Tampere University

Oskari Iisakka

DEVELOPMENT AND TESTING OF SOFTWARE FOR EVALUATION OF HIGH VOLTAGE COMPOSITE AND COMBINED WAVEFORMS

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Faculty of Information
Technology and Communication
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Examiners: Docent Kari Lahti
D.Sc. Pertti Pakonen
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ABSTRACT

Oskari Iisakka: Development and testing of software for evaluation of high voltage composite and combined waveforms
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In high voltage systems and electricity transmission networks the operational performance of components should be tested. This is achieved in testing laboratories by stressing the tested components with standardised test voltages. Since there are multiple different types of voltage stresses that can affect network components, combinations of these voltage stresses should also be analysed and used when deemed necessary. These standardised combinations of test voltages are called composite and combined voltages, or generally ‘mixed’ voltages. Need for such testing is especially true in today’s electricity networks with distributed energy resources where more and more power electronics, and new electricity network technologies are used. For a proper evaluation of these ‘mixed’ voltages an evaluation software is needed.

The aim of this thesis is to produce methods for combined and composite voltage evaluation based on the requirements given in standard IEC 60060-1. After producing these methods for test voltages, a software for evaluating combined and composite voltages was to be produced and its uncertainty calculated. The development of the evaluation methods was done by firstly reviewing relevant standards and secondly by reviewing the literature of the field of high voltage measurements. For the test voltages without standardised evaluation methods, new methods were produced to facilitate the calculation of specific test voltage parameters.

The current standard IEC 60060-1 includes direct methods for lightning impulse evaluation, which is one possible component voltage type for ‘mixed’ voltages. Other voltage types have no standardised evaluation methods but the parameters that need to be analysed have been defined. Standard IEC 61083-2 includes standardised uncertainty value calculations and methods which can be referenced for uncertainty evaluations.

Since the thesis project was done for calibration laboratory use the calculation accuracy of the software was of extra importance. To achieve acceptable accuracies many signal processing methods are required. Firstly, switching impulses are evaluated with the same methods that have been standardised for lightning impulses. This means that curve fitting is used to find the ideal impulse after which the differential from the measured is filtered. The filtered division is then added together with the fitted curve after which the pulse parameters can be evaluated. Composite and combined voltage evaluation exploit switching and lightning impulse evaluation methods when needed. The removal of alternating voltage content from composite voltages can be done by using curve fitting algorithms. The DC composite voltage evaluation was added to the developed analysis software as an extension to the evaluation methods defined in standard IEC 60060-1.

Combined voltages with DC voltage components were chosen not to be evaluated. Combined voltage evaluation was chosen to be executed in HV-com^2 project based on three separate input files, one with a measurement of the power frequency with at least one full AC cycle, one with a measurement data of the impulse and one with measurement data for AC voltage with the same sampling rate as the impulse was measured. The combined voltage data is measured by combining the impulse data and the AC data with the same sampling rate at which the impulse was measured.

Keywords: Evaluation methods, composite voltage, combined voltage, evaluation software, high voltage, calibration, high voltage measurement system

TIIVISTELMÄ

Oskari Iisakka: Korkeajännite yhdistelmä ja komposiitti aaltomuotojen analysointi ohjelmiston kehitys ja testaus
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Suurjännitejärjestelmiin ja sähköverkoihin kuuluvien komponenttien ja laitteiden toimintavarmuuden ja turvallisuuden tarkistaminen on tärkeää. Laitteiden jännitelujuuden varmistaminen tehdään testauslaboratorioissa standardoiduilla testijännitteillä, joilla tutkitaan jänniterasituksien vaikutuksia sähköverkon komponentteihin. Koska sähköverkoissa komponentteihin voi vaikuttaa samanaikaisesti useanlaisia jänniterasituksia, tulee myös näiden jännitetyyppien erilaisia yhdistelmiä tutkia ja niiden vaikutuksiin varautua. Yhtäaikaisesti vaikuttavia jänniterasituksia tai jänniterasituksien yhdistelmiä esiintyy erityisesti nykyaikaisissa sähköverkoissa, joissa energian tuotanto on hajautettu, niiden sisältämien moninaisten teknologioiden vuoksi. Näitä jänniterasituksien yhdistelmiä kutsutaan yhdistelmä ja komposiitti jännitteiksi. Hyvään ja tehokkaaseen jänniterasituksien yhdistelmien analysoimiseen on järkevää kehittää ohjelmisto.

Tämän diplomityön tarkoituksena oli kehittää tavat ja metodit komposiitti- ja yhdistelmäjännitteiden analysointiin sekä määritellä näillä periaatteilla valmistetun ohjelmiston epävarmuus. Analysointimetodien pohjaksi perehdyttiin alan standardeihin ja kirjallisuuteen. Sikäli kun oli mahdollista, seurattiin analysointiohjelmiston toteutuksessa soveltuvia standardeja. Standardien puutteellisuuden vuoksi yhdistelmä- ja komposiittijännitteiden analysointiin kehitettiin uusia metodeja tarpeellisten jänniteparametrien määrittämiseen.

Tämän hetken standardoinnissa on annettu suorat analysointimetodiohjeistukset salamasyöksyjännitteille, jotka ovat yksi mahdollinen osa komposiitti- ja yhdistelmäjännitteitä. Muille testijännitetyypeille ei ole standardoitu analysointimetodeja, mutta analysoitavat parametrit on määritelty. Samalla standardoinnissa on määritelmät salamasyöksy- ja kytkentäylijännitteiden epävarmuusarvioiden laskemiseen.

Koska työ tehtiin kalibrointilaboratorion tarpeisiin, tuli työn laskentatarkkuuteen erityisesti kiinnittää huomiota. Tarkkuuden saavuttamiseksi käytettiin monia metodeja. Ensinnäkin kytkentäjännitteet käsiteltiin samoilla metodeilla kuin salamasyöksyjännitteille on standardissa IEC 60060-1 määritelty. Eli mitattuun dataan ensin tehdään ideaalisen pulssimuodon sovitus, minkä jälkeen mittaustuloksen jäännökselle suoritetaan suodatus. Suodatettu jäännös ja sovitettu käyrä yhdistetään, minkä jälkeen vasta voidaan laskea pulssiparametreja. Yhdistelmä- ja komposiittijännitteiden analysoinnissa hyödynnettiin salama- ja kytkentäjännitteiden analysointia aina kun oli tarpeellista. Komposiittijännitteillä vaihtojännitteen erottaminen onnistui hyödyntämällä käyrän sovitus algoritmeja. Tasajännitteen parametrien analysoiminen komposiittijännitteissä lisättiin parannukseksi standardissa IEC 60060-1 määriteltyyn salamasyöksyjännitteen analysointimetodiin.

Yhdistelmäjännitteet, joissa toisena jännitekomponenttina on tasajännite, jätettiin analysoimatta tässä työssä. Yhdistelmä jännitteille määriteltiin vaadittavaksi kolme lähdetiedostoa, joista yhdessä on mittaus vaihtojännitteestä ainakin yhden kokonaisen jakson pituudelta, yhdessä on mittaus pulssista, ja yhdessä on mittaus vaihtojännitteestä pulssin ajalta samalla näytteenottotaajuudella kuin millä pulssi on mitattu. Yhdistelmäjännitteen saa tällöin muodostettua yhdistämällä pulssin ja pulssin näytteenottotaajuudella mitatun vaihtojännitteen.

Saavutetut laskennan parametrien epävarmuusarvot ovat hyväksyttäviä.

Avainsanat: Analysointimetodit, komposiittijännite, yhdistelmäjännite, analysointiohjelmisto, suurjännite, kalibrointi, suurjännitemittausjärjestelmät

PREFACE

This thesis was written for the High voltage laboratory of Tampere University in co-operation with VTT MIKES. I want to thank both for the help and guidance in the process of making and planning this thesis. A big thanks goes also to the thesis supervisors and examiners. I also want to thank all partner organizations taking part on the HV-com² project for the interesting and fruitful discussions about evaluation softwares and what they are supposed to do and how they would need to operate.

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Oskari Iisakka

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CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating Current
DLS	Damped least-squares
DC	Direct Current
FFT	Fast Fourier transform
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
HV-com^2	Project name for ‘Support for standardisation of high voltage testing with composite and combined wave shapes’
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
LI	Lighting Impulse
LS	Least-squares
LM	Levenberg–Marquardt
PD	Partial Discharge
r.m.s	Root mean square
SI	Switching Impulse
THD	Total Harmonic Distortion
V-t	Voltage-Time

C	capacitor
β	overshoot magnitude
β'	relative overshoot magnitude
f	frequency
I	current
k	coverage factor
O	true origin
O_1	virtual origin
R	resistor
S	switching device
t	time
t_d	time delay of the impulse base curve
τ_1	time constant 1
τ_2	time constant 2
T_{AB}	time interval between 30% - 90%
T_d	time above 90%
T_e	peak time
T_p	time to peak
t_s	statistic time lag
T_z	time to zero
t_z	formative time lag
T_1	front time
T_2	time to half
Δt	time delay
U	voltage
U_b	base curve maximum
u_{B7}	software uncertainty effect
U_e	extreme voltage value
U_t	value of the test voltage
U_0	original voltage value
∂U	ripple voltage
∂	ripple factor

1. INTRODUCTION

In high voltage systems and electricity transmission networks the operational performance of components should be tested. This is achieved in testing laboratories by stressing the tested components with standardised voltages. Since there are multiple different types of voltage stresses that can affect network components, combinations of these voltage stresses should also be analysed and used when deemed necessary. These combinations of test voltages are called composite and combined voltages, or together as ‘mixed’ voltages. For a proper evaluation of these ‘mixed’ voltages an evaluation software is needed. The aim of this thesis is to produce a software for composite and combined voltage evaluation, explain the processes and theory behind it and evaluate the produced evaluation software’s uncertainty components towards all evaluated parameters.

This thesis was done within EU project ‘Support for standardisation of high voltage testing with composite and combined wave shapes’ or HV-com^2. HV-com^2 is an EU project aimed at studying voltage combinations and how their effect should be considered in calibration and analysis purposes for the electricity network components. One part of the project was to have partner organizations produce software for composite and combined voltage evaluation. [1] Since composite and combined voltage evaluation requires a working evaluation method for all test voltages explained in standard IEC 60060-1, for example lightning and switching impulses, a working evaluation software for these is also required.

This thesis aims to explain the theory behind the requirements for composite and combined voltage, the processes needed for the evaluation, the evaluation software’s structure, and the uncertainty estimations for the final software. Firstly, the theory behind high voltage testing is explained after which the used high voltage test voltages are explained. To understand some of the used methods and phenomenon connected to combined and composite voltages, the different test voltage generators and measurement systems are explained. Since one objective of this thesis is to define and estimate the uncertainty components of the software towards the different evaluated parameters, the different uncertainty components related to complete measurement systems are also explained. After explaining the test voltage generation methods and measurement systems, the different signal processing methods and algorithms are explained. Finally, the process and structure of the produced evaluation software are explained after which the uncertainty components are estimated for all possible values with either standardised methods or comparing to reference values.

