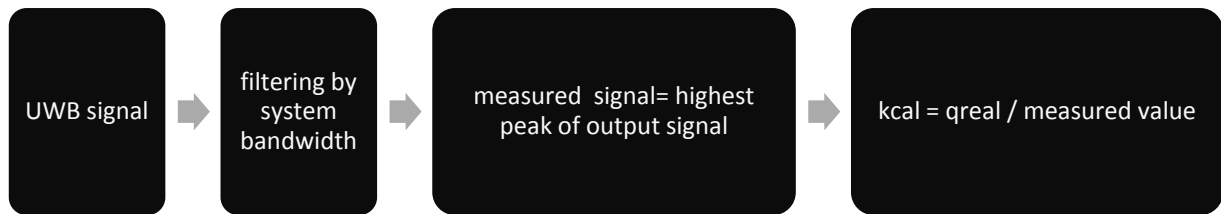


Figure 6.20: Determination kcal for highest peak value method



Figure 6.21: Determination kcal for IEC method

With each system, there are measured different pulse shapes and there is determined the calibration constant with these pulses. In ideal case, there is no difference between the different calibration constants of one system. When the method is less accurate, the dispersion between the calibration constants becomes larger.

The error for the IEC and peak value method is the dispersion between the calibration constants.

The error is determined in this way because the system has to be calibrated to a certain constant. When calibrating according to one calibration constant, obtained with a specific pulse shape, other

pulse shapes with the same charge could be measured with an error. It is important to know what the maximum error is that can be made. The maximum error can be obtained by measuring pulses with different shapes and determining the calibration constants for the system by these measured pulses. The maximum error that can occur is the dispersion between the calibration constants and is given by equation 6.13.

Before the errors are compared with each other, figure 6.19 displays the relationship between the peak value of the measured pulse and the charge. Because the curve is not linear, we can make the conclusion that this method is strongly pulse shape dependent.

The errors made with the different charge determination methods are plotted for all different system bandwidths, specified in low cutoff frequency of the system. Figure 6.23 shows the curves for different system bandwidths applying reflection 1. Figures 6.24 and 6.25 do the same for reflection 2. The error of the IEC and peak value method in figure 6.23 is zero because it is compared with itself. In figure 6.24 and 6.25 the IEC and peak value method error is determined by the dispersion of the calibration constants for reflection 1 and 2.

For the IEC method an order 8 filter is used with a bandwidth of 30kHz-200kHz. The frequency spectra of the first and second reflection are plotted in figure 6.5. It shows that the bandwidth of 30kHz – 200kHz lies not totally in the flat area of the second reflection. But because the bandwidth is small, the error that is made is low. When increasing the bandwidth, a larger error in determination of charge is made. Because the standard recommends that the bandwidth used before the signal is arriving at the IEC filter must at least cover the IEC bandwidth, the lower cutoff frequencies above 100kHz are not recommended to be used when measuring according to the standard. Because the measuring the IEC filter has a bandwidth of 30kHz – 200kHz, a low cutoff frequency above 30kHz is not even recommended in this case.

Figure 6.24 shows that the peak value method is a very bad method for charge determination of PD in cables. The dispersion between the calibration constant of the first reflection and the second is huge. Figure 6.22 shows the relationships between the peak values with the charge of the different reflections. This line is far from linear, the peak value of the pulse is decreasing far more than the charge of the pulses. As already mentioned it can be concluded that this method is shape dependent and a bad method for determining charge of PD's in cables.

In case the integral of highest peak method results are studied in figure 6.23, the error of 10% made for small pulses corresponds to a low cutoff frequency of about 32kHz. For the wider pulses, this frequency lies at about 8kHz, see figure 6.25. These cutoff frequency values are very low and reach very fast the 10% error limit. Therefore the method is not very suitable for usage of a very diverse set of sensors. This method is only usable when sensors with very low bandwidth are used. Then it can measure a large diverse set of pulses with a good accuracy. This is logical, because the time response measured with sensors at this small low cutoff frequencies are very likely the original pulse.

Figure 6.23 shows that the frequency spectrum peak method is a good method for determination of charge of small pulses, using sensors with low cutoff frequency below about 350kHz (within 10% accuracy). For longer pulses this frequency decreases rapidly, what could be expected. Figure 6.18 shows that the wider the pulses, the earlier the steep decrease in the frequency spectrum starts. Measuring with a relative high low cutoff frequency, gives a relative low peak value in the spectrum.

This is because the frequencies below the cutoff frequency are filtered and the frequencies above the cutoff frequency do not have large magnitude in the signal. Because the flat area of the frequency spectrum corresponds to the charge, it is recommended to use this method in the flat region of a PD pulse.

In chapter 8 is investigated another method. With this method the gain of the sensor is compensated. Applying this in simulations using software made filters instead of real sensors, will always give a perfect result. This is the reason why the method is investigated in the chapter with real experiments.

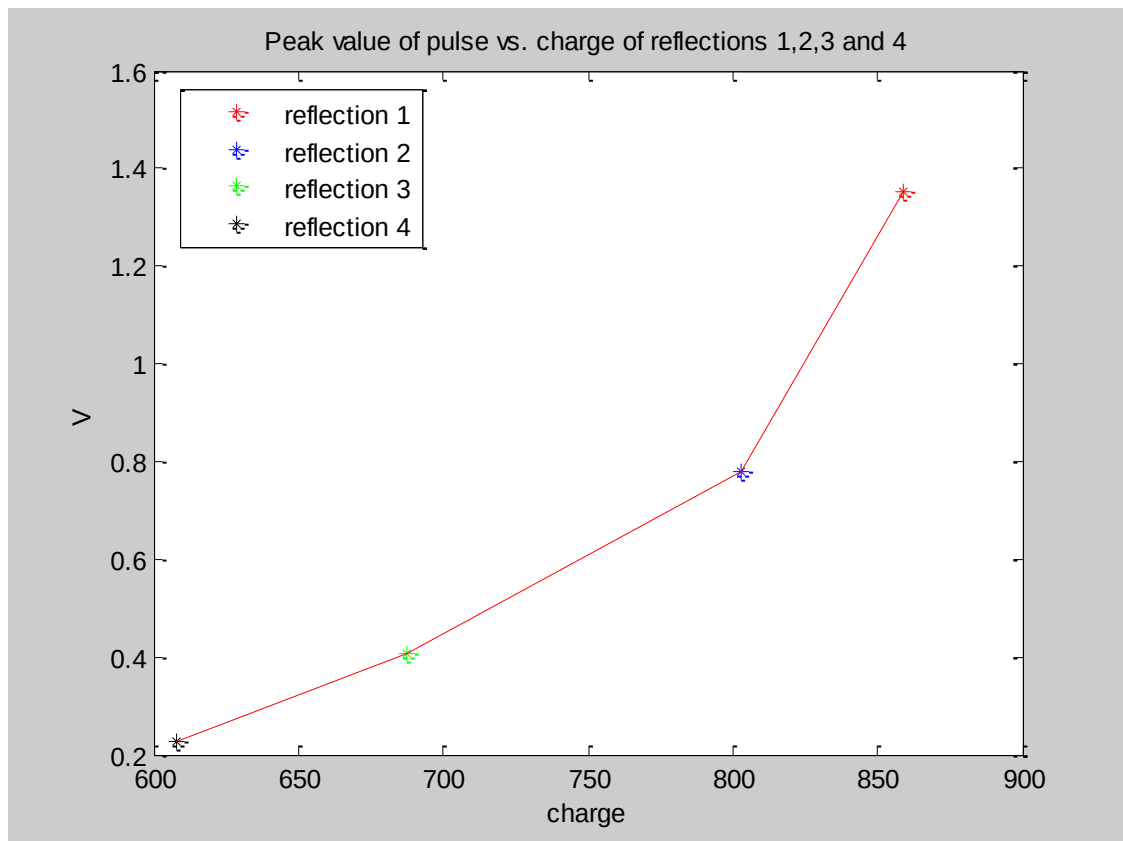


Figure 6.22: Relation between peak value of UWB pulse and charge of pulse in table 3

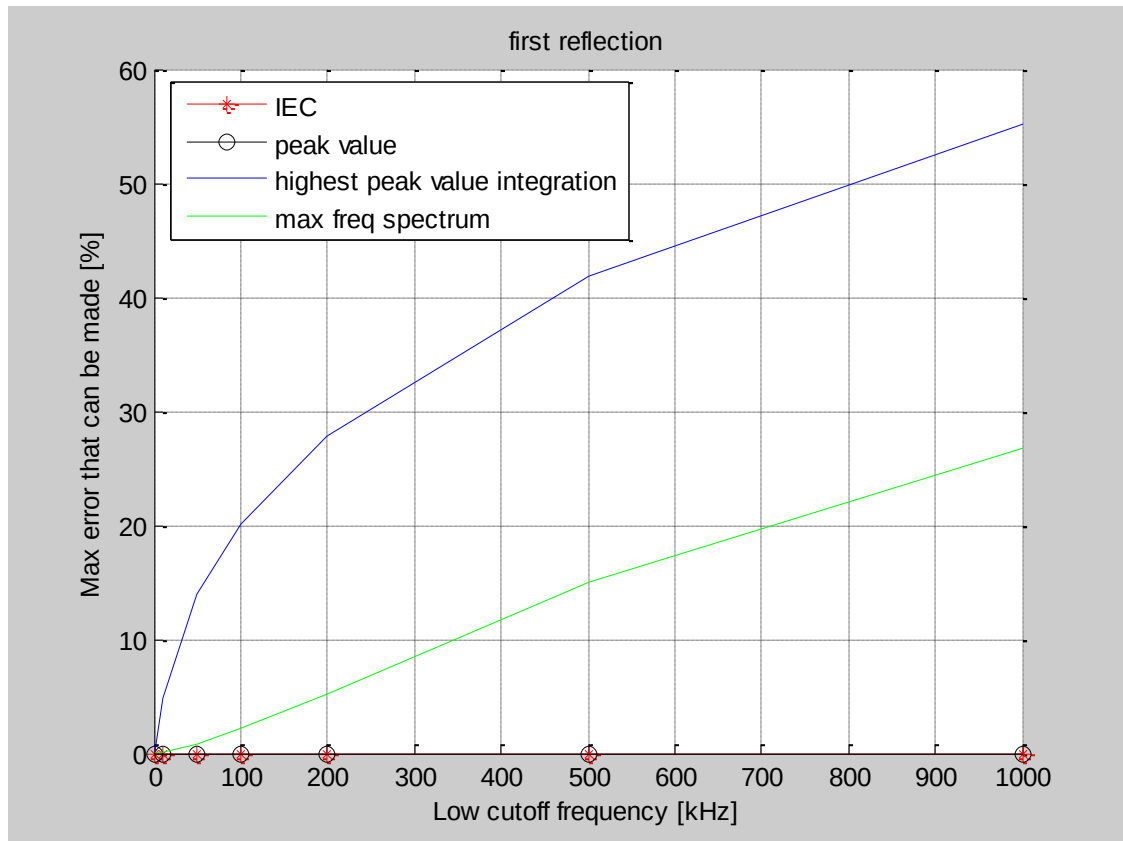


Figure 6.23: Error making with different charge determination methods and different systems

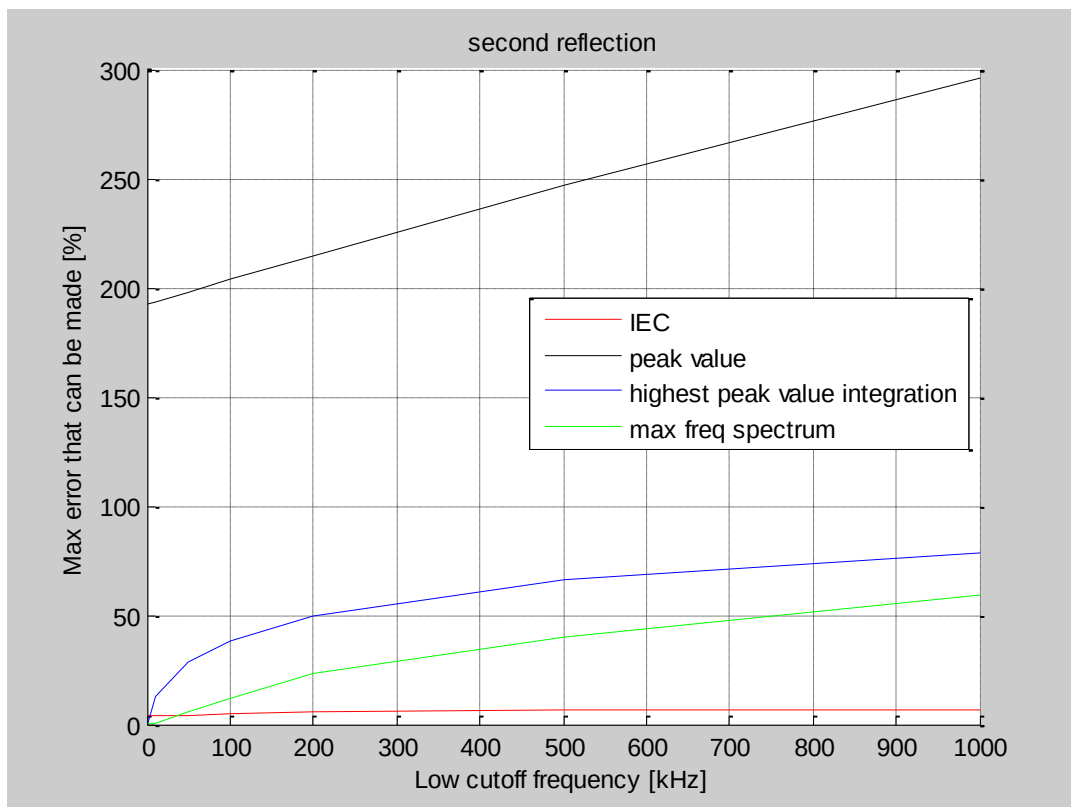


Figure 6.24: Error making with different charge determination methods and different systems