2. THEORY AND DEFINITIONS OF HIGH VOLTAGE TESTING

To understand what a software that evaluates high-voltage composite and combined waveform parameters tries to achieve and what it analyses the theory and phenomenon behind it needs to be understood. First the concept and reasoning for high-voltage testing and what the high-voltage (HV) test waves are, should be explained. This chapter aims to achieve this by first explaining the reasons behind high-voltage testing for why it is done and why the specific test voltages are used. Secondly, this chapter aims to explain what the standardised high-voltage test voltages are and what the standards find important in these voltage forms.

Technical standard is an established criterion for a technical task, usually a formal document to establish uniform engineering practices. The two main sources for general standards in high-voltage engineering are US based “IEEE (Institute of Electrical and Electronic Engineers) Guides” and the second being European based IEC (International Electrotechnical Commission). In Europe there is also a third standards development organization CENELEC, producing standards for European Union- and EFTA regions. This thesis uses the definitions of the standard voltages from international IEC standardization.

2.1 Theory behind testing

Before analysing the different High-Voltage (HV) test, test waveforms and measuring systems it is important to understand why these tests are performed. They are mainly performed to make sure that the different components in HV networks and applications can withstand all the different main voltage stresses without compromising the network or application operation due to greater failure rates than planned of the insulation systems of the components.

In this chapter the physical reasons and the main causes for these disturbances are first explained. The concept of voltage-time characteristic, which is used to measure voltage stress on components, is also introduced. Lastly, the so-called Equal area criterion is explained. The Equal area criterion is a theorem which utilizes voltage-time characteristics to explain and define measurable causes for insulator breakdown surges.

2.1.1 Physical basis

The knowledge and applications of electricity have been progressing throughout history and due to the need of transmitting more energy at higher power and transmission voltages are used. The transmitted power follows approximately formula of $P_L = U^2 / Z_L$, where P_L is the transmitted power, Z_L is the impedance of the transmission line and U is the transmission voltage. Since the impedance of the transmission line cannot be notably decreased in practice, the only way to transmit more power and to match the increased energy demand is to use higher transmission voltages. Using these high transmission voltages causes many technical requirements for the components used in the transmission grid. To verify that the components fulfil their requirements, such as air or SF_6 based insulations can withstand the existing voltage stress, standardised high-voltage tests are needed. [2, pp. 1-3]

It is defined in standard IEC 60071-1:2019 that the basic principle for HV testing is that the used testing waveforms should represent voltage stress characteristics that real voltage forms could stress the components in service [3]. Following this definition, every used HV testing waveform describes a voltage form that can occur with HV systems in everyday use. As the understanding on power systems has evolved, aside from the used voltage sources of AC and DC voltages, testing waveforms for lightning impulses (LI) and switching impulses (SI) were developed. [2, pp. 3-5] The AC and DC are continuous voltages while LI and SI pulses are one-time (transient) phenomena.

Lightning impulse test voltages are used to simulate the effects of external voltage stress sources that are caused for example by lightning strokes [4, p. 460]. These overvoltage impulses are found to have a front time of couple of microseconds and the tail time of several tens of microseconds. [2, p. 4]

After it was understood that power systems can have internal impulse overvoltages a separate test voltage waveform for these stresses was developed. These overvoltages are called switching impulses and they are caused in the power systems by switching operations like connecting or disconnecting parts of the system or by network faults and fault extinction [4, p. 461]. These overvoltages are defined as generally having front times of couple of hundred microseconds and tail times of couple of milliseconds. Both LI and SI test voltages can be generated with the same test voltage generator types. [2, p. 5] Since lightning- and switching impulses often happen in real networks as oscillatory, it is good for testing purposes to have testing impulses sometimes with oscillation [5]. However, oscillating testing impulses do not fulfill the standard IEC 60060-1 requirements.

The last main types of HV test voltages are combined and composite voltages. Sometimes the terms are combined and called ‘mixed voltages’. These test voltages simulate simultaneous occurrences of the earlier mentioned voltage stresses. These are achieved by superimposing either of the impulse test voltages with a continuous base voltage form (AC or DC) based on what kind of voltage stress is wanted to be tested. The difference between combined and composite test voltages is where the tested insulation system is located compared to the separate voltage sources. Combined test voltages are defined for three-pole insulators where the voltage components are affecting the insulator from different poles, and the composite test voltages are for insulators that are for two-pole test objects where the superimposed voltage stresses affect the insulator directly. [2, p. 6]

The general use for HV testing with protection devices in HV networks is to make sure they work properly. In general, it is wanted to make sure that with HV testing that protection units do not react or operate when the network is operating under normal high voltages. Additionally, it is required that the protection trips with overvoltages of correct size to guarantee that the protection devices work properly and the network works as safely as possible. [2, pp. 8-9] For example, high-voltage DC (HVDC) tests are done these days to represent and test HVDC cable characteristics in different conditions, such as in submarine and underground conditions to test different cable designs [2, p. 271]. The main application for high-voltage AC (HVAC) tests are multiple lifetime-, withstand tests and partial or dielectric discharge measurements. [2, p. 89] More about this subject can be found on chapter 2.1.4 Insulation coordination.

2.1.2 Voltage-Time characteristic

Voltage-Time, or Volt-Time, (V-t) characteristic is an important property of an insulation system. The voltage-time curve gives the voltage withstand as a function of voltage stress duration. Breakdown surges are somewhat random and highly related to external variables and do not happen at same voltages. Therefore, it is important to know and record voltage stress’ voltage over time which is called voltage-time characteristic. It also allows analysis of all possible voltage stress forms to be done after their form has been recorded and understood as explained for lightning- and switching impulses in chapter 2.1.1.

For a breakdown process to start there needs to be free exited electrons available. For the actual breakdown process to happen the exited electrons must be able to generate a breakdown channel through the insulator. Since this does not happen instantly, an electric field of sufficient strength needs to affect the electrons for long enough. This process also depends on the insulator geometry and materials used.

Voltage-time characteristic is a model that helps in visualising the voltage stresses over an insulator. It also helps in visualising and calculating the breakdown surge voltage values. [4, pp. 359-362] It is especially helpful in visualizing and understanding breakdown methods and reasons in insulation, whether that being partial breakdown or full breakdown of insulation. The V-t characteristic is mostly helpful in understanding the equal area criterion which is explained more in chapter 2.1.3 in more detail.

2.1.3 Equal area criterion

Equal area criterion is the basis under which the evaluation methods for LI test voltages for high voltage testing are based upon as described in IEC 60060-1 Annex B [6]. The equal area criterion was first published by D. Kind in 1958 “Die Aufbaufläche bei Stoßspannungsbeanspruchung technischer Elektrodenanordnungen in Luft “ (eng. The construction area of surge voltage stress at sphere gap through air). The study describes what effect lighting impulse voltages have when the LI voltage surge happens through an air gap. [7]

The equal are criterion defines that any insulator has a critical voltage stress value. If the insulator is stressed with a voltage stress value higher than this value for long enough time, a breakdown through the insulation will happen. The equal area criterion defines that the breakdown will happen always proportional to the area formed by the time integral of the voltage stress after it exceeds the critical voltage stress value until breakdown. Basically, the area between the critical voltage stress value and the true stress is always the same leading to breakdown surge through the insulator. This is visualised with the help of voltage-time characteristic [8].

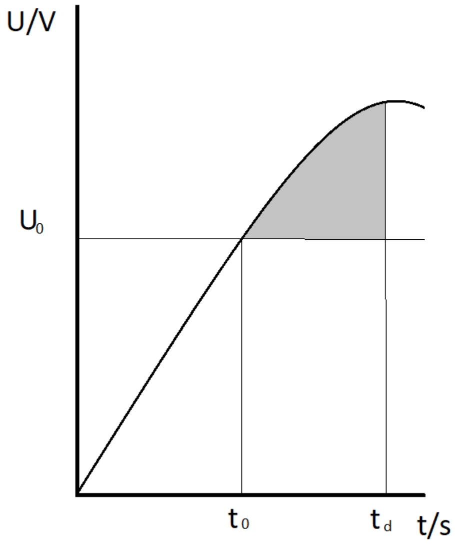

Figure 1: Example of equal area criterion

Equal area criterion explains the breakdown process well in simple and uniform insulator cases, but since external influences on the system are almost always random and the insulators are usually non-uniform the breakdown voltage values are statistical in nature. Also depending on the effective overvoltage, the breakdown voltage value and time are usually not the same for different impulse forms. These values usually depend on the two-time constants of the breakdown process, statistic time lag t_s and formative time lag t_f. Statistic time lag defines how and when a free electron appears and starts to form the breakdown channel. This constant is usually statistically distributed and depends on the pre-excitement of the charge carriers in the insulator and its geometry. The formative time lag is the time it takes for the breakdown channel to form. This time delay depends on the breakdown channel formation mechanism between the insulator anode and cathode in the breakdown process. Since the time lags are statistical in nature, when applying the same impulse to an insulator, only a part of them cause a breakdown. [4, pp. 359-362] Figure 1 shows an example of equal area criterion. The shown U_0 is the critical voltage level where the breakdown channel starts to form, t_0 is the time moment when the critical voltage level is crossed, and t_d is the time moment when the breakdown happens.

Since the breakdown process is not straightforward, a single absolute breakdown voltage can not be defined. In most cases it is more useful to define a minimum static breakdown voltage V_s. The minimum static breakdown voltage is the minimum voltage value where the breakdown process starts to develop in the insulator [4, p. 360], this same voltage value is the same that the equal area criterion uses as one of its border values. Since according to equal are criterion the breakdown process is also related to the effective time the voltage stress affects the test object above the static breakdown voltage, it is preferable to measure multiple values of the used test waveforms.

2.1.4 Insulation coordination

The electrical insulation in use in high voltage networks is stressed with the operational voltage with the added overvoltages and voltage drops. The used electrical insulation needs to be guaranteed to operate reliably in service under the voltage stress. The basic aim in insulation coordination is to have the different components within an electricity network operate with same withstand voltages and under the correct characteristics of protection elements so the protection elements would trigger in fault situation before the insulation fails. Ideally protection elements in electricity networks conducts electrical current only when the voltages over the protection level and acts as an ideal insulation below it. These protection devices are then placed in strategically important sensitive points of the network. The selection of the insulation level based on the network’s voltage level with an acceptable safety margin is called insulation coordination. [2, p. 8]

Insulation coordination is method used in high voltage networks to make sure that the insulation between different networks operate under same principles. This means that a standardising method needs to be in effect to make sure that different voltage levels operate within same safety margins between each other. Insulation coordination is a method that aims to fulfil the quality assurance and reliability needs of high voltage system components. [2, p. 451] This standardizing is realized through for example the IEC 60071 standard [2, p. 8].