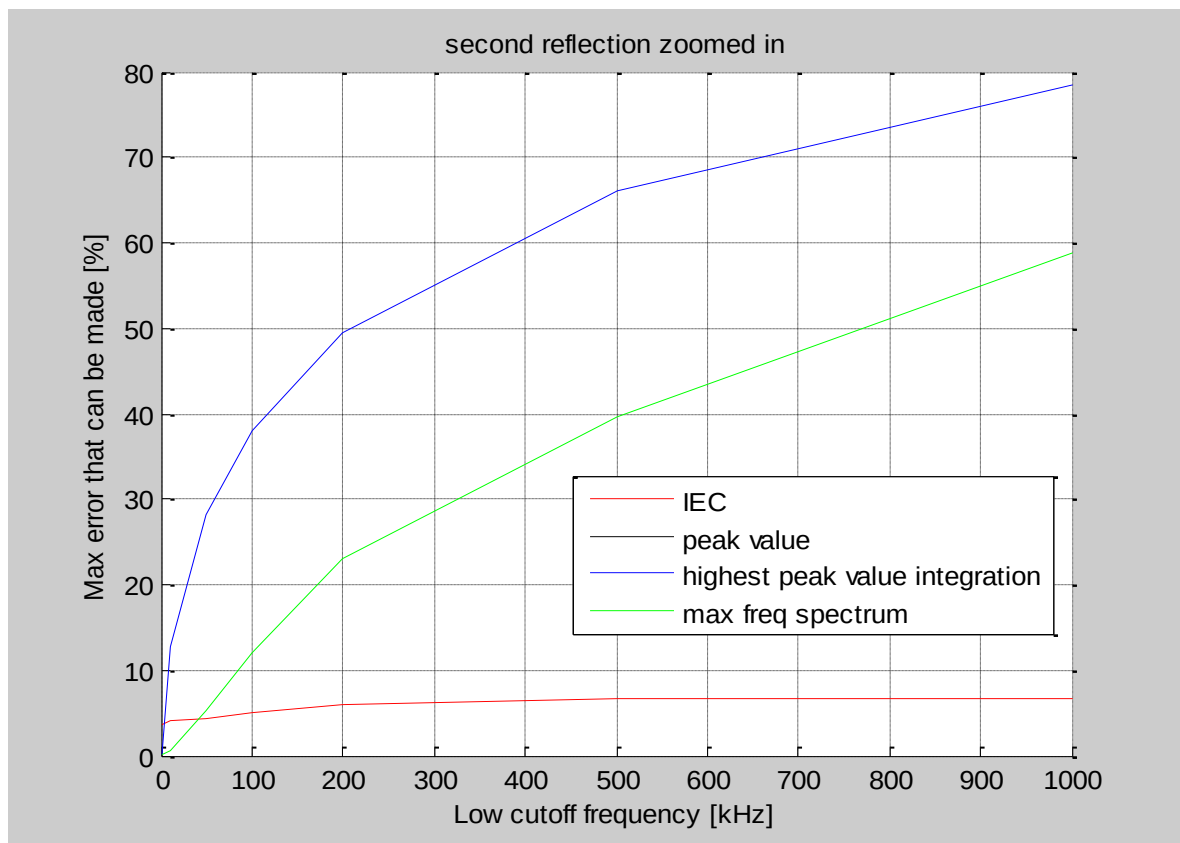


Figure 6.25: Error making with different charge determination methods and different systems
zoomed

6.4.4 Conclusion

PD measurement according to the standard, the used sensors have to cover the IEC bandwidth. Therefore this method cannot be used for measuring with sensors that have a lower cutoff frequency above 100kHz. When using the correct sensors the method is very accurate for charge determination of pulses with a rise time < 100ns.

For measuring small pulses with rise time < 60ns, the frequency spectrum peak method can be used for very accurate charge determination, using sensor with low cutoff until about 350kHz. For wider pulses this method requires sensors with a lower low cutoff frequency.

By using the peak value of the measured PD pulse, there can be made a very large error. This is a very inaccurate method for determining charge of PDs in cables.

The integration of the first peak method is only accurate for sensors with a very low lower cutoff frequency. Therefore this is not the most preferable method to use for PD measurement in cables.

For PD measurement in cables, the frequency spectrum peak method has the advantage of a small time response compared with conventional measurement. Depending on the high frequency content of the measured pulses, a wide range of sensors can be used while the charge is determined in an accurate way. Therefore, this is the most preferable method to use.

7 Influence of the measuring circuit on the measurements

7.1 Introduction

When PD measurement is performed with a combination of coupling capacitor and measuring impedance, the measuring impedance creates together with the coupling capacitor a filter. For measuring according to the standard it is important that this filter covers the bandwidth of the applied IEC filter. For charge determination of PDs in cables with conventional measurement it is desirable to measure with a filter that has a bandwidth with a low lower cutoff frequency. This chapter shows the influence of different measuring component combinations on the bandwidth of the system.

7.2 Influence of different measuring components on the gain of the system

First we are going to define the ratio between the operating voltage, and the voltage over the measuring impedance, or output voltage / input voltage. Equation 7.1 gives the ratio between the output voltage and the input voltage.

$$\frac{V_{out}}{V_{in}} = \frac{Z_m}{Z_c + Z_m} V_{in} = \frac{Z_m}{\frac{1}{j\omega C} + Z_m} V_{in} = \frac{Z_m j\omega C}{1 + Z_m j\omega C} \quad (7.1)$$

Thereby

Z_c = Capacitor impedance

Z_m = Measuring impedance

V_{in} = Input voltage over the combination of coupling capacitor and measuring impedance

V_{out} = Output voltage, the voltage over measuring impedance

Equation 7.1 shows that $\frac{V_{out}}{V_{in}}$ decreases when C decreases. Therefore it seems to be preferable to select the coupling capacitance as large as possible. But a larger capacitance causes a larger reactive power consumption. In the High Voltage lab of the TUDelft there are commonly 1nF coupling capacitors. When a measuring impedance is ordered, it has to be designed in a way it matches with the used coupling capacitor to achieve the desired frequency response.

7.3 Measurements

This subchapter shows gains of combinations of coupling capacitors and measuring impedances. Next to this also a gain of a HFCT is shown.

7.3.1 Coupling capacitor combined with measuring impedance

Now the gain of some combinations of measuring impedances and coupling capacitors is determined to make clear that the coupling capacitor and the measuring impedance have to be matched to each other. Figure 7.1 shows the gains of the different coupling capacitor and measuring impedance combinations. The components used are:

- Tuneable Haefely measuring impedance
- Coupling capacitor of 1056pC
- Seitz calibrator 3706
- MV cable 640m
(see appendix A)

The gain of the system is obtained relatively easily. First a calibrator pulse is injected at the end of a MV cable. The pulses are recorded with only an oscilloscope probe at $1M\Omega$ input impedance at UWB at the beginning of the cable. The first pulse of all reflections is recorded and used for determination of the gain of the system because this pulse is the shortest one and has the longest constant frequency response from DC until the frequency content decreases. The injection of the calibrator pulse takes place at the end of the cable because in that case it is clear that the calibrator has no influence on the frequency response of the system. The pulse is recorded for an injected charge of 500pC and 1000pC.

Secondly the same measurement is performed, but then the calibrator pulse is measured with the combination of coupling capacitor and Haefely measuring impedance.

For gain determination, the frequency spectrum of the recorded pulses is calculated in Matlab, by the FFT function.

The last step is to divide the frequency spectra of the two recorded pulses. The frequency spectrum of the pulse measured with the coupling capacitor and measuring impedance is divided by the frequency spectrum of the UWB pulse. The gain follows out of this calculation.

It is clear that in case the Haefely measuring impedance is tuned to 1nF and there is made a measuring combination with 1nF, the gain is more or less flat and stable. The low cutoff frequency of the filter is about the same and is situated around 40kHz. We see that there is a difference between the two 1nF tuned gains. First in the flat area, the gain of the system with the non earthed capacitor frame is higher, so they can be measured with higher sensitivity. In case the coupling capacitor is earthed, there is formed a resonance peak around 4,4MHz with afterwards a strong decrease in gain. The system acts like a band pass filter.

When comparing the two 20nF gains, give more or less the same result. A difference is that the system with non earthed capacitor frame has a higher gain. Furthermore the system with the earthed capacitor frame has another resonance peak around 7,6MHz.

7 Influence of the measuring circuit on the measurements

Comparison of the 1nF gains with the 20nF gains, show big differences. The low cutoff frequency of the 20nF gains lies at about 500kHz. Therefore the sensitivity of the 20nF gains is lower than both 1nF gains for frequencies below 500kHz.

It can be said that for achieving the desired gain, it is very important the measuring impedance is designed for usage with the coupling capacitor that is going to be used in combination with it. The system only can be used for conventional measurements when the system fulfils the requirements for conventional measurements (see chapter 6.2.4). Also for unconventional measurements it is important to know the impulse response of the system, to say something about what is measured.

Chapter 6.3 discussed that the low frequencies are important for determination of charge of a PD pulse in cables. The charge can be determined of the height of the flat area, beginning at $\omega=0$. The longer the flat region reaches to the higher frequencies, the more can be filtered away from the low frequencies. For pulses in cables this flat region is very small, see figure 6.18. Because the higher frequencies of a pulse face high attenuation during travelling through the cable, the pulses expected to measure are not that small and steep and the frequency region of around about 150kHz is also important. Therefore a well tuned gain is needed.

7 Influence of the measuring circuit on the measurements

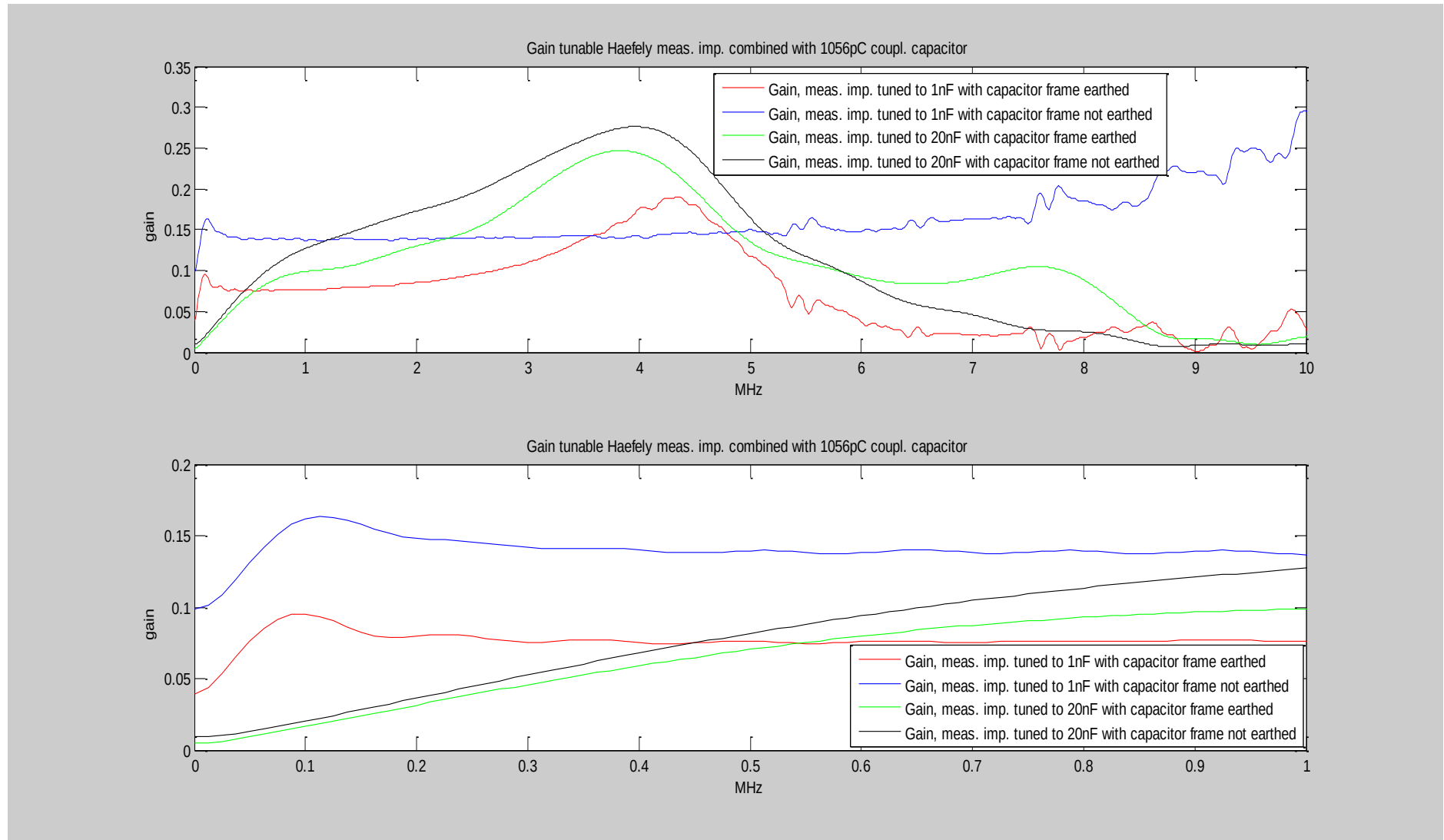


Figure7.1: Gains of the measuring combination of tuneable Haefely impedance AKV 568 and 1056pF coupling capacitor

7.3.2 High frequency current transformer

The problem for HFCTs is that they cannot be tuned. For HFCT the circuit in which the HFCT is placed can also influence the measurement. There can arise resonance peaks in the system frequency response. In that case, the specification of the manufacturer does not fulfill. Therefore also current transformers have to be calibrated before measurement is performed. Figure 7.4 shows the gain of a HFCT with a low cutoff frequency of 1MHz. The HFCT gain is determined by the signal gained in the way that is shown in figure 7.2. The calibrator is connected directly the 50 Ω input of the oscilloscope. The HFCT is placed around one wire that connects the calibrator with the oscilloscope. In this way there is fed the same pulse to the oscilloscope probe and the HFCT. The measured signals are shown in figure 7.3. With this signals the gain is determined and is show in figure 7.4. This is not a real situation, in real they are placed in a MV circuit.

Figure 7.2: Measurement setup

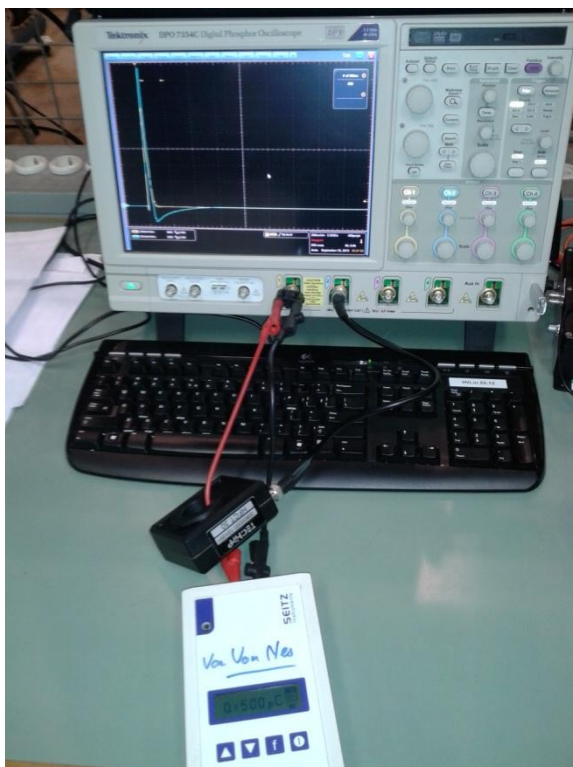
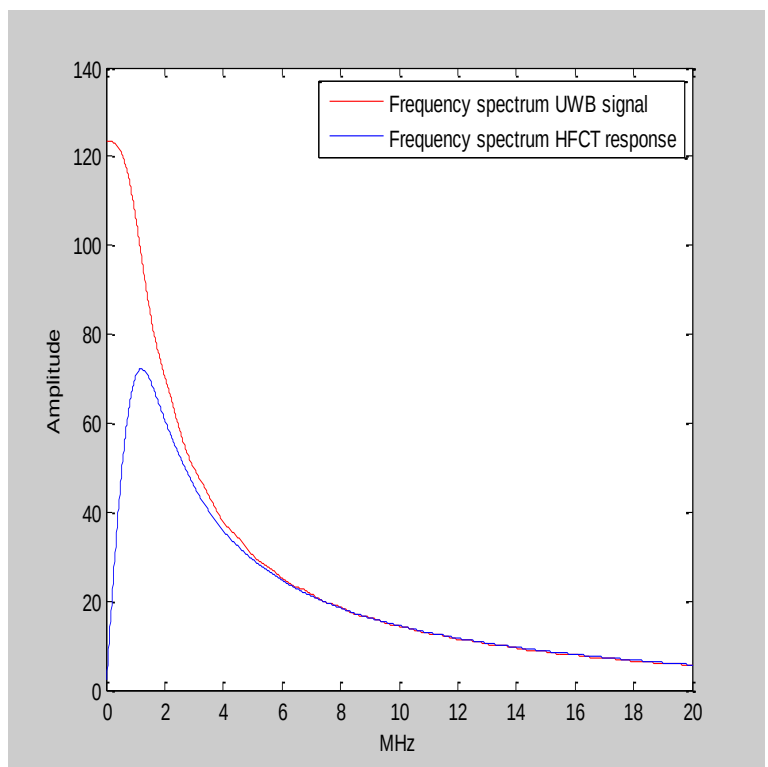


Figure 7.3: Measured signals at same time with HFCT



and UWB

For online measurements, HFCT are placed in different circuits around the earth electrode. Different impedances could be connected to the end of the cable. To know more about the measured pulse, the impulse response of the system is needed. When this is known, the sensor can be calibrated and the charge can be determined at an accurate way. In chapter 8 the calibration of different measurement systems is treated.

7 Influence of the measuring circuit on the measurements

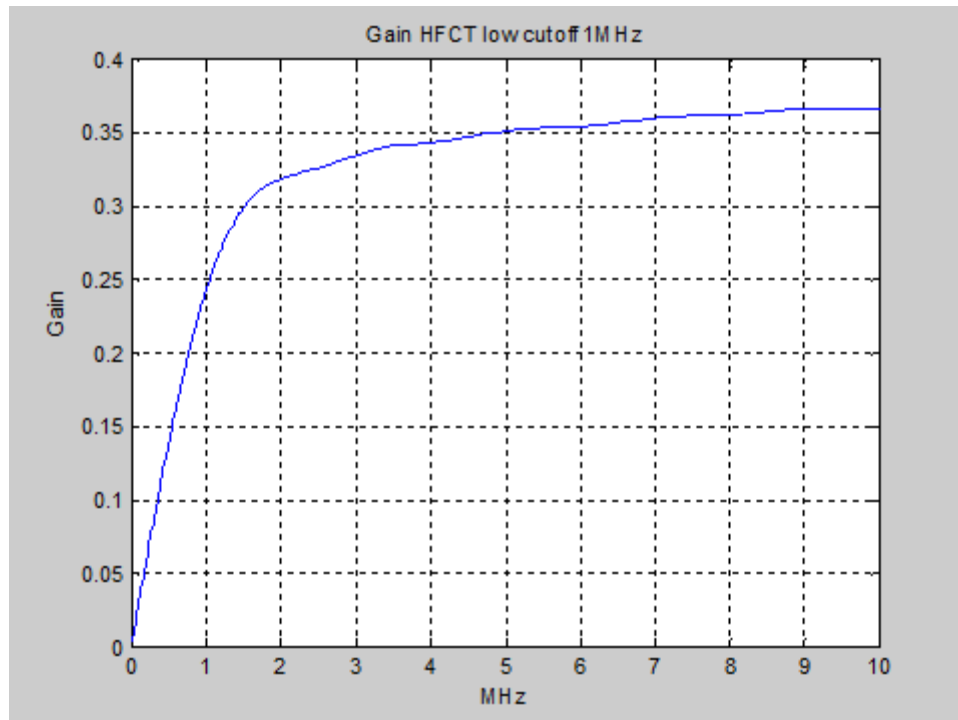


Figure 7.4: Frequency response HFCT, measured with setup of figure 7.2

7.4 Conclusion

It is shown that the combination of components in a PD measurement circuit can have large influence on the measurement. To know what is measured, it is important to know the frequency response of the system. When this is known, in case a combination of measuring impedance and coupling capacitor is used, the gain of the system can be tuned. In case it is not possible to tune the gain of the system, it might be a solution to calibrate the gain to obtain the right information about the PD pulse. This subject is treated in chapter 8.

8 Gain compensation of the measurement system

8.1 Introduction

In chapter 6.3 is mentioned already that the $X(f=0)$ of the Fourier transform corresponds to the sum of all measured samples and is proportional to the charge. Strong attenuation of high frequencies cause a small frequency spectrum, the flat region of the spectrum is very small. Because the lower frequencies are important for determination of the charge of a pulse, charge determination can become more difficult.

Sometimes PD is measured with a relatively high lower cutoff frequency. Next to this, the system could have a very undesirable frequency response, caused by components that influence each other. An undesired frequency response in especially the low frequencies, can filters required information for determination of the charge.

This chapter shows a method to compensate the gain of the system and makes it possible to determine the charge in an accurate way.

8.2 The method

The procedure for gain compensation is shown in figure 8.1. First the frequency response has to be determined for every measurement setup. When this is known, the measured frequency spectrum of the PD pulse can be compensated. Out of the compensated frequency spectrum the charge is determined by picking low frequencies values out of the spectrum.

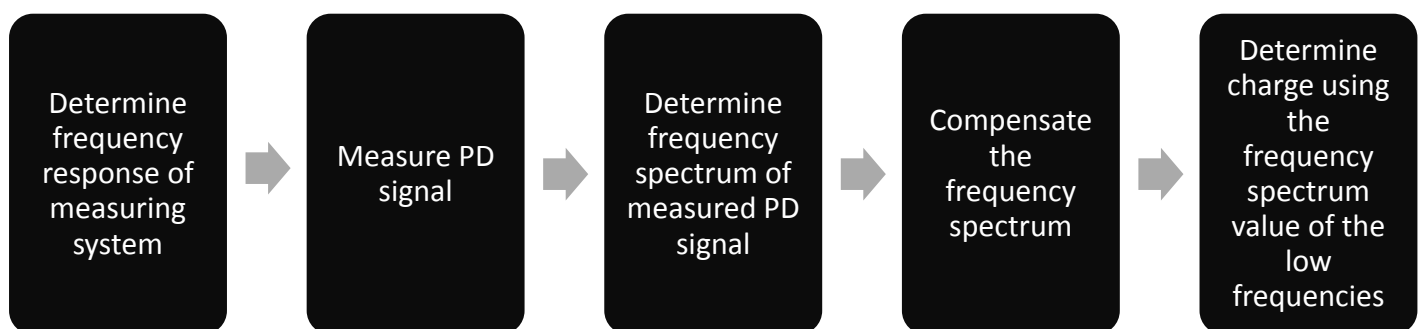


Figure 8.1: Method for charge determination by compensation of the gain of the measuring system

8.2.1 Determination of the frequency response of the system

The measured output of a system is given by equation 8.1.

$$y[i] = x * h = \sum_{j=0}^{M-1} x[j] h[i-j] \quad (8.1)$$

Whereby

Y = output signal

M = number of samples in input signal

X = input signal

h = transfer function of the filter

We see that the output signal is equal to the input signal times the transfer function of the system.

We are interested in the magnitude of the frequency response of the PD measurement system, or the response of the system to different frequencies.

In the ideal case there is used a $\delta(t)$ for determining the frequency response of the measurement system. Equation 8.2 shows that the $\delta(t)$ function contains all frequencies with magnitude 1.

$$X(\omega) = \int_{-\infty}^{\infty} \delta(t) e^{-j\omega t} dt = 1 \quad (8.2)$$

In real this is not possible. Therefore a calibrator pulse is used that can inject a pulse that has a sufficient high frequency content.

The first step is to inject a calibrator pulse into the test object and measure it with UWB at the place where the measuring equipment should be connected. In this way the total frequency content of the injected pulse is determined. With this information, the frequency spectrum of the pulse can be determined.

The second step is injecting a calibrator pulse in the same way as in the first step, but now the pulse is measured by the PD measurement equipment. As follow the frequency spectrum of the measured signal has to be determined. In practice the spectrum is not the same as measured at UWB because the measurement system has a frequency response that is not for every frequency equal to one.

The response of the measurement to the magnitude of different frequencies is:

$$Gain(\omega) = \frac{\text{Magnitude system FFT signal}(\omega)}{\text{Magnitude FFT UWB signal}(\omega)} \quad (8.3)$$

Now the gain of the system is know for every frequency of the calibrator pulse, there is known what information of the pulse is filtered. Knowing what information is filtered, a signal measured by the PD measurement system can be compensated by adding this filtered information. This to obtain the original frequency spectrum magnitude. The frequency response of the system has to be determined every time the measurement system changes.

8.2.2 PD signal compensation

After determination of the frequency response of the PD measurement system in the specific setup, PD measurement can start. When PD activity is measured, first the PD pulses have to be selected out of the measurement data. The next step is to determine the frequency spectrum of the selected PD pulse. Because the system filters some in formation of the PD pulse and we know what it is, we can compensate the measured PD signal. The magnitude of the frequency spectrum of the measured PD

signal is divided by the gain determined with equation 8.3 and the original magnitude of the frequency spectrum is obtained.

8.2.3 Charge determination

The charge of the compensated PD pulse can be determined by taking a magnitude value of the flat region of the frequency spectrum of the compensated PD pulse. This value is proportional to the charge. This method is described in chapter 6.4.

The combination of gain compensation and the charge determination with the frequency spectrum has the advantage that transformation to the time domain is not needed and there has nothing to do with phase, only with the magnitude.

In theory this is an ideal solution. In the next chapter some measurements are presented to check how accurate the method is in practice and to investigate if there are boundaries for this method.

8.3 Gain compensation in practice

Small steep pulses have a long constant frequency spectrum, that starts at 0Hz. The steeper the pulse, the more high frequency content the pulse contains and the longer the flat area of the frequency spectrum (see figure 6.5).

In case filtering some low frequencies, the peak value of the frequency spectrum stays more or less constant until a certain value of cutoff frequency. Figure 8.2 shows frequency responses of a short UWB pulse and the filtered pulse. The higher the low cutoff frequency, the faster the peak value of the filtered signal decreases. Because the high frequency content of pulses that have travelled a longer path is less, the decrease in frequency peak value is even higher. At a certain frequency, the frequency spectrum of the UWB pulse has a magnitude that has a 10% error with the value at 0Hz. These 10% error values are plotted in figure 8.3, for the 1000pC pulse sequence of appendix C.

The values are plotted to make an approximation until what low cutoff frequency the gain of the system at least has to be compensated. This to achieve 10% accuracy with charge determination of the pulses.