Insulation coordination is related to high voltage testing and combined- and composite voltages, since the relevant test voltages are related to the insulation coordination level. The insulation has to withstand a certain type of voltage stress during a certain period. This can be AC or DC stress over a minute, or an internal or external impulse voltage withstand test. [2, pp. 8-9]

Since the withstand voltages and external state of presence in electricity networks differs, there are different insulation coordination levels for every voltage level to choose from. This is chosen based on the network operator’s requirements for the network’s reliability or safety. [2, pp. 11-12]

2.2 High voltage testing waveforms

The main waveforms used in standard high-voltage test techniques depicted by IEC 60060-1:2010 are direct current, alternating current, lightning impulse, switching impulse, and combined and composite voltages [6]. These test voltage types are explained in this chapter. The test voltage types are explained from the viewpoint of existing IEC standard 60060-1. The use of standardized test methods around the world makes it easier that the systems are tested with approximately same voltage stresses, which allows for the tests to be comparable with each other. To understand better the basis for composite and combined test voltage evaluation which is the topic of this thesis, the different waveforms related to combined and composite voltages are explained in this chapter. Firstly, this chapter presents direct and alternating currents. After that, switching and lightning impulses are explained after which both combined and composite voltage waveforms are explained.

Both composite and combined high voltage test voltages are superpositions of two separate voltage forms. As Hauschild and Lemke explain in their book “High-Voltage Test and Measuring Techniques” the main difference between composite and combined test voltages is how the voltage sources are positioned compared to the test object. In combined test voltages the voltage components stress the test object from two separate high-voltage terminals and the ground, while with composite voltages the superposition of the voltage components stresses the test object between a singular high voltage terminal and the ground. [2, p. 401]

2.2.1 Direct current

Direct current (DC) voltage is voltage that has a mean value over time that differs from zero. In high-voltage applications DC is also called as HVDC or high-voltage direct current.

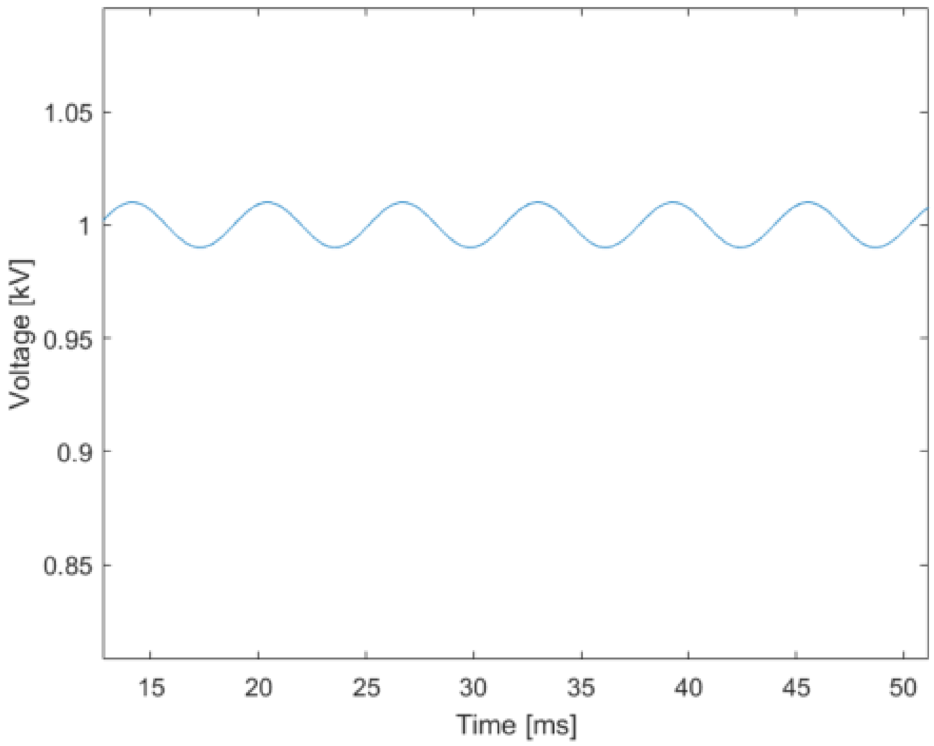

Figure 2: Example of DC voltage with ripple

The important parameters in DC voltage according to IEC-60060-1 are its mean value, ripple, ripple amplitude, ripple factor ∂ and voltage drop. The mean value is characterized as the arithmetic mean value of the DC voltage over the data set [4, p. 9]. Ripple is the deviation from the DC-voltage's mean value. Ripple amplitude is half of the difference between the ripple maximum and minimum values. Ripple factor is usually used to describe ripple parameters. It is described as ratio between the ripple amplitude and the mean value of the DC-voltage. The last parameter defined in IEC 60060-1 for DC test voltage is voltage drop, which it describes as reduction on the DC voltages arithmetic mean value over a couple of seconds. [6]

The requirement for DC test voltage according to IEC 60060-1 is that the voltage should have no more than 3% ripple factor [6]. This means that instant value of the DC voltage in high voltage tests should not differ from its mean value more than 3% to achieve acceptable measurements values for standardised high voltage test cases.

2.2.2 Alternating current

Alternating current (AC) is a periodical voltage form that alternates between negative and positive polarities with a set frequency. In high voltage cases the used AC is sometimes called HVAC or high voltage alternating current.

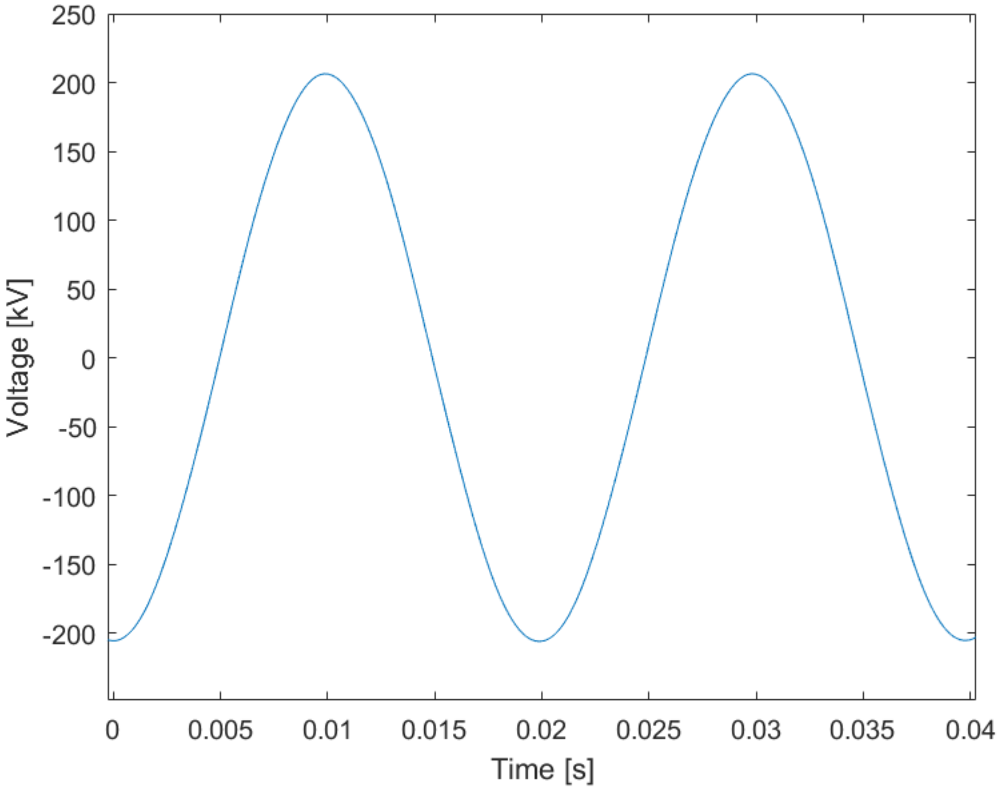

Figure 3: Example of AC voltage

The AC voltage parameters that are usually used for evaluation in high voltage testing are the peak value, the AC voltage's or current's value, its root mean square (r.m.s) value and voltage drop. The peak value is defined in IEC-60060-1 as the average of the magnitudes of the alternating current's positive and negative peaks. The AC voltage value is defined as its peak value divided by $\sqrt{2}$ and as the r.m.s value of the alternating current over a single complete cycle of it. Calculating r.m.s voltage is defined as square root of the mean of the square values of the voltage measurements. [6] As a formula r.m.s can be calculated as

$$U_{RMS} = \sqrt{\frac{\sum_{i=1}^{n} U_i^2}{n}}, \qquad (1)$$

where *n* is the integer amount measurements in a single cycle of AC and U_i is a measurement of voltage. Formula 1 explains the definition of root mean square in a more concise form. Additional AC parameters may be needed in testing. Such parameters can be its frequency which tells the time a cycle of the AC takes. IEC 60060-1 also proposes total harmonic distortion (THD) as a parameter to be used in AC evaluation for waveshape distortion [6].

Total harmonic distortion is a parameter used to quantify the amount of harmonics an alternating voltage (or -current) signal has. Shmilovitz, D explains in the article “On the Definition of Total Harmonic Distortion and Its Effect on Measurement Interpretation” that THD has two separate definitions. The first definition is that the harmonics are related to the fundamentals of the base waveform or to the signals root mean square in percentages. The second more accurate way to characterize THD is to compare the fundamental frequency component’s amplitude value and the amplitude values of the harmonic components of the signal. [9]

The requirement for AC test voltage according to IEC 60060-1 is that the voltage should operate with frequency between 45-65 Hz. Other frequencies can be used if needed depending on test cases. [6] IEC 60060-3 defines AC to be operating between 10 Hz to 500 Hz [10]. IEC 60060-1 states that testing AC should be sinusoidal is shape and the offset between its negative and positive peaks should be within 2 % [6]. These requirements for AC-voltage only describe what the standard IEC 60060-1 accepts as test voltage waveform for standardised high voltage testing conditions.

2.2.3 Lightning impulse

Lighting impulse (LI) voltage is an impulse voltage with a rising front time of less than 20µs. Impulse voltages are described in IEC 60060-1 as an intentionally implemented transient aperiodic voltages, which rise rapidly to their maximum values and return to normal conditions more slowly. [6] The LI voltages are designed to simulate external voltage stresses that high voltage systems may face e.g., due to lightning strokes. The used lighting test impulses are also subdivided into full lightning impulses and chopped lightning impulses. [11, pp. 5-6] Ideal lighting impulse voltage can be described as a double exponential waveform. The standard LI voltage is an ideal smooth lighting impulse with a front time of 1,2µs and time to half of 50µs [6] [12].

Figure 4: Example of a tail chopped lightning impulse (Adapted from IEC 60060-1:2010 [6])

There is also a sub-category of impulse voltages called chopped-impulse voltage. These impulses are either front chopped or tail chopped. Basically, these impulse voltages are such that the voltage collapses in the duration of the impulse before it would normally reduce. [6] Figure 4 shows an example of a tail chopped lightning impulse. The thesis will not go more into chopped impulses.

LI voltages are divided into two different parts. First, the part when the impulse raises from its apparent start to its maximum value is called the front. Secondly, the decreasing part after the impulse maximum value is called the tail. [11, p. 6] These two parts are used a lot in defining different parameters for high voltage impulses.