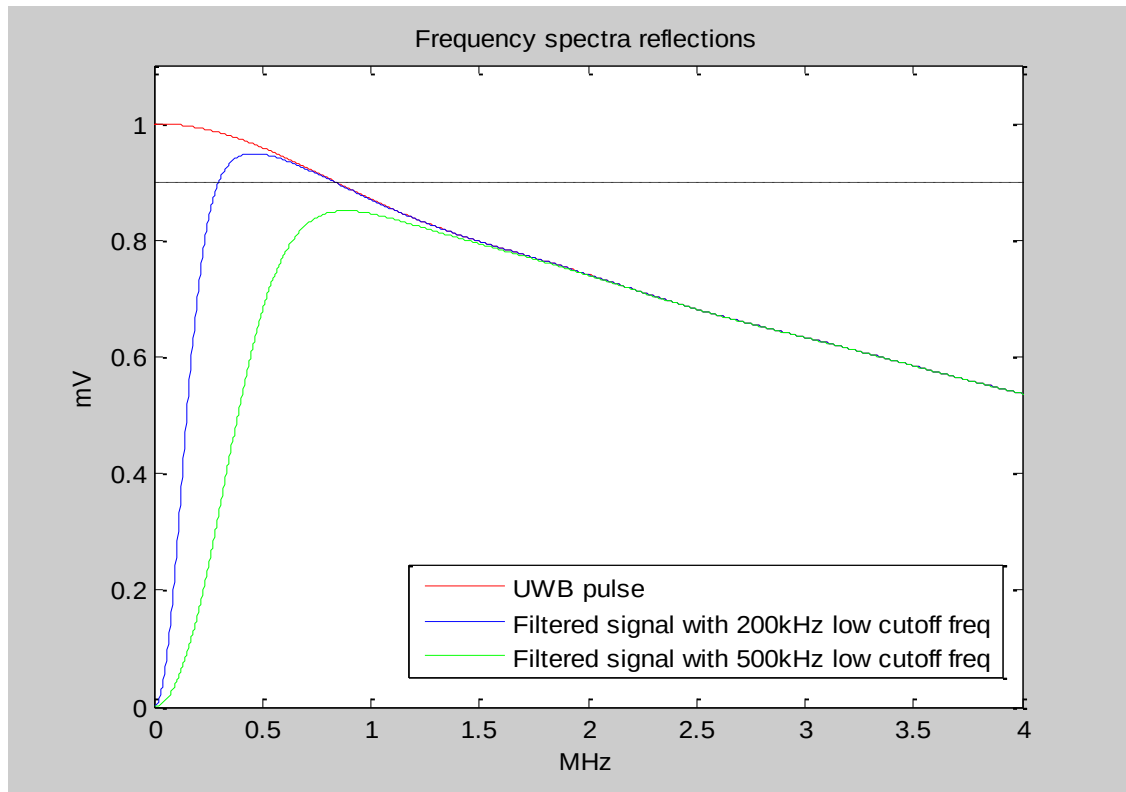


Figure 8.2: Frequency spectra of UWB pulse and its filtered responses

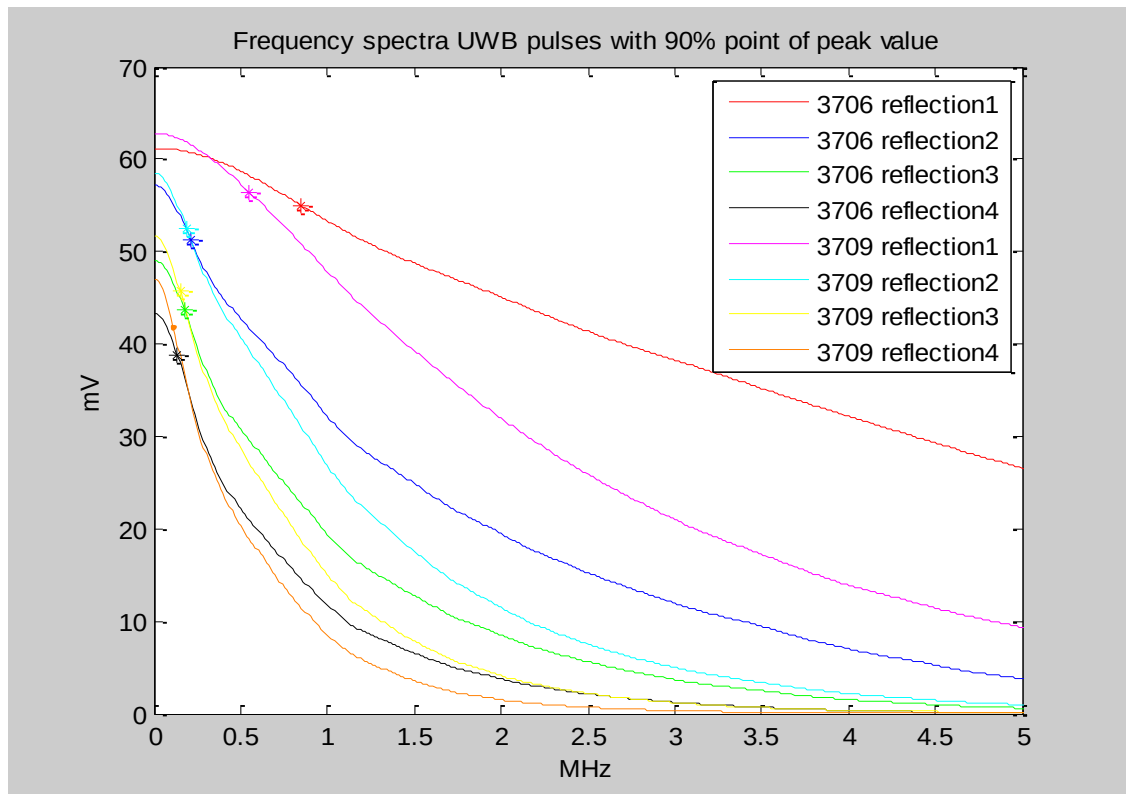


Figure 8.3: Frequency spectra of pulses with different travelling distance and their 90% value of the $X(f=0)$ frequency

Figure 8.3 shows that for the pulses with the longest propagation paths, a correct compensated frequency of 113kHz is needed to determine the charge in an accurate way within 10%. Table 8.1 shows all the 10% error frequencies. Pulses that have travelled a short path have a higher frequency where the spectrum value is 10% of $X(f=0)$. This value decreases strongly as the travelled path becomes longer.

Table 8.1: 90% of $X(f=0)$ amplitude of frequency spectrum of pulses with different travel distances

Pulse	Travelled distance	90% of $X(f=0)$ frequency [kHz]
3706 reflection1	640	850
3709 reflection1	640	550
3706 reflection2	1920	213
3709 reflection2	1920	188
3706 reflection3	3200	175
3709 reflection3	3200	150
3706 reflection4	4480	138
3709 reflection4	4480	113

In the next subchapter the charge is determined with compensation of the gain. A sensor with a relative high low cutoff frequency is selected to test whether the method is that accurate in real.

8.3.1 Gain determination

First we have to determine the frequency response of the measuring system. To really proof the system, we make use of a system with a high lower cutoff frequency.

Equipment used in the test setup contains:

- 640m MV cable
 - Tektronix oscilloscope
 - 1nF coupling capacitor
 - Haefely AKV 568 measuring impedance
 - Oscilloscope probe
 - Haefely calibrator
 - Seitz calibrator
- (see appendix A)

First some reference pulses are recorded. With the Seitz and Haefely calibrators there is injected a pulse at one side of the cable. This pulse is measured at the other end. In this way the calibrator has no influence on the measurement system. It is assumed that there arrives always the same pulse at the measuring point. The measuring impedance of the oscilloscope is set to $1M\Omega$ and the impedance of the measuring system is very large compared with the characteristic impedance of the cable. In that case total reflection will occur.

To collect a series of pulses with different shapes and the corresponding travelling lengths, there are recorded 4 reflections at charges of 500pC and 1000pC. The properties of the UWB reference pulses used are shown in Appendix C.

9 Summary and conclusions

To determine the gain correctly, the gain is determined with reference pulses of 500pC and 1000pC, injected by two different calibrators, the Seitz and Haefely calibrators. The corresponding reflections of the two calibrators are also measured with the measurement system. The system consists of a 1nF coupling capacitor and a Haefely AKV 568 measuring impedance set on position 20nF (tuned to 20nF), so totally not tuned to the 1nF coupling capacitor. This makes that the bandwidth filters a very large low frequency content of the arriving reflections. For pulses 506 of appendix C the measured reference pulses and the pulses measured with the measuring system are shown in figure 8.4. This gives an impression of differences in time domain between the pulses measured at UWB and the measurement system.

Figure 8.4 displays that the sensitivity of the UWB measurement device is far larger than the sensitivity of the PD measurement system. Especially for pulses that have travelled a long path through a cable. These pulses have a small high frequency content, while the measurement system measures only higher frequencies with a relative high sensitivity. This is shown in figure 8.6, where the gain of the system is plotted.

When the reference pulses and the pulses measured with the measurement system are recorded, the reflections can be selected of the long recorded signal.

After this, the frequency spectra of the reference and measurement system pulses are determined. The spectra of reflection 2 of pulse 506 of Appendix C are shown in figure 8.5. The frequency spectra of the pulse measured in two ways differ a lot from each other. It shows that the system acts like a high pass filter with a low cutoff frequency of about 400kHz. The important low frequencies, about below 200kHz, are not measured with a constant gain. Therefore they are not scalable by just a constant to obtain a value that is proportional to the charge.

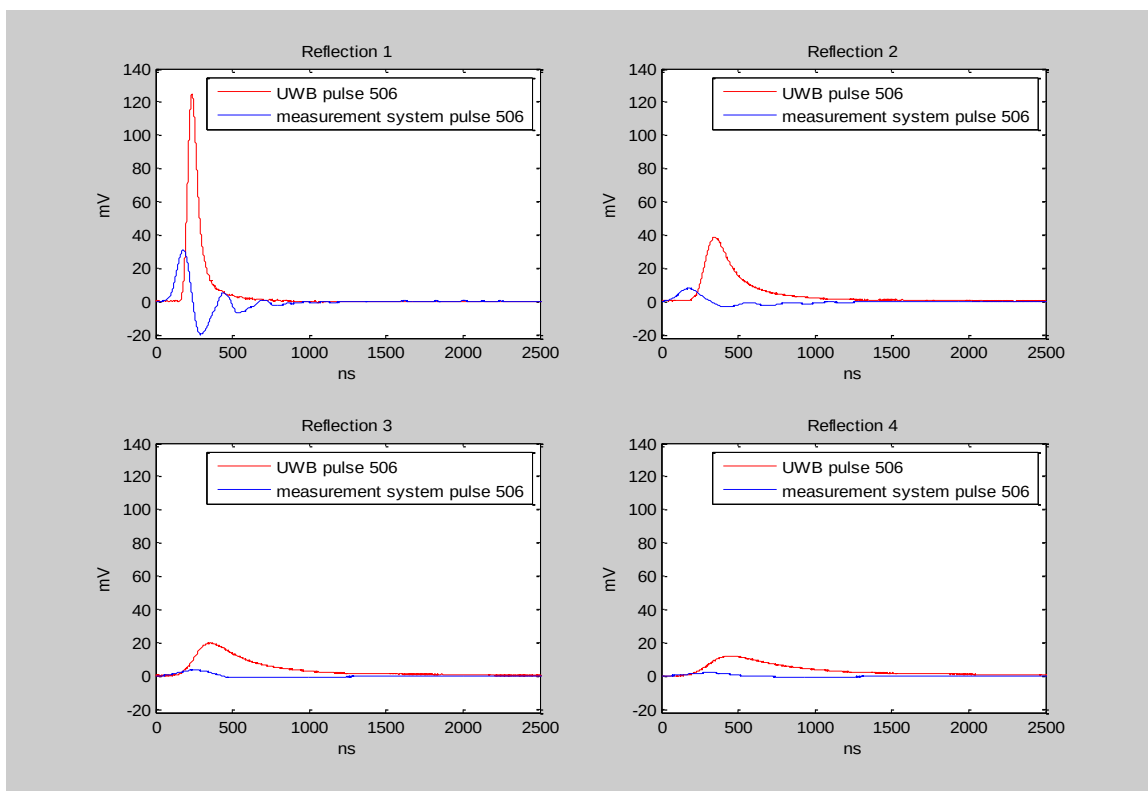


Figure 8.4: Pulse 506 at different travelling distances

9 Summary and conclusions

The red line of figure 8.5 is desired to measure. To achieve this, the ratio between the measured signals of system and the oscilloscope probe has to be determined for every measured frequency. This is done by equation 8.3 with the first reflection of pulses 506, 509, 1006 and 1009 the gain is determined according to this method. The results and the mean of all are plotted in figure 8.6 For the different pulse shapes and charges, the gains in the low frequency region are pretty much the same. Therefore the gain should be pulse shape independent. The mean gain of the determined gains is used for compensation. When selecting system measured pulse of the measurement data, it is important to remove the DC component of the signal. This can be done by removing correctly the offset of the signal. When the DC value has been removed, determination of the gain gets more accurate. As a consequence of determination of the gain of the system with different pulse shapes, give a lower dispersion between the determined gains.

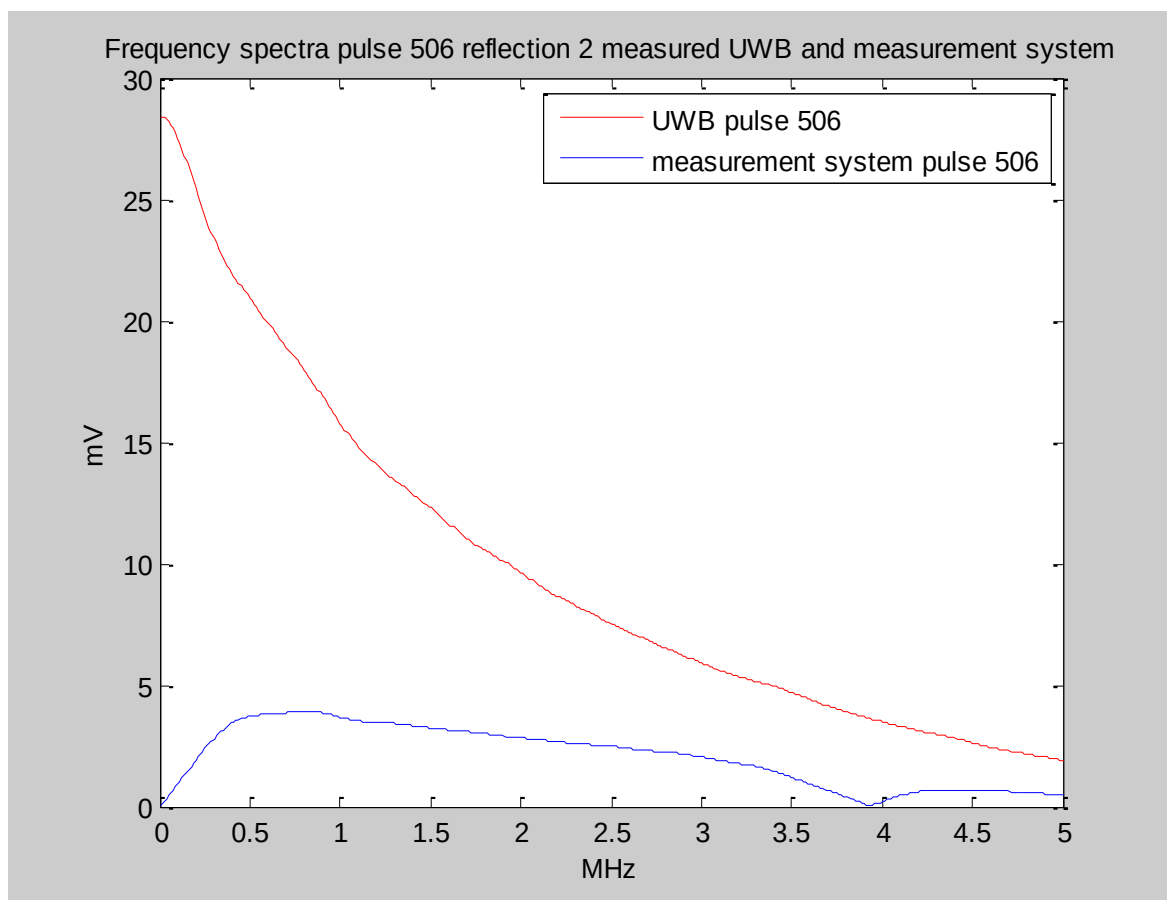


Figure 8.5: Frequency spectrum of UWB pulse and measured pulse

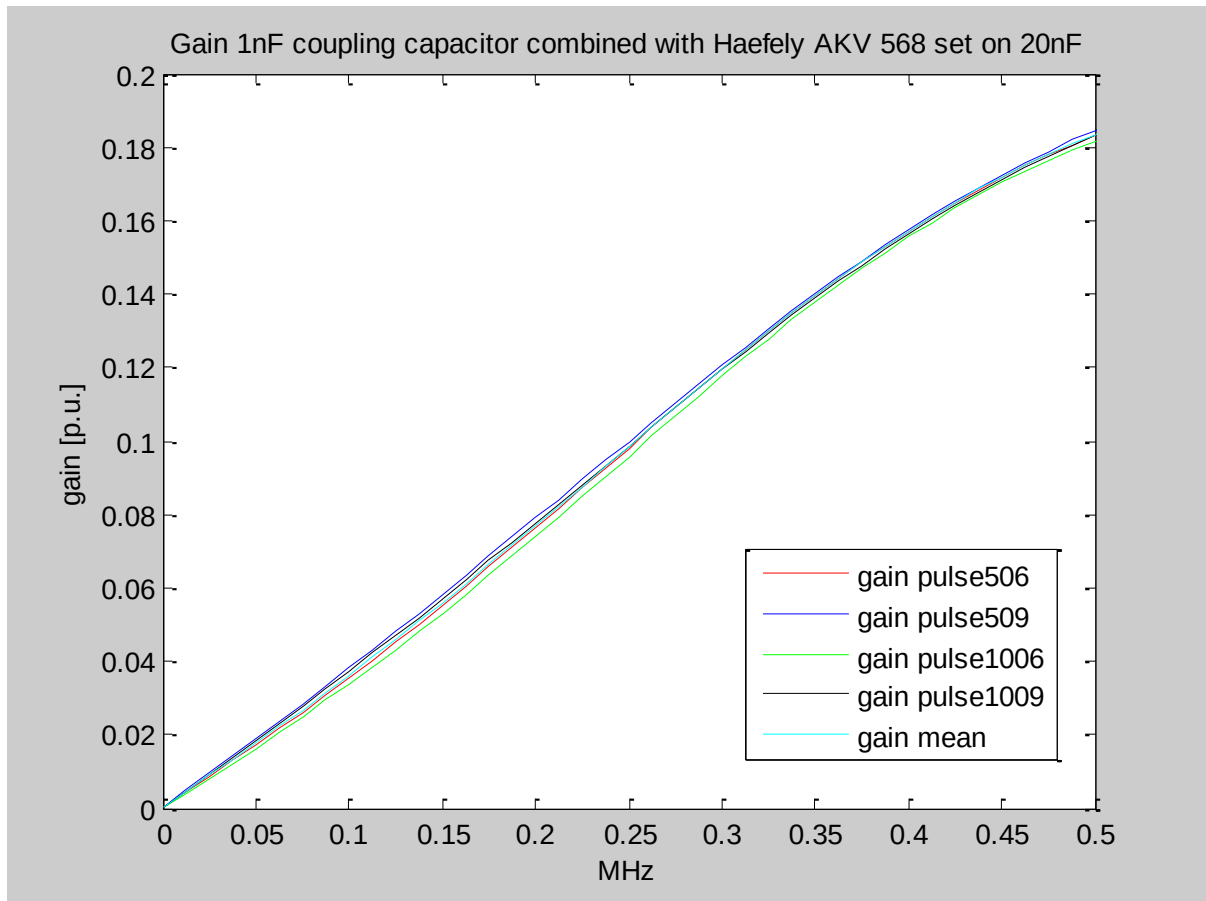


Figure 8.6: Gain of system determined with different calibration pulses

8.3.2 Gain compensation

Now the gain of the measurement system is determined, the correctness of the method can be tested. The gain is determined by the first reflections of pulses 506, 509, 1006 and 1009, thus for two different pulse shapes with two different charges. We are going to verify all 4 reflections of the pulses.

First, the frequency spectrum of the pulses is determined, afterward the spectrum is divided by the gain. In figure 8.7 the frequency spectra of the reflections of pulse sequence 506 there are plotted. It shows the UWB frequency spectrum and the compensated frequency spectra. It shows that the frequency spectra are compensated very well. Only close to the origin the compensated signal becomes very different from the UWB signal. Therefore we can't take the value at $\omega=0$ for determining the charge.

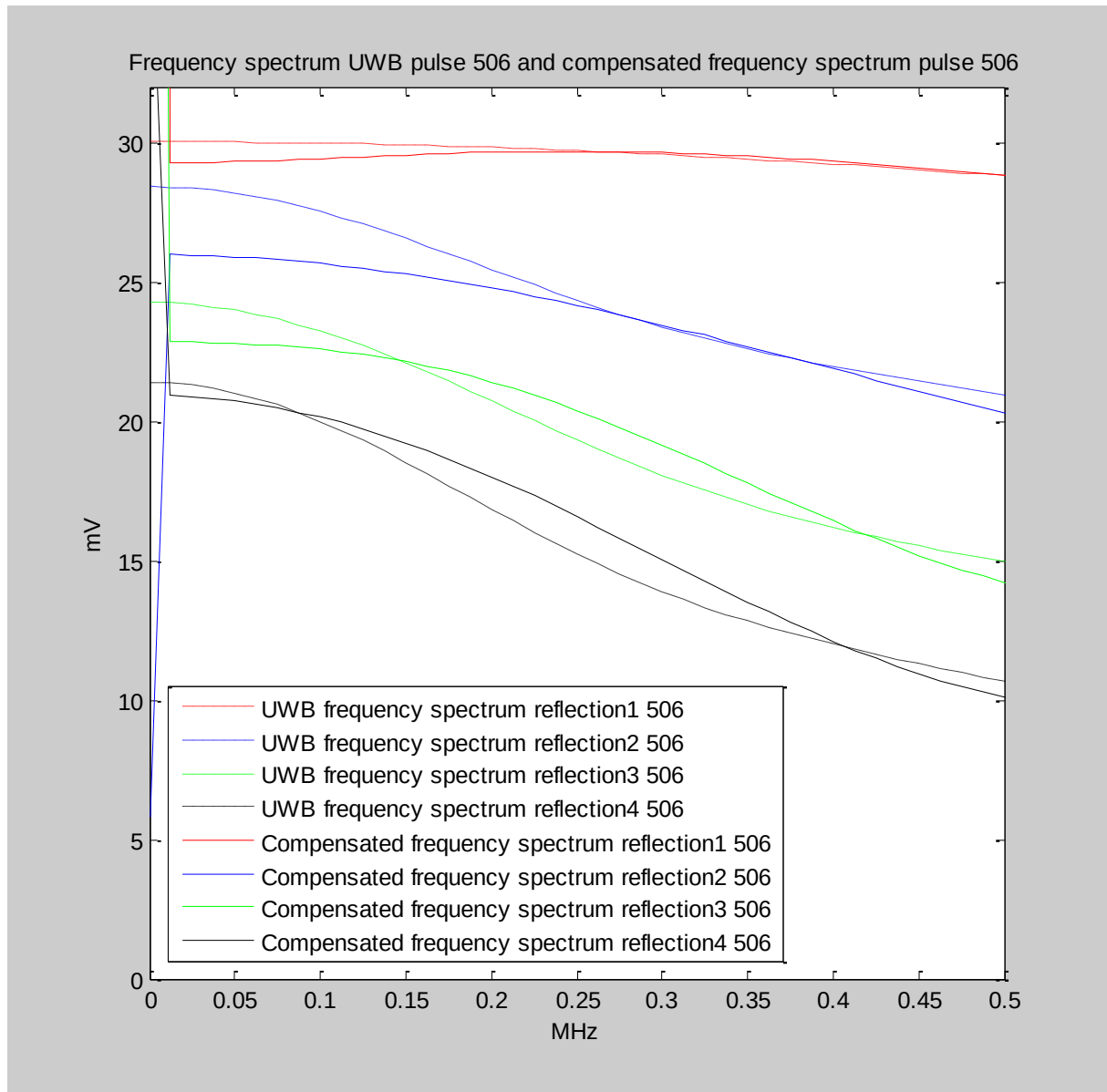


Figure 8.7: Frequency spectra UWB pulses and compensated measured signal

When we take a value out of the frequency plot of the compensated signal, there is a certain error between this value and the value at 0Hz (the sum of all time domain samples) of the UWB signal. For the pulse sequence 506 this error is plotted in figure 8.8.

When we take the mean of the frequency values between 50kHz and 90kHz, for the reflections of pulse 506, the charge is determined within 10% accuracy. In the next step, we check whether this charge determination method is also accurate for all reflections of the pulses 509, 1006 and 1009. Figure 8.9 shows the errors that are made. The charge of all pulses in the sequence is determined within 10% accuracy. For this system and this set of pulses the method is quite accurate.