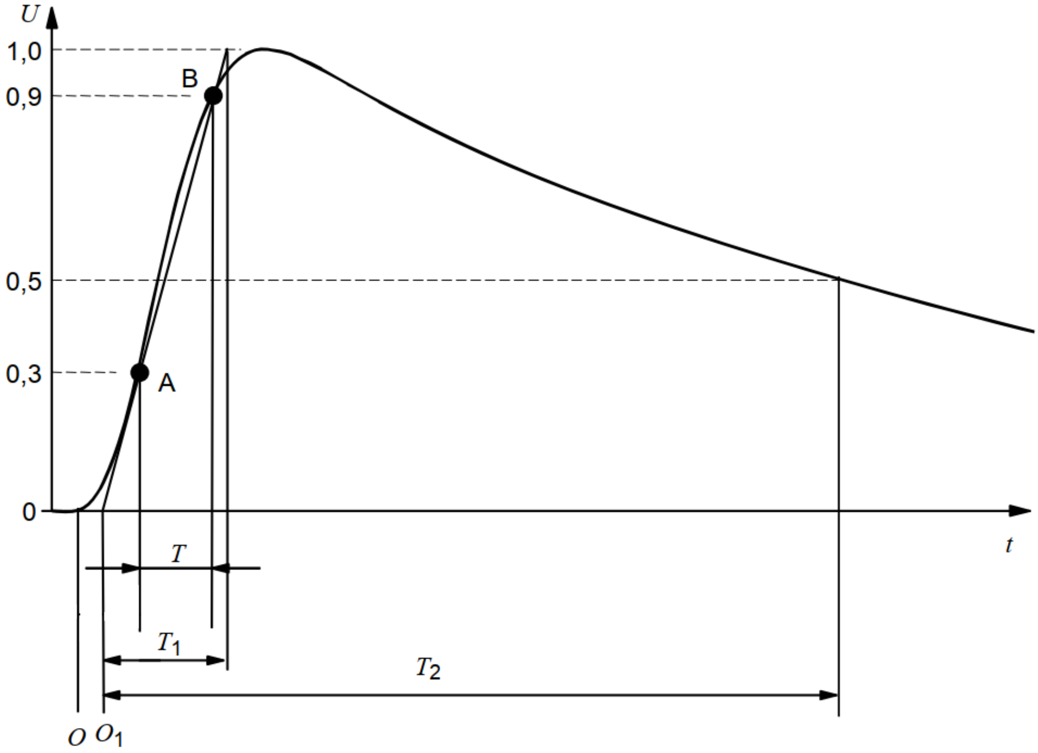

Figure 5: Important parameters of lightning impulse voltages shown on a standard model

Many important parameters have been defined for lightning impulse evaluation. Standard IEC 60060-1:2010 defines parameters for LI voltages, such as overshoot, recorded curve, base level, base curve, residual curve, extreme value U_e, base curve maximum U_b, value of the test voltage U_t, overshoot magnitude β, relative overshoot magnitude β', front time T_1, virtual origin O_1, average rate of rise, peak time T_e and time to half-value T_2. [6] Figure 5 shows an example on where and how the parameters of T_1, T_2 and O_1 are presented. The parameter of T shown on the pulse is a help parameter calculated as the time difference between 30 % and 90 % voltage values on the rising front of the impulse used to calculate the virtual origin O_1 and front time T_1. Figure 5 also shows that the virtual origin and true origin O are not necessarily the same.

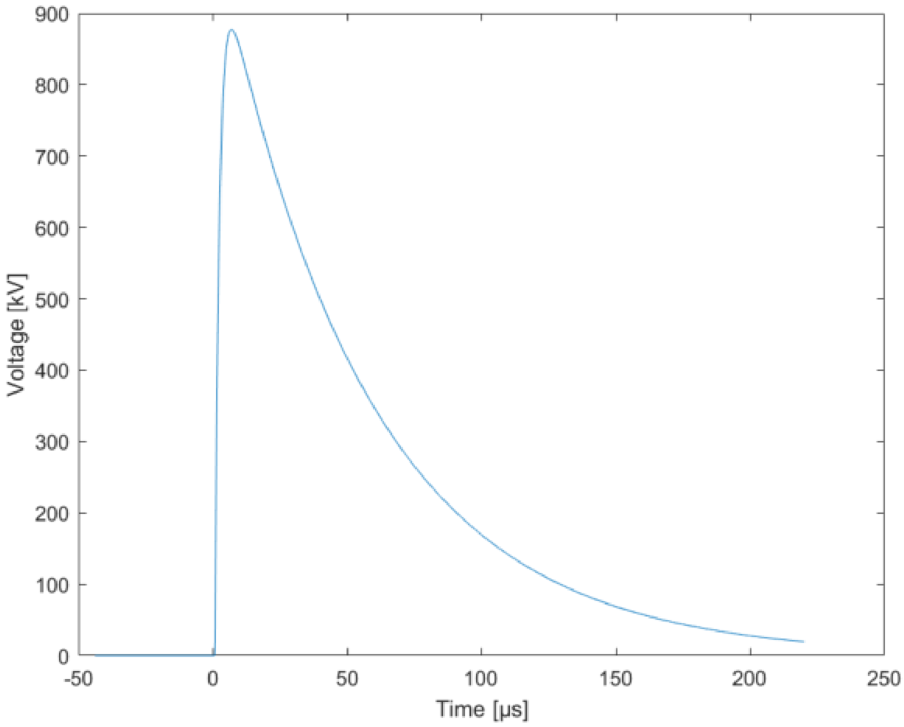

Figure 6: Example lightning impulse

The extreme value of the impulse is the absolute maximum value of the recorded impulse curve. Time to half-value is defined as the time the impulse takes to reduce to half its extreme value from its virtual origin. The front time is defined as 1/0.6 times the average rate of rise. Average rate of rise is the time between moments of 0.9 times the extreme value and 0.3 times the extreme value of the impulse in the impulses recorded curve. The virtual origin is defined as the time moment that is 0.3 times the front time. Peak time is defined as the extreme value of the recorded curve divided by the average rate of rise. [6]

Since with true impulses it can be hard to define when the pulse starts and when it reaches its peak value due to for example noise and oscillations, the front time T_1 is used to tell the waves front time. Front time explains the nominal rate at which the impulse arrives at its peak value from its nominal start. The front time T_1 is usually calculated as the time the impulse takes to rise from 0.1 to 0.9 of the impulses peak value multiplied with 1.25 but in case of high voltage LI it is recommended to calculate it by multiplying 1.67 with the time the impulse takes to rise from 0.3 to 0.9 of the impulses peak [13]. [14, pp. 81-82] This different way to define and calculate the front time is based on the typical behaviour of high voltage impulse generators. Typically, the generators' operation causes a leap to take place at the start of the impulse, distorting the time when the impulse arrives at 0.1 of the peak value. This is also done to remove the effects of low voltage oscillation on the impulses front time calculation [12]. In general, with high voltage impulse analysis, the impulses parameters are defined differently compared to low voltage systems' impulse analysis due to special circumstances arising from the pulse generation and measurements [11, p. 6]. The value calculation from 0.3 to 0.9 is the preferred standardized method in high voltage evaluation.

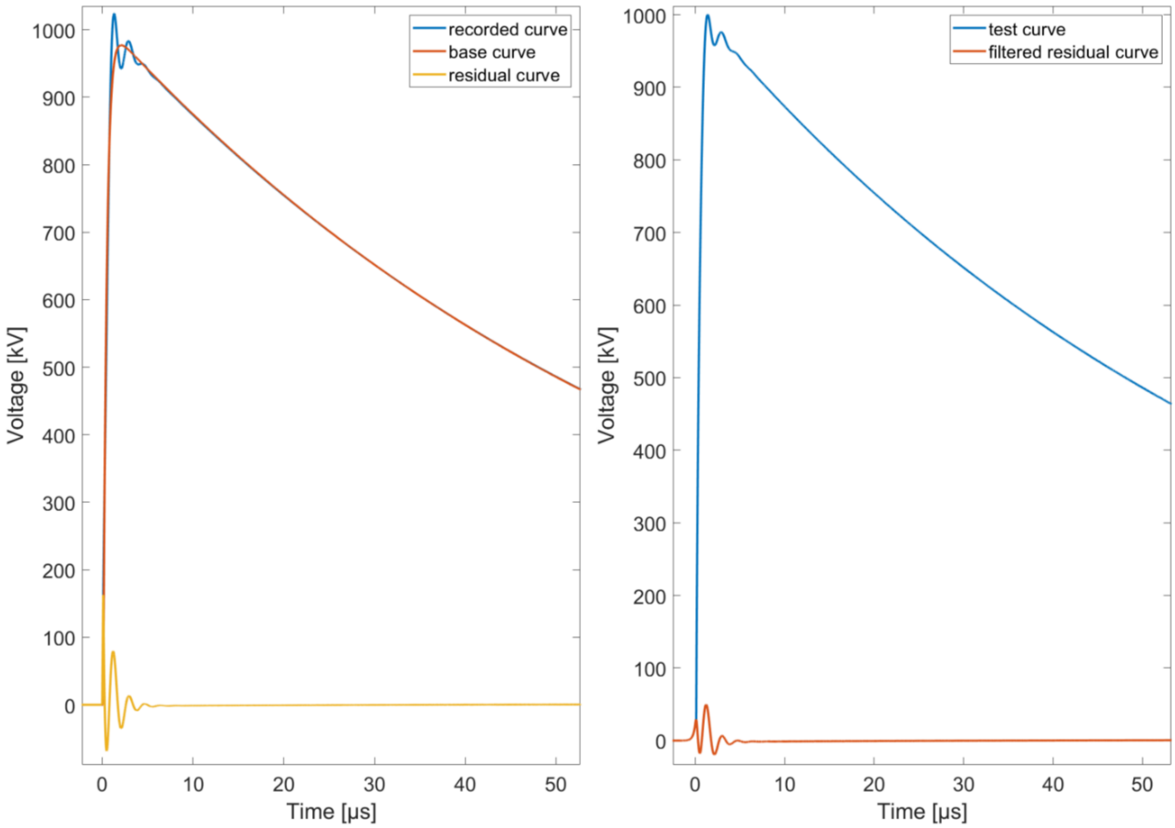

Figure 7: Lightning Impulse pseudo curve example with pseudo curves: recorded curve, base curve and residual curve on the left, and test curve and filtered residual curve on the right.