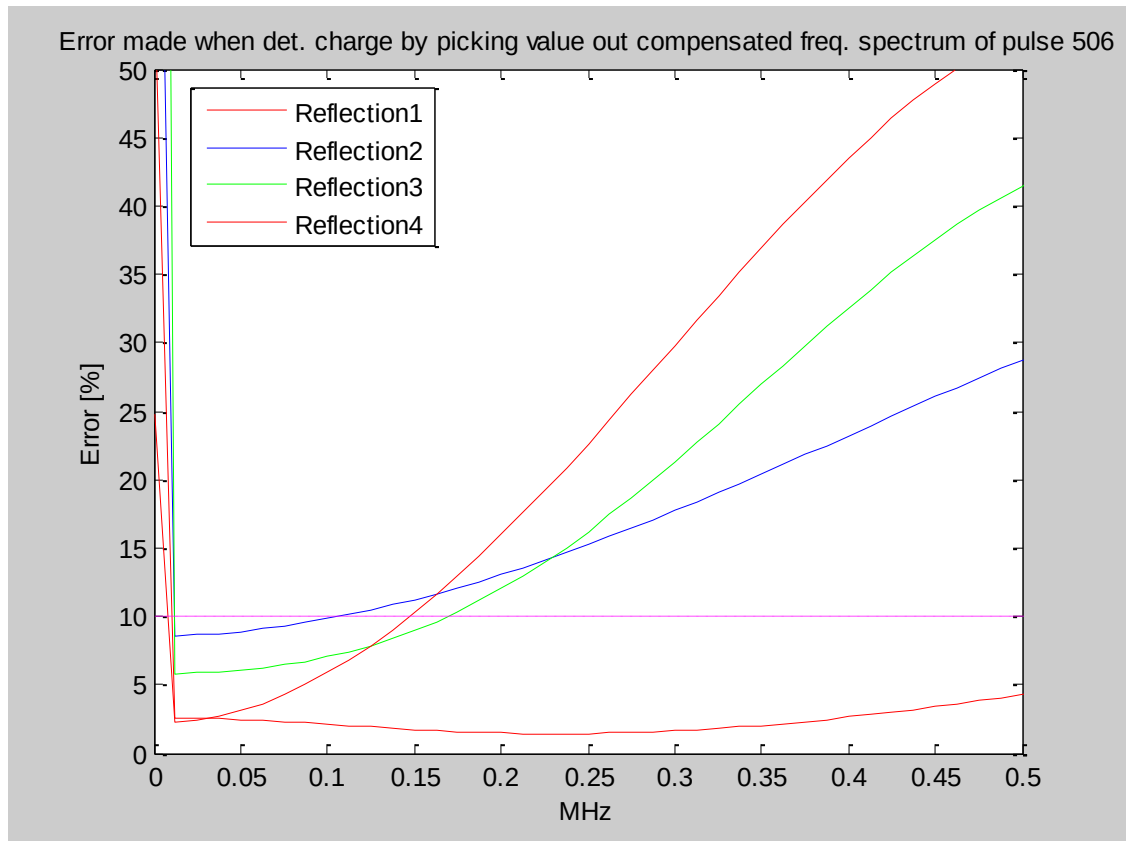


Figure 8.8: Error made when picking frequency spectrum value for charge

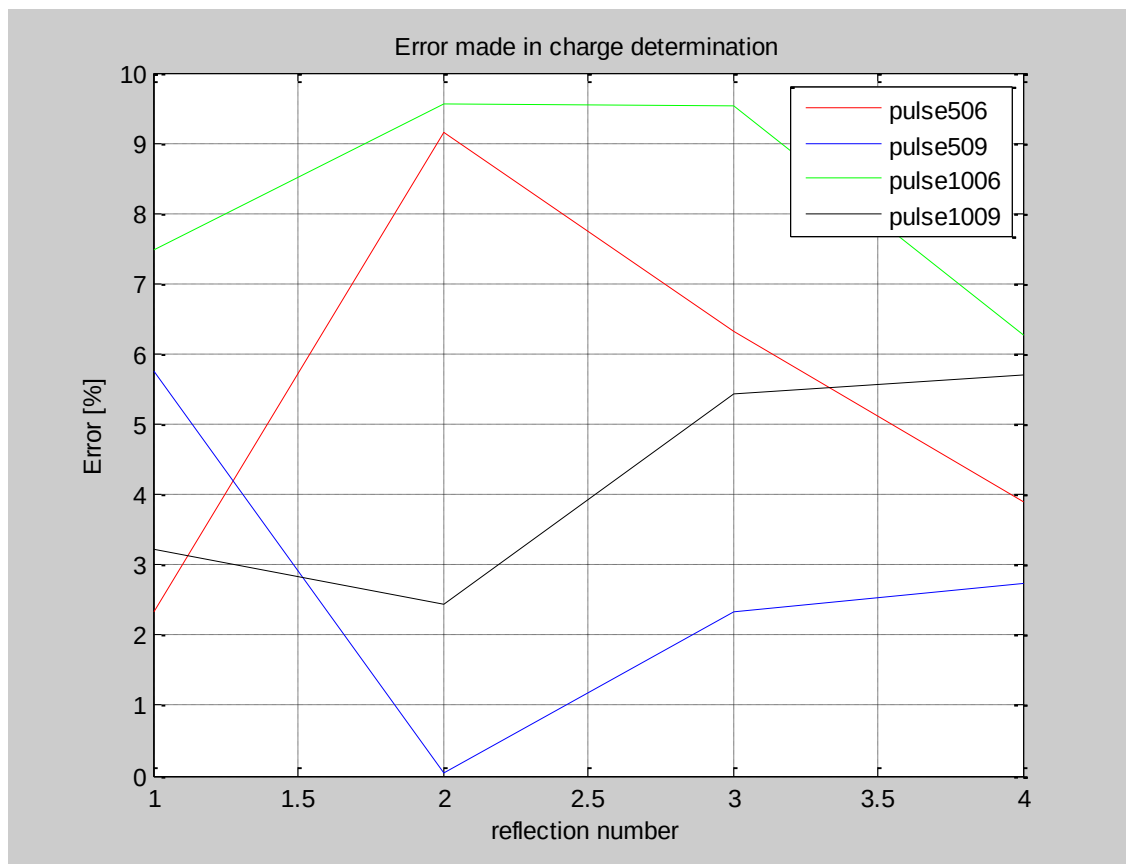


Figure 8.9: Error in charge determination with gain compensation method for different pulses

8.3.3 Applying gain compensation method to a high frequency current transformer

We repeat the same charge determination procedure as described in subchapter 8.3.2, for an HFCT connected directly to the oscilloscope. Like in figure 7.3 two different wave forms are injected with the Haefely calibrator and the Seitz calibrator that are shown in figure 8.10

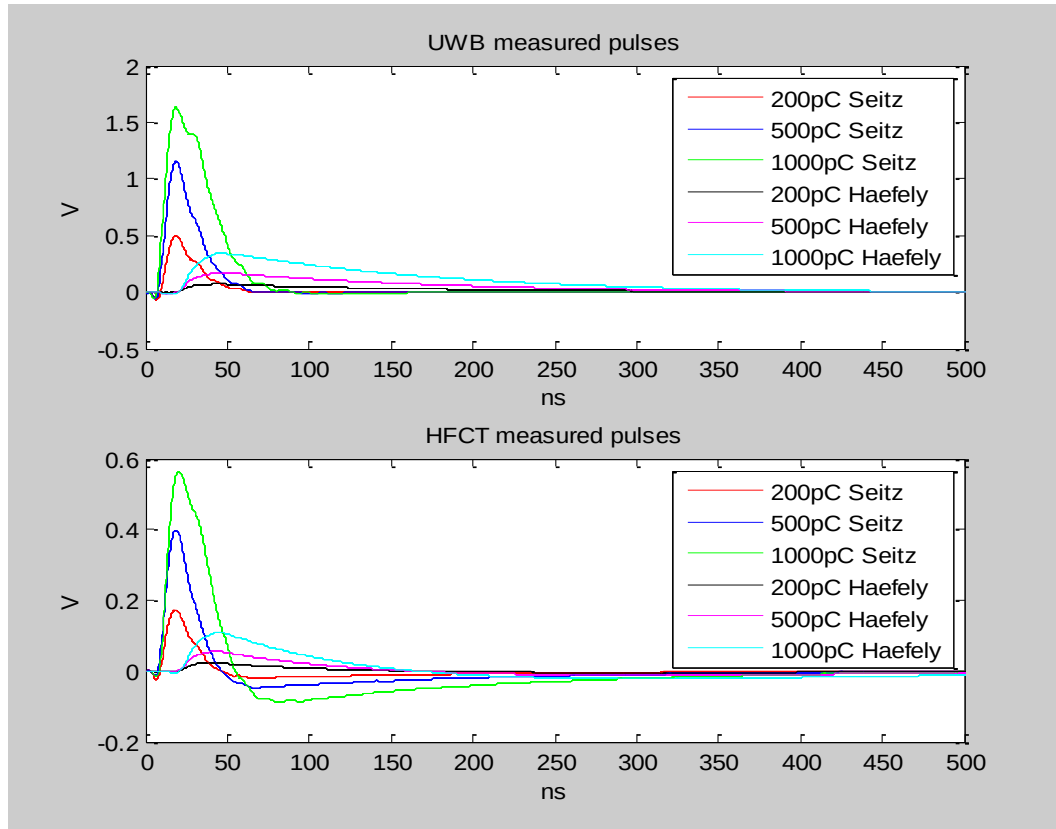


Figure 8.10: UWB pulses of different shape and charge

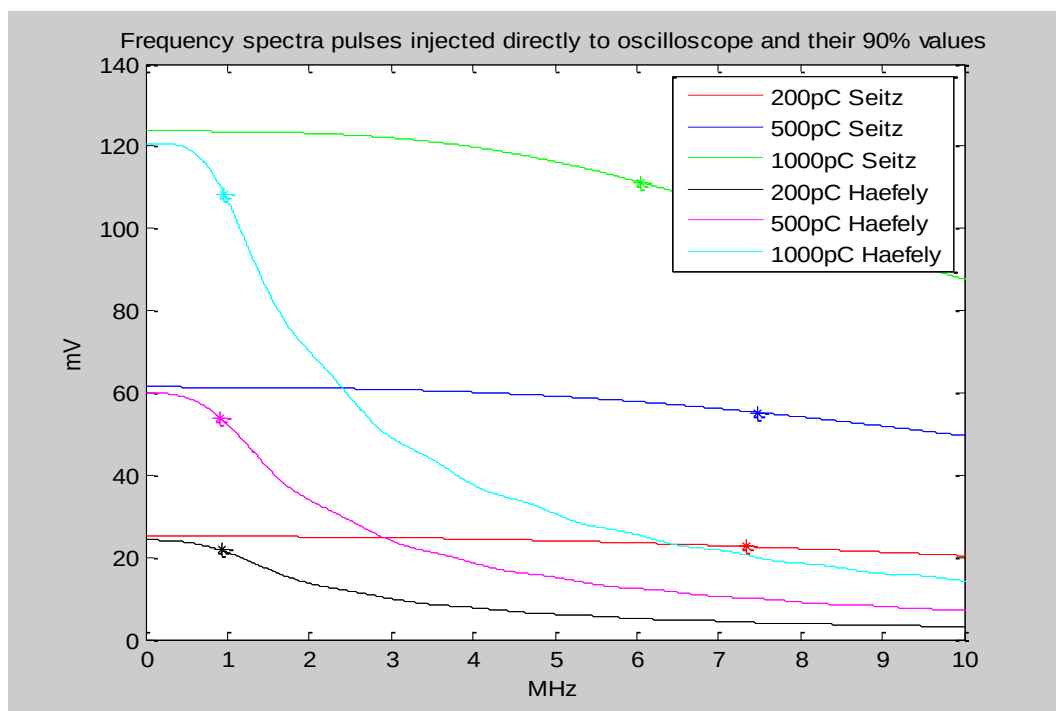


Figure 8.11: Frequency spectra of pulses figure 8.10 and their 90% values of the max value

9 Summary and conclusions

Now the pulses are recorded, we check the frequency at which the spectrum is within 10% error of the $\omega=0$ frequency value of the UWB pulse signal. This corresponds to 10% of the value that is directly proportional to the charge. The values are plotted in figure 8.11 For the steeper pulses, the pulses of the Seitz calibrator, the high frequency content is much larger than of the Haefely pulses. Therefore the 10% difference values of the Seitz pulses lie at a far higher frequency. The values for all the pulses are given in table 8.2

Table 8.2: 90% value of frequency spectrum for different pulses

Pulse	90% of $X(f=0)$ frequency [kHz]
200pC Seitz	7350
500pC Seitz	7475
1000pC Seitz	6037
200pC Haefely	925
500pC Haefely	913
1000pC Haefely	963

The pulses of the Seitz calibrator have all 10% difference with the $\omega=0$ value around 6MHz -7MHz. For lower frequencies the spectrum is flat. Therefore the peak of their frequency spectrum is proportional to the charge. The peak value method of chapter 6.4 can be used and frequency spectrum compensation is not necessary. We apply the compensation method at this sensor as an extra check of the method.

The 10% difference values of the Haefely calibrator are between 900kHz and 1MHz. Because the low cutoff frequency of the sensor lies at about 1MHz the frequency spectrum of the pulses is already attenuated at their 10% difference values. The compensation method is really needed in this case. First, the gain is determined and plotted in figure 8.12. These gains for the different pulses lay close together especially in the lower frequency regions.

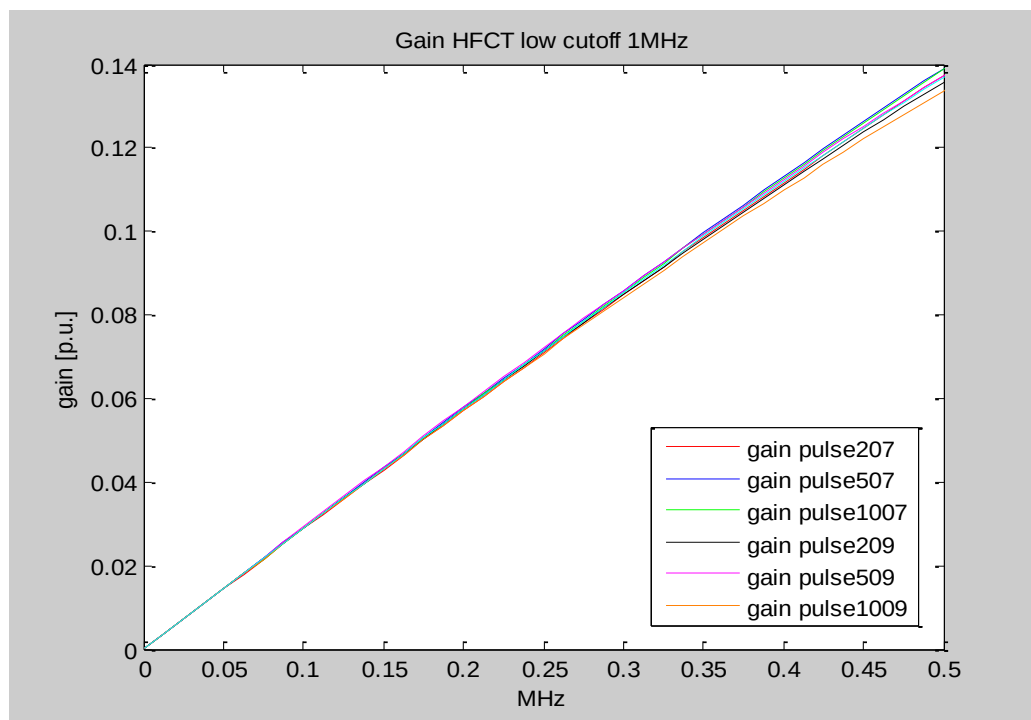


Figure 8.12: Gain of HFCT determined with different pulses

9 Summary and conclusions

As can be seen in figure 8.13 the gain compensation works very well. The Haefely pulses are making an error above 10% in the region where the UWB spectrum is also making a 10% error. For charge determination, just as in the previous experiment, the mean of the frequency spectrum between 50kHz and 90kHz is taken. The errors made are quite small, as can be seen in figure 8.14.