To minimize the effects of unwanted high frequency oscillations and other disturbances standard IEC-60060-1 defines a curve fitting and filtering procedure to be implemented. For these procedures to be possible to help evaluate lightning impulse voltages, there are multiple pseudo curves that need to be generated called base curve, residual curve, filtered residual curve and test curve. Figure 7 shows an example of the relation the pseudo curves have to each other. This evaluation is explained in the standard IEC 60060-1:2010's Annex B. The raw initial impulse curve is called recorded curve which is gotten straight from the raw measurement. Base curve is a virtual curve that is made by fitting a double exponential curve using least-squares fitting method on the recorded curve. More on curve fitting methods is explained in chapter 4.1. Residual curve is defined as the residual that is left after the generated base curve is removed from the recorded curve. The filtered residual curve is then the residual curve after it has gone through a low-pass filter, more on filtering in chapter 4.2. The filtered residual curve is used in overshoot magnitude β and relative overshoot magnitude β' calculations by calculating its maximum amplitude and comparing it to the base curves maximum amplitude. At the end, test curve is the final analytical lightning impulse curve where the base curve and filtered residual curve are added together. [6]

Some of the parameters defined for lightning impulses utilize the pseudo curves in their definitions. The base curves maximum is defined as the maximum value of the base curve. Value of the test voltage is defined as the maximum value of the test voltage curve. Overshoot magnitude is defined as the difference between the original recorded curve's maximum and the fitted base curves maximum. The relative overshoot magnitude is the ratio between the overshoot magnitude and the extreme value of the lightning impulse. [6]

The base curve that is used to fit an impulse curve on the recorded data is done with the formula

$$u_d(t) = U\left(e^{-\frac{(t-t_d)}{\tau_1}} - e^{-\frac{(t-t_d)}{\tau_2}}\right), \qquad (2)$$

where τ_1 is the time constant of the exponential decay, τ_2 is the time constant of the exponential growth, *t* is the time moment, t_d is the time delay or starting time and *U* is the maximum value of the impulse [13]. The maximum value of the impulse can be negative or positive depending on the polarity of the impulse. It is recommended that the base curve formula 2 is used with Levenberg-Marquardt algorithm for fitting an impulse into the recorded data. [6]

The relevant standard for lightning impulse measurements IEC 60060-1 has defined tolerances for couple of the main parameters for the generated lightning impulse to be acceptable for standard measurements. Firstly, the value of the test impulse is wanted to be within ± 3%, the front time needs to be within ± 30 % and time to half-value needs to be within ± 20 %. It is also admitted that these tolerances are not always possible to reach, and the tolerances of the impulse form can be defined differently in the various device specific standards. [6] The reason why the parameters have different tolerances in size and especially the relatively huge variance towards the time parameters is because the test object and the test circuit have varying amounts of interactions between themselves which affect the waveforms in such ways that the time parameters are especially easily affected. [11, p. 9]

2.2.4 Switching impulse

Switching impulse (SI) voltage is a high voltage impulse with front time of 20 µs or more [6]. The analytical difference between SI- and LI voltages is that SI is considerably longer in effective duration.

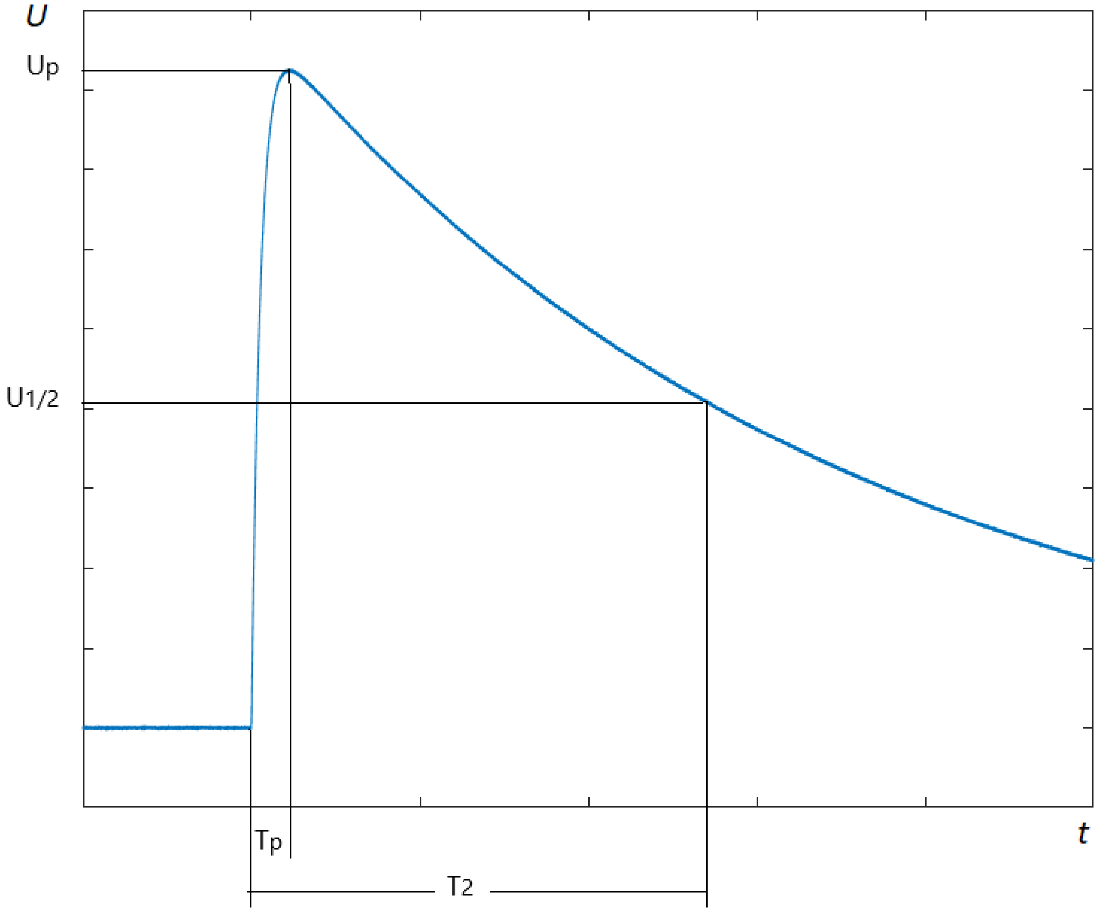

Figure 8: Switching impulse main parameters

The important parameters defined for SI voltages for high voltage testing in IEC 60060-1 are the maximum value of the test voltage, time to peak T_p and time to half-value T_2. Several additional parameters have been defined for switching impulses, which are true origin *O*, time above 90% T_d and time to zero T_z. As they are help parameters, they have no defined tolerances. The definition for the value of the test voltage, is simply the maximum value of the recorded impulse. The definition for time to peak, is the time the impulse takes from its true origin to the value of the test voltage. The true origin of the signal is the instant when the impulse starts or only increases or decreases in value until the maximum value. Time to half-value is defined as the time the impulse takes from its true origin to increase to its maximum and decrease to half of the maximum value again. Time above 90 % is defined as the time the impulse is over its 90 % value of its maximum.

Time to zero is the time the impulse takes between its true origin to increase to its maximum value and decrease to its passage first through zero or the offset value. A final parameter used in IEC 60060-1 for SI impulse evaluation is T_{AB} which is simply the time interval between the impulses fronts 30% - 90 % of the impulses absolute value. It is the same parameter which LI's front time T_1's calculation is based on [11, p. 8]. [6] Figure 8 shows a visual example of where the main SI parameters are in a switching impulse. The main parameters that are shown are T_p, T_2 and the impulse peak value U_p. The figure also shows the help parameter $U_{1/2}$ which denotes the half value of the impulse peak.

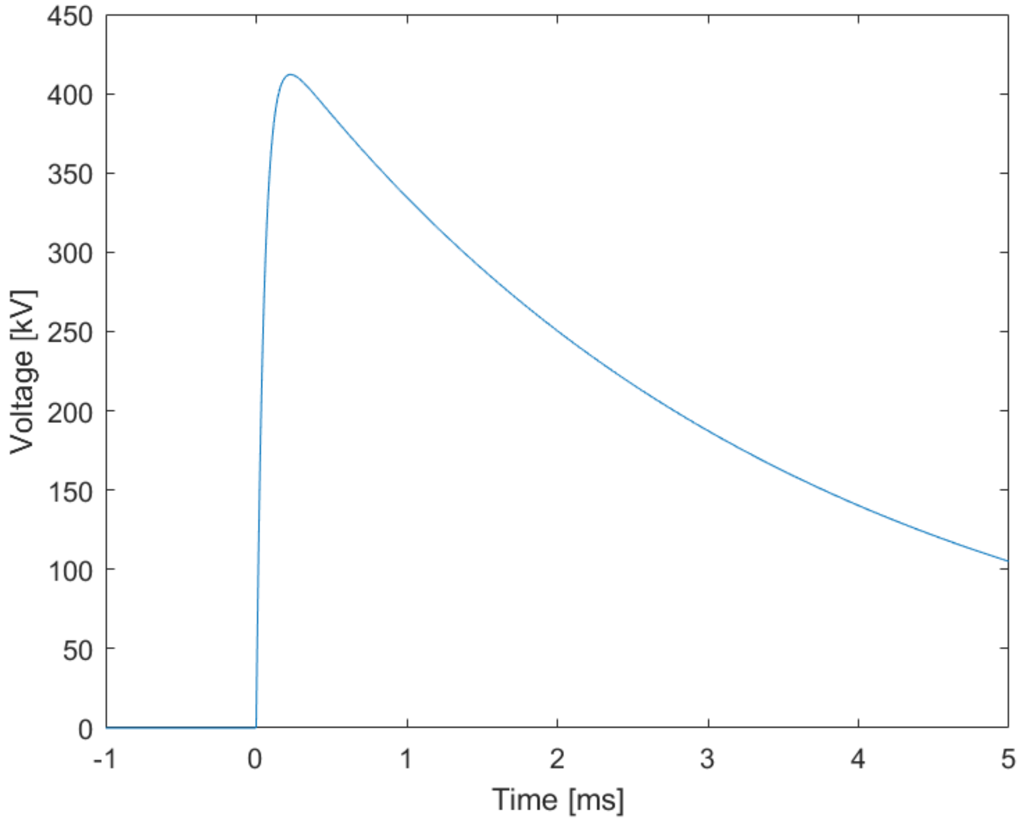

Figure 9: Example switching impulse

As can be seen when comparing Figure 6 and Figure 9 that the SI and LI voltages are very similar in voltage shape as they are both double exponential waveforms. It can be also seen that the SI voltage is considerably longer in effective time duration.

Since the SI and LI voltages are so similar with the difference of effective time duration, in the committee draft of 'IEC 60060-1 Edition 4 standard for switching impulse' it has been proposed that SI impulse is standardised in the same way as LI voltages. The new SI voltage definition would have the same front time T_1 and half time T_2 as defined with LI voltages in chapter 3.3 apply to SI test voltages [15]. This would mean that the same evaluation methods shown in IEC 60060-1 Annexes B and C for LI would also apply to SI test voltage evaluations.

In the current version of standard IEC 60060-1:2010 the standard switching impulse voltage is defined as having time to peak of 250 µs and time to half of 2500 µs [6]. If the SI voltages are defined with front time and time to half as with LI voltages, the standard SI voltage would be defined as having a front time of 150 µs and with the same time to half-value of 2500 µs.

The current problem with IEC 60060-1:2010 regarding SI impulses is that it has a single definition for SI voltages time to peak value, but multiple differing calculation methods for it. Firstly, it defines the time to peak as the absolute time between the impulse true origin and the peak value. It then defines the calculation for the standard switching impulses time to peak as to be calculated with formula $T_p = KT_{AB}$, where $K = 2.42 - 3.08 \times 10^{-3}T_{AB} + 1.51 \times 10^{-4}T_2$. It also points out that according to standard IEC 60060-3 the defined calculation for the time to peak as $T_p = 2.4T_{AB}$ [10]. [6] This means that there exists three different simultaneous definitions for time to peak that are all different from each other for standard impulses. Additionally, standard IEC 60060-1:2010 allows the calculation and methods for non-standard switching impulses time to peak-value to be calculated in any way possible [6]. The first definition is the one that is used more in depth in this thesis.