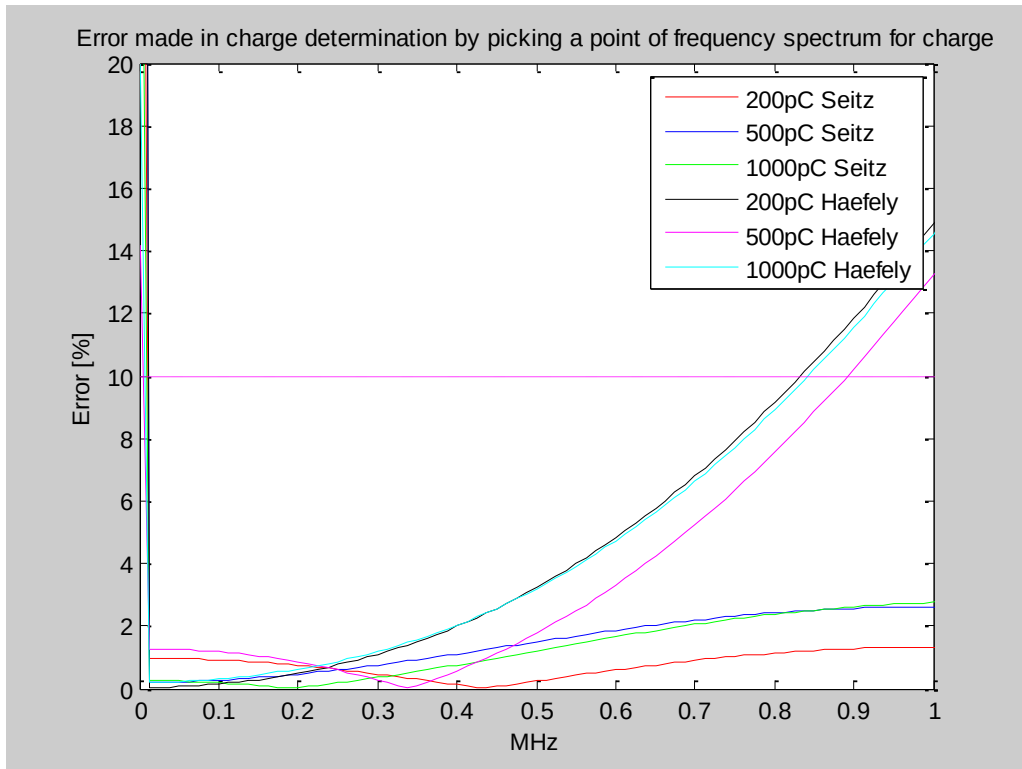


Figure 8.13: Error made when picking frequency spectrum value for charge

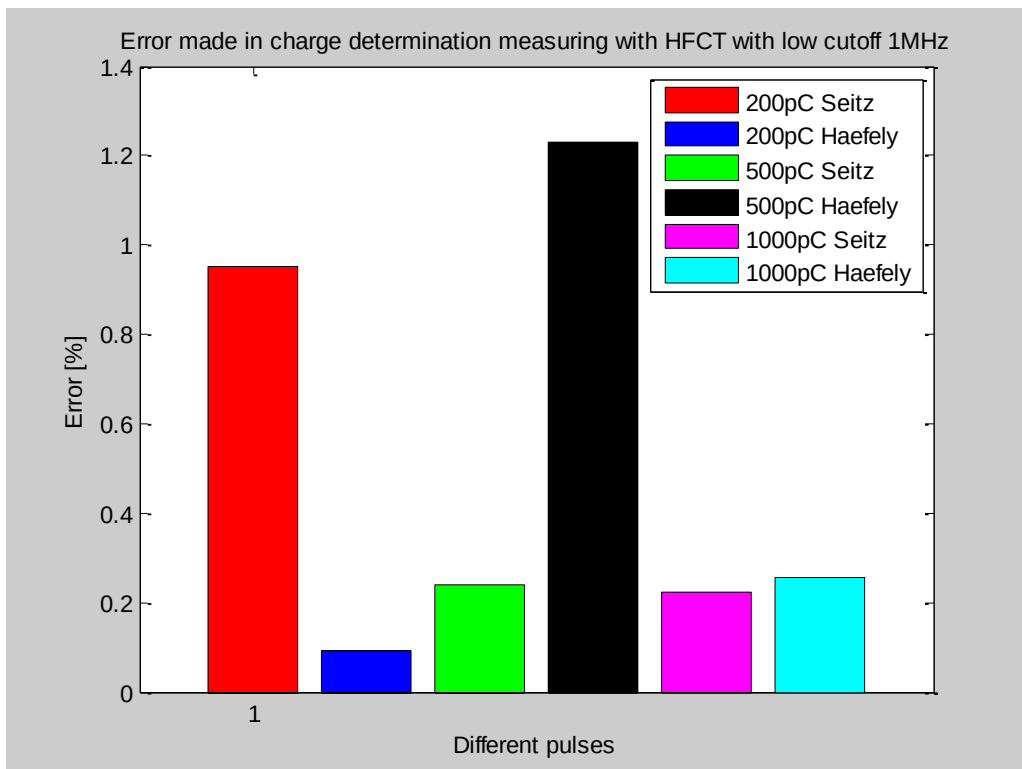


Figure 8.14: Error in charge determination with gain compensation method for different pulses

8.3.4 Comparison of gain compensation method with determining charge by means of taking the peak value of the frequency spectrum

This sub chapter gives an insight about the need for gain compensation in some cases. The system and pulses of chapter 8.3.3 are use. This time the charge is determined by the method that uses the peak value of the frequency spectrum of a measured PD pulse, measured by a sensor. This method is described in chapter 6.4. The difference between this method and the gain compensation method is that this method makes use of 1 calibration constant for all frequencies and the gain determination methods uses a separate calibration constant for every frequency.

As shown in figure 8.15, to determine the charge properly, the calibration constant of the sensor has to be determined. The calibration constant is the ratio between the maximum of the frequency spectrum of the HFCT measured pulse and the UWB pulse. If this is done correctly, the maximum value of the HFCT frequency spectrum has a frequency that lies in the flat piece of the UWB spectrum. This is more or less the case in figure 8.15. It turned out that $k_{cal} = 2.95$. The charge can be determined by equation 6.12 and the error is zero for the pulse used for calibration.

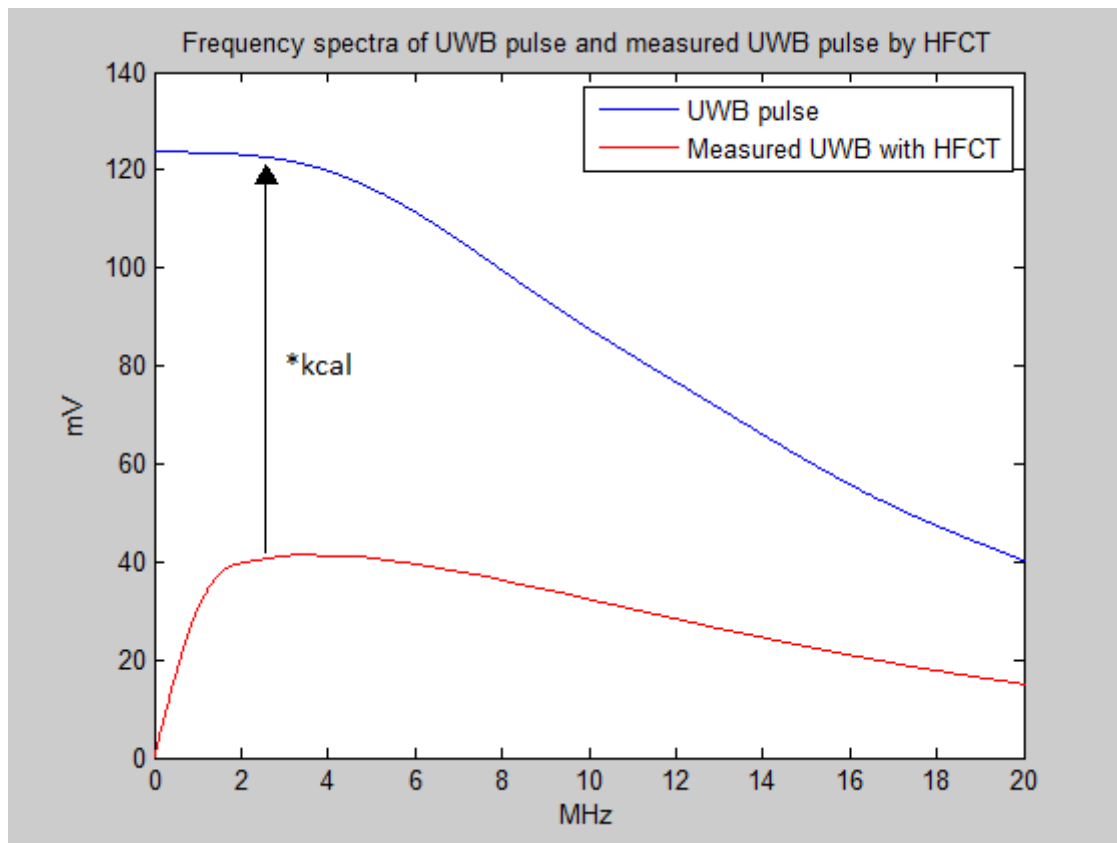


Figure 8.15: Frequency spectrum of an UWB pulse and frequency spectrum of the same pulse measured by an HFCT.

In case there are measured pulses with less high frequency content, there are made some errors. This can be seen in figure 8.16. The error made in this measurement is determined by equation 6.10 and is 38%. In figure 8.14 there is plotted the charge determination error of the same pulse (cyan) using the gain compensation method. The used pulse, the 1000pC Haefely pulse, has a decreasing

high frequency content where the gain of the sensor is increasing. When comparing the two charge determination methods for the 1000pC Haefely pulse, we see that the gain compensation method has an almost negligible error, while the frequency spectrum peak method has an error of 38%.

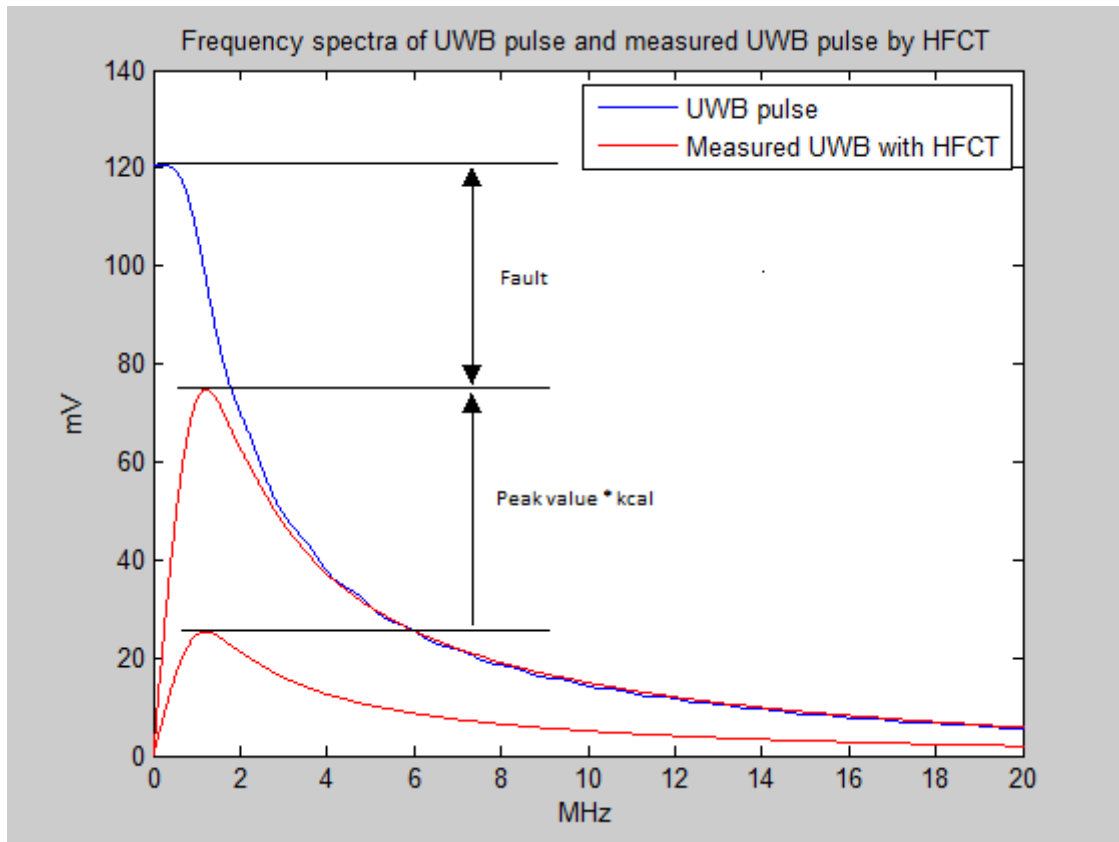


Figure 8.16: Frequency spectrum of an UWB pulse and frequency spectrum of the same pulse measured by an HFCT.

8.4 Conclusion

For PD measurement in cables, using measurement systems with a relative high lower cutoff frequency, in theory compensation of the gain can be a useful method to determine charge in an accurate way. In this chapter it is proven that the method is accurate for the experiments that are done. When comparing the gain compensation method with the frequency spectrum peak method, it shows that there is a need for gain compensation pulses with a sensor with a too high low cutoff frequency.

A disadvantage of the method is that for every measuring system the gain of the system has to be determined.

9 Summary and conclusions

9.1 Conclusions and summary

During ageing of a defect in a power cable, different PD mechanisms could occur. In general aged defects have a lower inception voltage than virgin defects.

Some defects have inception voltage (V_i) and extinction voltage (V_e) below operating voltage (V_o). When 50Hz voltage is applied, PD is initiated in these defects. Another case occurs when $V_i > V_o$ and $V_e < V_o$. In this case PD can be initiated at an overvoltage and can continue during operating voltage. The last case occurs when $V_i > V_o$ and $V_e < V_o$. In this case PD will be initiated at overvoltage.

During propagation of a PD pulse through a cable, the amplitude and the shape of the pulse is change. Strong attenuation of the high frequencies cause the decrease of amplitude. The charge does not decrease that strongly. Therefore the integral of the pulse is not changing significantly and the pulse becomes wider. Dispersion causes asymmetry in the pulse and causes a shorter rise time, but in practice the influence is not significant.

There are several types of PD measurement devices on the market, offline as well as online. All using different voltage sources. Each voltage source has its advantages and disadvantages. Frequency is proportional to the power a source has to deliver. For application of 50Hz voltage large sources are needed, something that is unpractical in field. Therefore different energizing systems are developed.

A VLF system makes use of very low frequency and therefore the source can be small. Disadvantages of this power supply is the difference in stress compared with stress applied with 50Hz voltage. VLF requires a higher test voltage.

Resonant systems are relatively large and heavy. They make a circuit and therefore only the ohmic losses have to be powered. The stress applied to the cable by a resonant system looks the most at 50Hz voltage stress. Next to this, the system can operate continuously. Triggering of virgin cavities has a higher probability.