2.2.5 Combined voltage

Combined voltage is explained in the standard IEC 60060-1 as combination of 2 different voltage types explained in 3.1, 3.2, 3.3 and 3.4. Combined test voltage is the voltage that appears between two energised terminals on a test object which has three terminals with the third being earthed [2, p. 404]. The test voltages need to be generated with separate voltage sources, and the sources energize different terminals of test object. The combined voltages voltage components are measured separately and added together in evaluation phase to form the actual combined voltage stress and waveform. [6]

The parameters used to characterize combined voltages are value of the combined voltage and time delay *Δt*. The value of the combined voltage is defined as the maximum potential difference between the two energized terminals of the test object or as the maximum absolute value of the combined voltage. Time delay is defined as the shortest time between the maximum values of the two voltage components of the combined voltage. [6] Since DC voltage does not have a realistic maximum outside the ripple voltage and possible noise spikes, the time delay between DC and any other type is 0. If the time delay is zero, the pulses are said to be synchronous [6].

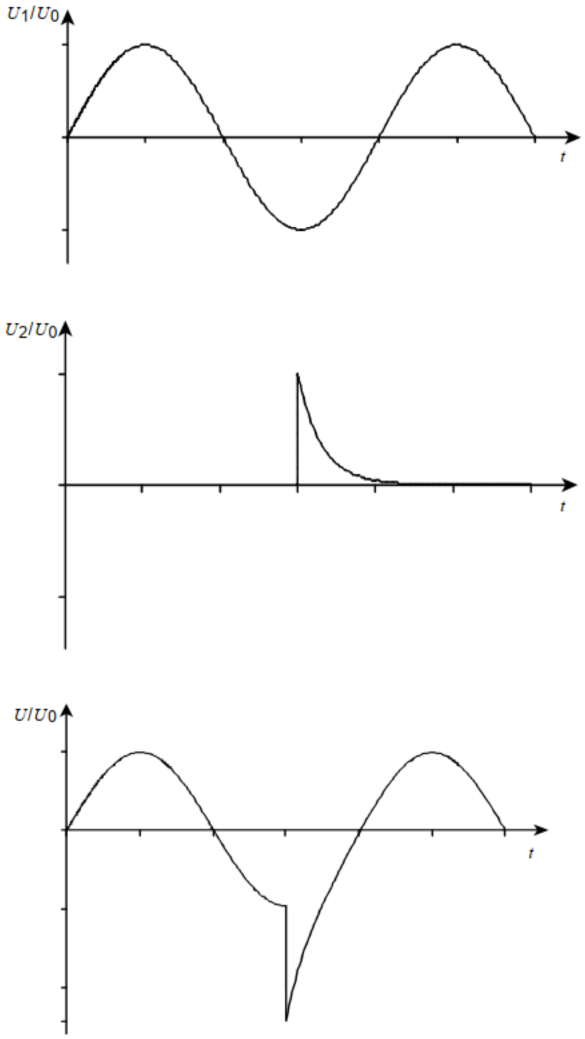

Figure 10: Example of a combined voltage

Standard IEC 60060-1 also defines that the two separate voltage component's own parameters defined in their own sections of the standard are to be also evaluated as a part of combined voltage evaluation. The tolerance of combined voltage's time delay *Δt* is ± 0.005 T_p, where T_p is either the front time or time to peak of an impulse or quarter of a cycle of AC voltage. The T_p used in the tolerance calculation is the longer time of the two voltage forms involved in the combined voltage. [2, pp. 404-405] [6]

Figure 10 shows an example of a combined AC + switching impulse voltage. The figure shows the two component voltages on the top and the differential of the component voltages or the combined voltage at the bottom.

2.2.6 Composite voltage

Composite voltage is defined as a superposition of two separate voltage sources. The difference between combined and composite test voltages is that the composite test voltage is supplied to the test object through a single terminal, whilst in the combined test voltage’s case, the voltage sources were connected to separate terminals of the test object as explained in chapter 2.2.5. The composite test voltage differs from the combined test voltage since unlike with the combined test voltage, the composite voltage is measured such as it manifests. The two component voltage sources can be measured separately as an additional source of information, but only the measurement of the composite voltage is needed according to standard IEC 60060-1. The component voltages in composite test voltages can be according to international standard IEC 60060-1 any combination of direct-, power frequency alternating voltages, switching – or lightning impulses. [6] Realistically, only superpositions possible for composite voltages are direct or alternating voltages with lighting- or switching impulses. Figure 11 shows a realistic example of a composite voltage, which is a superposition of an AC voltage and a lightning impulse.

The basic parameters used to characterize high voltage test composite voltages according to IEC 60060-1 is the maximum absolute voltage value of the composite waveform. Secondly as with combined waveforms, composite voltages require the time delay between the component voltage maximums to be evaluated. Thirdly, for composite voltages it is require that all the component voltage waveforms are to be evaluated as defined by the standard. [6]

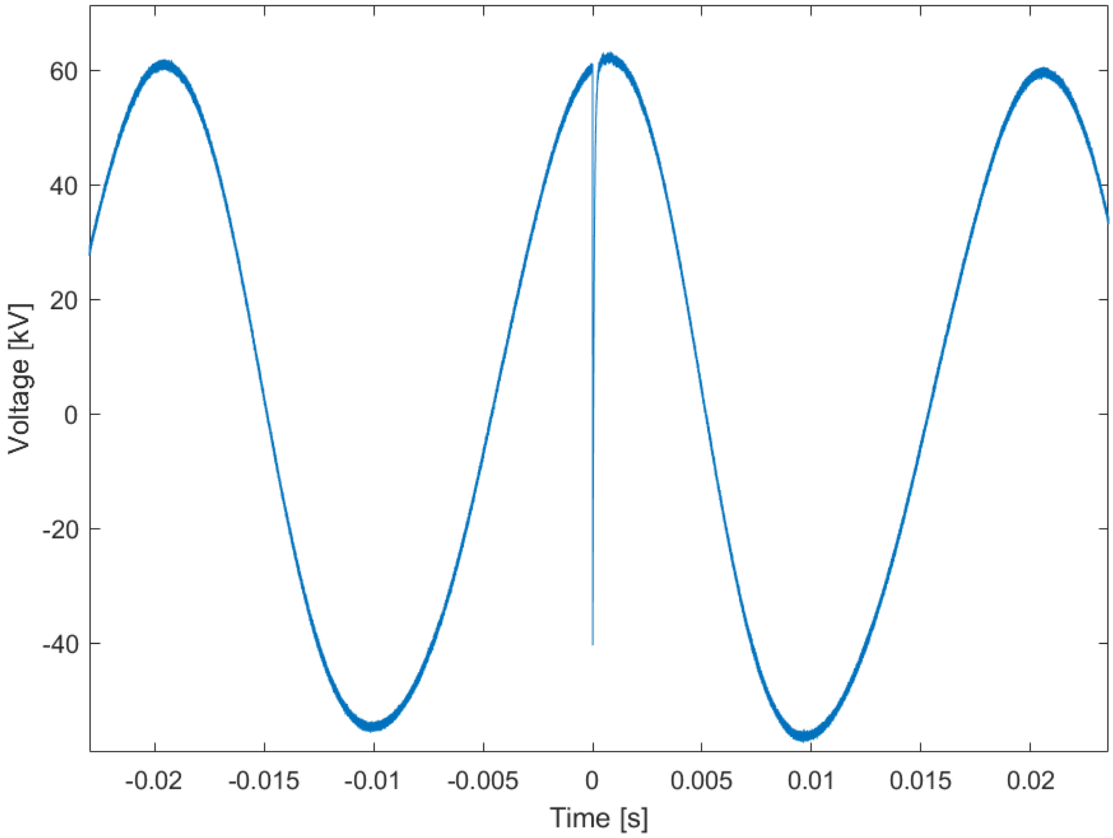

Figure 11: Example composite AC+LI voltage

The time delay is the time between the maximum values of the two composite voltages [6]. When DC voltage is one of the composite voltage's component the time delay is zero since DC voltage does not have a reasonable instant of maximum. The maximum between alternating power voltage and an impulse is calculated between the impulse's maximum and the closest negative or positive sine peak of the power alternating voltage.

The same tolerances hold for composite voltages as explained for combined voltages in chapter 2.2.5. The tolerance for time delay Δt is ± 0.005 T_p, where T_p is the longer of the two voltages involved in composite voltage generation. [2, p. 407] [6]

3. TEST CIRCUITS AND MEASUREMENT SYSTEMS

In order to test HV components capabilities to survive with acceptable reliability in HV networks from different voltage stresses, testing circuits and measurement systems have been developed and partly standardised to make sure that the components fulfil basic requirements to operate safely in service. This chapter goes over the general testing circuits used to test HV waveforms, how the measurements are done and the measurement system uncertainties. This will be done, since the used testing circuit may affect the measurements done for the HV components with the HV waveforms. Explaining the used test circuits also explains why some details were needed to be done with the evaluation software.

3.1 Test circuits

The HV test circuits consist generally of multiple components. Firstly, the high voltage generator which generates the test voltages. Secondly, the power supply unit which generates the base voltage form. Next the high-voltage measuring system which is used to measure the test waveforms which are usually converted from high-voltage to medium- or low-voltage. Next there is the control system which controls the high voltage test circuits components. Lastly, the test object which the voltage stress is supplied to. [2, pp. 29-31]

Generally, every type of test voltage requires different testing circuits and generators to be tested on. This is intuitive since same method cannot be used to generate alternating current and direct current. Yet within the generator types used for all voltage forms there is also deviation depending on the needed parameters of the test voltage. Deviation is also caused by the inside and outside conditions of the testing situation such as weather effects and testing object’s special characteristics.

3.1.1 AC and DC test circuits

AC and DC testing circuits and generators for High-Voltage testing are the most basic and easiest to implement. The power frequency test voltage is usually generated with a step-up transformer with a feeding regulating transformer. Alternative way to generated it is by means of a series-resonant or parallel-resonant circuit. [6]

As explained, the HVAC test voltage can be produced in multiple ways depending on the test need. The main methods are with test transformers and transformer cascades. The other main way is to use a resonant circuit with reactors and variable inductors or with set inductors and variable frequency power source (converter circuit). [2, p. 89] The use of transformers or converter allows the generator to operate at low voltages which the transformer or converter then describes to HV testing side.

Test transformer based HVAC test circuits comprise of HV generator, a transformer to adjust the output voltage, a reactor to compensate reactive power and a high voltage measuring system. These are the general components of an HVAC test circuit. The number of winding used in the transformer depends on the used system. [2, p. 90] For example, a system can have two or more HV transformer windings in series. This way the voltage stresses the HV winding faces is lessened since they can have less winding cycles in them making them more robust.