DAC systems energize the cable slowly. Therefore the required power is relatively small and the devices can stay also small. When the resonance frequency kept below 300Hz, the stress is very comparable with 50Hz voltage stress. Because of damping, this stress only stays for a short time. Therefore several shots are needed, especially for ignition of PD in virgin cavities.

Online measurement stresses the cable in exact the same way as at operating voltage. There is no external source needed and the total system is small. PD with V_i above operating voltage can only be measured when overvoltage occurs. PD with V_i and V_e above operating voltage are more difficult to detect than with other systems. Therefore sometimes a combination of online and offline measurements is desirable.

The systems are available from tens of kV until extra high voltage. For offline measurement, resonant systems are available for the highest voltages.

For PD measurement, capacitive and inductive sensors are applied; for online measurements especially inductive, for offline often capacitive. Capacitive sensors have a higher sensitivity, but inductive sensors are galvanic isolated.

Localization of the defect can be done with TDR, but when measuring at two sides of a cable, the length that can be measured is doubled for the same sensitivity. The disadvantage of double side measurement is that this method required synchronization of measurement data.

PD measurement can be performed according to the standard (conventional measurement) or not (unconventional measurement). For conventional measurement the specifications of a measuring system are prescribed. Following these guidelines, results in the possibility to calibrate the measured value to the real charge. Charge determination is independent of pulse shape, unless the flat part of the measured PD frequency spectrum decreases before the high cutoff frequency of the bandwidth of the IEC filter. Wideband and narrowband IEC filters can be applied. With wide band, the polarity of the pulse can be determined easily; this is hard with narrow band. Furthermore the time response, and thus the pulse resolution time, of narrowband is much larger than of wideband. Because of the long time response of conventional measurement, there is an enhanced chance to get superimposition of measurement pulses. Therefore conventional measurement is not suitable for localization of the origin of the PD generating defect. Therefore unconventional measurement is needed.

For unconventional measurement there is no standard. Therefore different sensors with different bandwidths can be used. Different manufacturers measure with different sensors with different bandwidths. The responses are different if different with sensors with different bandwidths are applied. Because there is no standard, not all systems determine charge in the same way and the results of different systems cannot be compared.

There is investigated the influence of the cutoff frequencies on the time response. Filtering low frequencies, causes that the integral of the signal goes to zero. In that case, taking the integral of the whole pulse does not make sense for determination of charge. The highest peak integral only gives an accurate value for the charge in case the lower cutoff frequency is below about 10kHz. The higher the lower cutoff frequency of the system, the shorter the time response. But in case measuring with a high lower cutoff frequency, while the frequency content of the pulse has already decreased strongly in the region of the lower cutoff frequency, the sensitivity is decreased. Filtering only higher frequencies does not lead to a zero integral, because the DC component is not filtered out. Filtering of high frequencies has a large effect on the sensitivity. Filtering high frequencies lead to decrease of the amplitude of the pulse. Because the charge is not attenuated strongly, the pulse becomes wider. Therefore filtering high frequencies cause a longer time response with less sensitivity compared to the UWB measurement.

To calibrate unconventional PD measurement systems there have been evaluated a couple of approaches. The peak value of the PD pulse is a very inaccurate indication for the charge. The integral of the first peak only gives a good approach for very low cutoff frequencies. An accurate method is taking the peak of the frequency spectrum closest to the DC frequency. A PD pulse is just a $\delta(t)$ frequency response with filtered away some high frequency content and with a scaled amplitude. Therefore the frequency response stays flat at a constant value until the high frequencies are filtered. The method is very accurate, until the low cutoff frequency of the system reaches the frequency area where the frequency spectrum of the PD pulse is decreasing. Therefore there is a

relationship between steep pulses and the low cutoff frequency for determining accurately the charge.

Next to difference in sensors, the measuring circuit has also influence on the circuit. Inductive or capacitive components may influence the measurement. Therefore it is important to know what is measured and therefore the gain has to be determined. When the gain of the system is not flat in the desired low frequency area, determination of the charge by peak value of the frequency response is not accurate. In this case the measured frequency spectrum can be compensated by the gain of the system.

For PD pulses that have travelled a long distance (about 4km) through a power cable, the flat part of the frequency spectrum reaches until about 100kHz. Measurement of these pulses with a sensor with a low cutoff frequency of for example 500kHz is not preferable. The measurement does not contain a peak value of the frequency spectrum that corresponds accurate to the integral of the pulse, and thus to the charge. When it is measured with these systems, the frequency response of the measured pulse can be compensated by dividing by the gain of the sensor. All frequencies are compensated, therefore the frequencies in the lower area are directly proportional to the charge. The charge is determined by measuring a calibration pulse at UWB. In practice it is important for determining the gain of the system, to take the whole PD pulse and remove the DC component by choosing an accurate offset. To verify the accuracy of the gain, two different pulse shapes can be used to check it. A disadvantage is that for every measuring setup the gain has to be determined.

Because now there is also an accurate way to determine charge of PD pulses using a various set of sensors, unconventional measurement results of different systems can be compared. Next to this, unconventional measurement results can be compared with conventional PD measurement results.

Therefore it is possible to compare measurement results of different PD measurement systems that are used for PD measurement in power cables.

9.2 Recommendations

There are discovered accurate methods for charge determination for unconventional PD measurement. However, these are not tested yet for real PD. Further research steps on this topic should be:

- Checking the accurate charge determination methods with real PD.
- The charge determination methods working with the measured frequency spectrum should be tested in one setup with the conventional method. Thereby each half of a generated PD pulse should travel through an equal cable and be measured by the two system.
- The method that determines charge with the peak value of the frequency spectrum should be tested for real PD in cables, but also for PD in GIS.

A Appendix

This appendix contains pictures of components and equipment used during experiments.



Figure A.1: MV cable used during experiments



Figure A.2: Haefely tuneable measuring impedance AKV 568



Figure A.3: Calibrator 3706, Seitz 141

Calibrator 3707 is exactly the same as the calibrator in figure A.3.

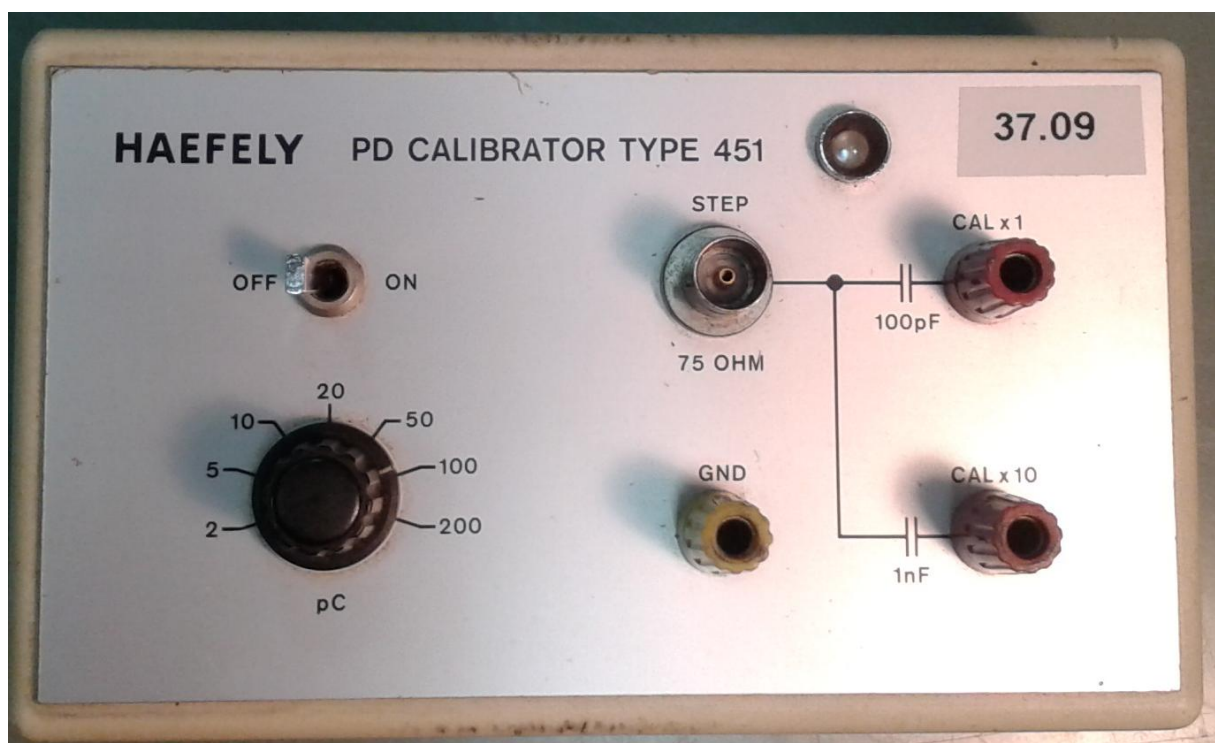


Figure A.4: Calibrator 3709, Haefely 451



Figure A.5: Tektronix DPO 7354C Digital Phosfor Oscilloscope

B Appendix

This appendix describes the relation between the gain of a HFCT and the low cutoff frequency.

The drop time is a parameter that defines behaviour of a HFCT for lower frequencies [18]. The drop time of an HFCT is:

$$D = \frac{1}{\tau} = \frac{R_{load}}{L_{winding}} = 2\pi f_{-3dBLow} \quad (B.1)$$

Where $f_{-3dBLow}$ is the low cutoff frequency of the HFCT.

This gives:

$$L_{winding} = \frac{R_{load}}{2\pi f_{-3dBLow}} \quad (B.2)$$

The load resistor R_{load} normally is 50Ω , because this matches with the impedances of the coaxial cable and the oscilloscope. In this way the measurement is not influenced by reflection.

$$R_{load} = 50\Omega \text{ (Matches with coaxial line and impedance of oscilloscope)} \quad (B.3)$$

As can be seen in equation B.2 the inductance of the winding is constant for a low cutoff frequency and an 50Ω resistor. The inductance of a winding around a toroid can be approximated by:

$$L_{winding} = \mu \frac{N^2 A_{toroid}}{2\pi r} \quad (B.4)$$

This gives

$$N = \sqrt{\frac{L_{winding} 2\pi r}{\mu A_{toroid}}} = \sqrt{\frac{\frac{R_{load}}{2\pi f_{-3dBLow}} 2\pi r}{\mu A_{toroid}}} = \sqrt{\frac{R_{load}}{\mu A_{toroid} f_{-3dBLow}}} r \quad (B.5)$$

Where N is the number of turns, A_{toroid} the cross sectional area of the toroid, μ the permeability of the core material and r is the toroid radius.

The gain of an HFCT can be approximated by:

$$Gain_{HFCT} = \frac{R_{load}}{N} \quad (B.6)$$

Combing this with the above equations gives:

B Appendix

$$Gain_{HFCT} = \sqrt{R_{load} \mu f_{-3dBLow} \frac{A_{toroid}}{r}} \quad (B.7)$$

It turns out that the lower the low cutoff frequency is, the lower is the gain of the HFCT.

[18]

C Appendix

This appendix contains a table with properties of calibrator pulses used during experiments.

Table C.1: Properties of set recorded UWB pulses

Pulse sequence name	Used calibrator	q inj.	q at measuring point	Travelled distance through MV cable	Rise time	Decay time
506	3706	500pC	421,4 pC	640m (first reflection)	41,2 ns	108,8 ns
506	3706	500pC	398,8 pC	1920m (second reflection)	91,6 ns	410,4 ns
506	3706	500pC	340,5 pC	3200m (third reflection)	140,4 ns	699,2 ns
506	3706	500pC	300,1 pC	4480m (fourth reflection)	186 ns	1165,6 ns
1006	3706	1000pC	858,9 pC	640m (first reflection)	42,8 ns	112 ns
1006	3706	1000pC	802,7 pC	1920m (second reflection)	92,4 ns	414 ns
1006	3706	1000pC	687,6 pC	3200m (third reflection)	140 ns	704,4 ns
1006	3706	1000pC	607,8 pC	4480m (fourth reflection)	188,4 ns	1191,6 ns
509	3709	500pC	432,4 pC	640m (first reflection)	61,2 ns	265,2 ns
509	3709	500pC	402,5 pC	1920m (second reflection)	129,2 ns	568,8 ns
509	3709	500pC	355,6 pC	3200m (third reflection)	194,8 ns	919,2 ns
509	3709	500pC	325,6 pC	4480m (fourth reflection)	267,2 ns	1461,2 ns
1009	3709	1000pC	881,5 pC	640m (first reflection)	61,6 ns	264,8 ns
1009	3709	1000pC	820,5 pC	1920m (second reflection)	129,2 ns	566 ns
1009	3709	1000pC	725,0 pC	3200m (third reflection)	196,4 ns	927,6 ns
1009	3709	1000pC	659,4 pC	4480m (fourth reflection)	262,8 ns	1456,4 ns

Acknowledgements

The months working on my thesis project in the High Voltage laboratory was a very pleasant periods of my study time in Delft. It was a time of facing interesting challenges, it was a time of learning, but next to this, is was joyful to be a part of the High Voltage group..

I would like to express my gratitude to Prof. dr. Johan J. Smit for making it possible to do this project at the High Voltage department.

I would like to thank my daily supervisor Dr.ir. Armando Rodrigo Mor for making it possible to work on this interesting topic. I want to express my gratitude and appreciation to him for the way he mentored me through the project, and for helping me with his very large experience and knowledge. He was very inspiring. In spite of his often busy agenda, he always made time for me.

A lot of important support I received from Ing. Paul van Nes and Wim Termorshuizen. Mr. Van Nes was very willing to assist me with suggestions and information. He supported me with his years-long experience in the field of High Voltage. Dhr. Termorshuizen was always willing to help me with searching for equipment I needed for my project. For both I want to express my gratitude for that.

I would like to thank my girlfriend Henrieke. You were always supporting and motivating for me in many ways. You were there for me when I was struggling during the project.

I had a great time doing my thesis project within the High Voltage group. Therefore I want to thank the whole group and in particular my roommate Serge.

Delft, April 2014

Bert van Veen

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