The first example of a transformer circuit is a tank-type test transformer. This type of test transformer is kept in a cooling tank. Usually, these transformers have their acting parts encased in the metal tank where either a HV winding or multiple HV windings in series of the transformer circuit are kept. The biggest advantage of a tank-type test transformer is that is can produce high test currents and powers due to its high cooling capacity. [2, pp. 95-96]

The next example of a HVAC test circuit is cylinder-type test transformer. In these test transformers the transformer winding is located inside an insulated cylinder casing. These transformer circuits cannot be used for long times without forced cooling. This means that these testing transformers thermal properties need to be taken into account when used to make sure there are no thermal problems and the transformers have issues with reactive test power generation. These transformers are good for transformer cascades for their small volume in indoor test laboratories since they can be simply stacked on top of each other. [2, p. 98]

Transformer cascades are applied to produce higher test voltage values than single unit test transformers. Transformers used in test transformer cascades have an additional winding on them besides their primary and secondary windings on the HV side called transfer winding. This winding’s primary application is to supply voltage to the cascade’s next stage’s transformer’s exciter winding. Normally the transformers are identical between the stages of the cascade excluding the final stage. Transformer cascades are extremely useful in production of high test voltages but the restriction for the power the test transformer cascade can produce is the rated power of the lowest levels of the transformer cascade. [2, pp. 102-104] When producing high test currents, there can be two or more test transformers connected in parallel in the lowest levels of the test transformer cascade. Since the transformers require capacitive current the cascade transformers need tuneable reactors to compensate for the capacitive current needs of both the transformers and test object to make sure the lower levels of the cascade transformer are not overloaded [2, p. 105]. Figure 12 shows an example of a two-stage transformer cascade circuit.

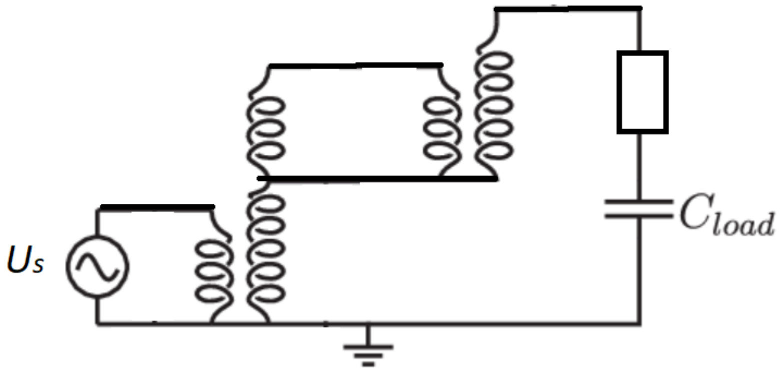

Figure 12: Example of a 2-stage transformer cascade circuit

Series resonant circuits, or oscillating circuits, used in HVAC systems can be constructed in a couple of ways. The first way is to manage the HV generators internal impedance in such a way that the natural frequency of the testing circuit matches the feeding frequency of the HV test voltage. The second way is to feed the testing circuit with a frequency adjustable converter. In the first way, the resonance frequency cannot be fulfilled or found if the load is of low or of high capacitance. The series resonance, when the resonance frequency is the natural frequency of the circuit, achieve such effects that the fed voltage is increased. The circuits are fed with an exciter transformer which matches the voltage fed from the HV generator to the required output voltage and is designed to match the systems maximum necessary feeding power. [2, pp. 105-107]

Parallel resonant circuits are the other resonant test circuit type used with HVAC testing setups. These circuits are utilized with relatively low test voltages but with high capacitive test objects. The circuits capacitive currents are fully supplied by the HVAC reactor in case the circuit is used in resonance. In this circuit type, the exciter transformer is placed in parallel to the HVAC generator, unlike with series resonant circuits where the transformer was in series. By doing this, the full control of the voltage in the parallel resonant circuit is under the transformer’s control. A special test circuit is a transformer test circuit where the HV side of the circuit is fully compensated. [2, pp. 107-108]

The third main type of resonant test circuit used in HVAC testing is inductance-tuned resonant circuit with a fixed frequency. In these circuits the used transformer has an adjustable gap in its magnetic core. Adjusting this gap changes the transformers inductance. Since the change in inductance value of the transformer does not linearly follow the air gap length, the length at which the air gap can be modified is restricted to be a relatively confined range. The more accurate value to follow in the air gap modification is the phase angle between the feeding voltage and the voltage from the reactor. Resonant circuit may be installed with a load capacitor to make possible resonant test circuit operation with a non-capacitive test object. [2, pp. 109-111]

Just like with HVAC test voltage generation, there are multiple ways to achieve HVDC voltages depending on the used test circuit and the needed voltage parameters. Generally, HVDC test voltages are achieved by producing the voltage by rectifying HVAC voltage [4, p. 10]. The simplest example is a single-phase way to produce HVDC test voltages by connecting a rectifier and a load capacitor, either a test object or a smoothing capacitor, to a HVAC transformer circuits output. These multiplier generators are also called Cockcroft–Walton generators. Since normal diodes limitation is to handle voltages of up to a few 1000 V, for HV rectifiers multiple diodes are needed in series to handle the necessary 100kV or MV voltages. Doing this produces a so-called half-wave rectifier circuit. The operation principle is that the used rectifier only opens for one of the polarities of the AC waveform and blocks the voltage at the opposite polarity. When the load capacitor is connected to the circuit, the rectifier is only open when the voltage through the transformer is higher than the capacitors voltage. The load capacitor starts to discharge when the AC waveform arrives at its maximum and starts to charge when the rectifier opens. Because the capacitor continuously alternates between discharging and charging the output HVDC is not ideal and has a relatively high ripple voltage ∂U component in it. The DC ripple is directly tied to the load resistance. This means that the DC voltage is smoother with decreasing capacitive load and increasing resistive load. When using the half-wave rectifier circuit with a test object that can cause high pulse currents, the transformer is not able to supply the circuits energy demand which can cause a voltage drop described in chapter 2.2.1. To avoid this, the smoothing capacitor should be large enough to supply this energy demand. [2, pp. 271-276] Figure 13 shows an example of a rectifier circuit with a load capacitor C1. The output DC waveform is not a perfect straight line as can be seen from the red line, but an approximation with voltage ripple ∂U component. As the voltage source $U1$ a power frequency voltage source such as a transformer circuit can be used.

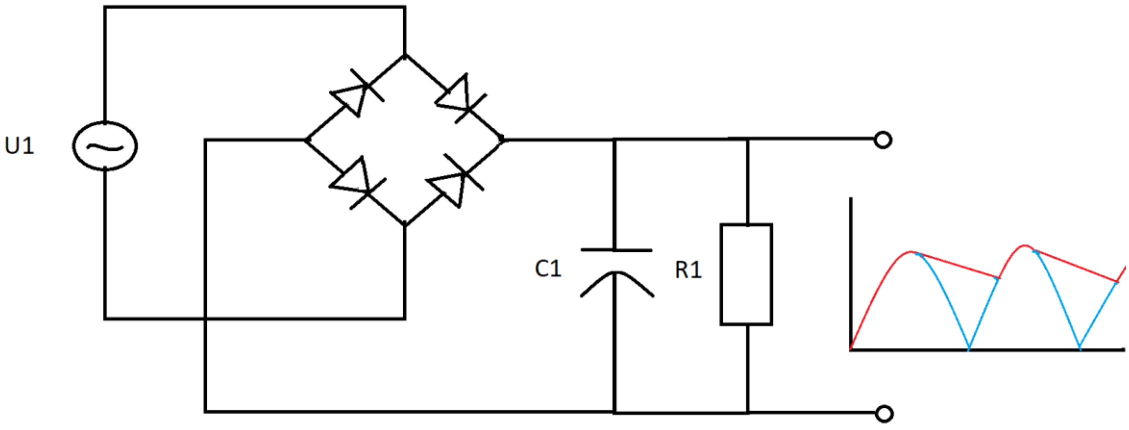

Figure 13: A rectifier circuit with a load capacitor. Output voltage waveform shown on the right.

The upgraded version of the half-wave rectifier circuit is the two-pulse half-wave rectifier circuit, where both of the single-phase AC voltages polarities are utilized. This is done by having two parallel rectifiers targeted, one for each polarity of the transformer's supplied voltage. Another upgraded version of the basic half-wave rectifier circuit is the doubler or multiplier circuits. These circuits use doubler capacitors or blocking capacitors, to charge and keep the voltage at a wanted level. This is done by using an additional rectifier parallel to the doubler capacitor to oscillate the voltage at a wanted level and double or multiply the voltage supplied to the rectifier supplying the smoothing capacitor and the DC side of the circuit. In theoretical form, the doubler circuit doubles the output voltage of the circuit, so adding multiples of the doubler parts always multiplies the output voltage by the number of doublers that are connected to the circuit. These HVDC test circuits that comprise of multiple doubler rectifier capacitor combinations are called cascade circuits. An example of this style of multiplier circuit is the Greinacher cascade circuit. [2, pp. 273-277] Figure 14 shows the Greinacher cascade HVDC multiplier circuit.

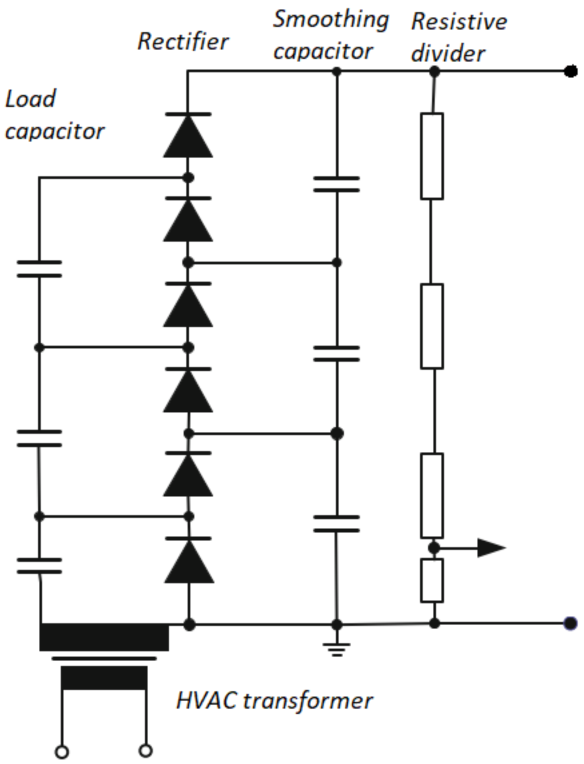

Figure 14: Example HVDC circuit - Greinacher cascade [2, p. 274].

The cascade HVDC generators are quite useful in high-voltage testing. The polarity of the output voltage can be changed by flipping the rectifiers in the generator. It is effective to be used with capacitive loads but is limited in use with highly resistive loading situations. [2, p. 277] With these types of multiplier circuits, the caused ripple voltage is also multiplied.

HVDC multiplier circuits can also be arranged in a way that every level of the cascade structure has a connection to an HVAC transformer in a cascade structure. When arranged like this, the HVDC multiplier circuits output ripple is at the same level as the simple rectifier HVDC circuit would have at output. All the levels in these types of multiplier circuits are one-phase two-pulse rectifier circuits. Since the used transformers cannot be grounded, they have to be isolated differently from the stress caused by the HVDC circuit. The secondary winding of the transformer is connected to a smoothing capacitor, while the primary winding is connected to the primary winding of the next transformer in the line or the rectifier. The other way to utilize HVDC circuits with cascade transformers is by making the system modular where every module includes a rectifying one-pulse or two-pulse rectifier circuit with its own transformer cascade level. These circuits are versatile and can produce different voltage levels and their polarity can also be switched on the fly. [2, pp. 279-281]

The standard IEC 60060-1 requires that the HVAC generator is stable enough to operate almost unaffected even through the effects of the leakage currents. It is also suggested that the used test object and all possible additional capacitors should have high enough capacitance so that the disruptive-discharge voltages that are measured in the system are unaffected by the non-disruptive partial discharges. [6]

3.1.2 Switching and lightning impulse test circuits

The basic implementation for switching- and lightning impulse generation in high voltage testing circuits is that a storage capacitor is slowly charged to fit a value suitable to produce the desired impulse voltage peak value. The storage capacitors are then quickly discharged on the test network and the test object with the help of a high-voltage switch. The waveform of the impulse is defined by the effects of the connected network's and test object's impedances. For switching impulse voltage generation, it is also possible to use inductive storages and transformers. The final test waveform is defined by the network and test object which the storage capacitors are connected to. [11, p. 23]

In the impulse generation, when the voltage of the used high voltage switching device, such as sphere gap reaches its firing voltage, the impulse capacitor or capacitors release their charge quickly through the switching device. The switching device may be a sphere gap or an electronic switch. The discharge through the switching device is supplied through a discharge circuit. The discharge circuit consists of damping and load resistors and the load capacitor. The impulse capacitor is loaded through a one-sided rectifier. The main effects are that the damping resistor affects mainly the front time T_1 of the impulse and the discharge resistor affects the time to half value T_2 of the final impulse. [11, p. 23]

There exist two main types of circuits for generating impulse voltages. Both consist of the same components. The difference between them is the positioning of the said components, specifically the location of the discharge resistor. In the first type, the discharge resistor is located before the damping resistor and in the second type, the discharge resistor is located after the damping resistor. In general, the first type of impulse generator is more suitable to lighting impulse generation and less suitable to switching impulse generation, while the second one is more suitable for switching impulse generation. [11, p. 23] Figure 15 shows circuit diagrams of a single stage of these impulse generator types. In the Figure 15 capacitor C_1 is charged with a voltage source, then discharged through the switching device S into the pulse shaping components discharge resistors R_2, damping resistor R_2 and wave shaping capacitor C_2.

U_0 is the impulse shaped output voltage. The switching device *S* can be for example a sphere gap.

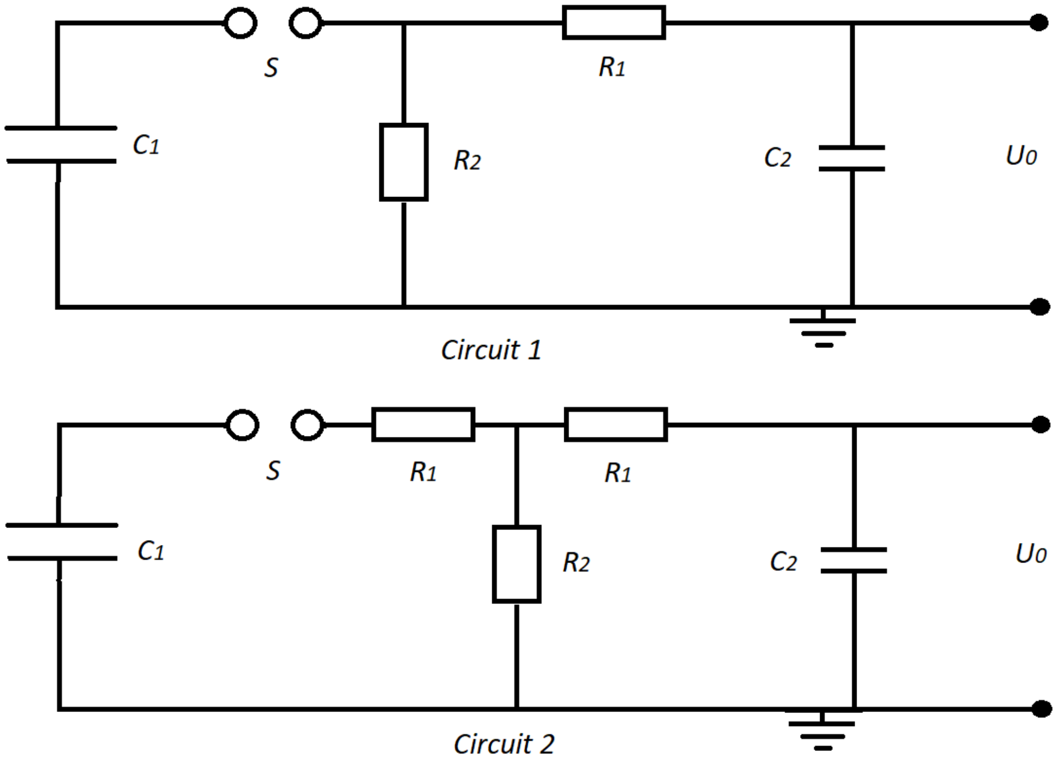

Figure 15: Examples of basic impulse generation circuits

Multistage or voltage multiplier circuits are used when the wanted impulse peak exceeds the voltage rating of a single storage capacitor. To achieve high impulse voltages the single stage circuits are packed on top of each other. Each stages' impulse capacitor is charged slowly to the wanted voltage level. When the wanted voltage is achieved, the impulse capacitors are connected in series through the triggering of switching elements. This way the charged voltages at each stage add up to the wanted impulse voltage. As with cascade generators for HVDC test voltage generation, the polarity of the multistage or multiplier impulse circuit can be switched by reversal of the rectifier in the circuit. To achieve simultaneous activation of the different levels of the voltage multiplier circuit, when using sphere gaps as connector elements, the lowest level sphere gap should be of a bit reduced spacing so that it triggers earliest, causing a voltage potential to appear at the other side of the other levels' sphere gaps triggering them simultaneously. Since the impulse capacitors may have residual charge left in them after the impulse generation, a good earthing after the testing is important as with all other high voltage applications. [11, pp. 24-25]

One problem that arises with these multistage impulse generators is that when they are used at low impulse voltages and increasing number of active stages, the switching devices on some levels may not trigger causing the output impulse to not be of wanted form and magnitude. This can be fixed by having separate generators that are in charge of firing the switching elements controllably. [11, p. 25]

Both the measurement system and the test object are usually connected in parallel to the impulse generator’s load capacitor. This way, if the load capacitor is kept as high as possible in capacitance value, the impedances and capacitive values of the test object or measuring system will not affect the waveshape of the generated impulse more than minorly. [11, p. 27]

Standard lighting impulse generators are incapable of generating impulses with high steepness due to the generating systems self-inductance. The limiting factor of the generated impulses steepness or time to peak is the inductance of the impulse generator [5]. If lightning impulses are wanted to be generated with steep fronts, a separate peaking circuit needs to be in operation. The peaking circuit utilizes a capacitor tenth or fifth of the size of the impulse capacitor which is charged with the generator when the switching device is activated and then discharged to the load through its own resistor thus steepening the output impulse. [11, p. 29]

Switching impulse voltages in HV testing application can also be generated with the use of impulse-exited testing transformers with voltage jumps. In this type of circuit, a charged capacitor is connected to a testing transformers low voltage winding, which causes a switching impulse to appear on the transformer’s high voltage winding side. The impulses generated this way have longer time to peak and time to half values than standard impulses. Switching impulses with oscillation can also be generated with this method. [11, p. 28] One must still make sure that the transient caused with this method does not lead to unwanted overloading of the system. [5] The switching impulses generated with test transformers are usually not perfect standard form switching impulses of double-exponential waveform.

3.1.3 ‘Mixed Voltage’ test circuits

Generally, the ‘mixed voltage’ or HV combined/composite voltage test circuits utilize two separate types of test circuits. Firstly, either a HVDC or HVAC test circuit and then a separate circuit for switching- or lightning impulse generation. It is also possible to have ‘mixed’ test voltages of combination of both HVAC and HVDC voltages, as is needed in some insulation tests for HVDC components. [2, p. 401]

When using combined voltages of impulse and alternating current in high-voltage testing application, the impulse generator needs to operate with controllable switching devices, basically the switching devices need to be triggered controllably. This must be done because the ‘mixed’ voltages with alternating current and an impulse require the impulse to be triggered at correct phase position compared to the alternating current form. [11, p. 25]

As with the definition between combined and composite voltages the generation and test circuits of composite and combined test voltages differentiates on how the superposition of the voltage stress is formed on the test object. Combined voltages effect the test object from separate terminals to ground and the composite voltage superposition affects the test object from a single terminal to ground. In both cases, the voltage stress from the other test voltage source and -circuit needs to be blocked so they will not affect each other’s operation. This could be done by utilizing such blocking elements that let the circuits own voltage to pass while blocking the other source’s influence as much as possible. [2, p. 401]

The basis is that combined voltages appear on three terminal test objects such as circuit breakers and disconnectors while composite voltages appear at two terminal test objects. In case of combined voltage tests the protection elements are also needed, since if the test object breaks the other voltage source would be stressed by the other. Proper blocking elements would be such that have for example different impedances for different voltage types. For example, inductors have no impedance at zero frequency (DC voltage) but extremely high impedance at high frequencies (for example lightning impulses). Still the impedance of the coupling protection should be minimal compared to the test objects impedance. [2, pp. 402-403] For these reasons the utilized blocking elements depends on both the protected voltage source and the voltage source protected from it. It also means that the protection or coupling elements used in the ‘mixed’ voltages test circuits also affect the operation of the separate voltage generators.

Since the composite test voltages according to its definition needs the separate voltage sources connected together at a single terminal of the test object to achieve the superposition of the voltage components to stress the test object, the effect the voltage generators have on each other can manifest a large role on the operation of their operation. [2, pp. 406-407]

3.2 Measurement systems

No matter what, all measurement systems affect the signal they measure [16, p. 147]. This is true for all measuring systems, by that for example voltage measurements, time measurements or temperature measurements. Therefore, it is important to understand how measurement systems are built for high voltage measurements to understand and explain the possible effects they have on the measurements.

Since the currents and voltages measured in high voltage application and test circuits are typically at voltage levels of couple of hundreds of kilovolts, direct measurements are not possible. Since the measurement system cannot always measure the high voltages directly, the measurements are usually done for so called measurement signals that are proportional to the true measured value. The measurement signal is brought to an oscilloscope or some other measuring system through high voltage divider and a measuring cable. [17, pp. 1, 30]

The general standard covering the measuring systems is IEC 60060-2 [2, p. 408] [6]. Standard IEC 60060-2 defines how measuring systems for HVDC, HVAC, LI and SI should operate and how accurate they should be. The standard defines that all measurement systems are expected to measure test voltages according to standard is IEC 60060-1. [18] The requirements for measured values according to standard IEC 60060-1:2010 were explained in chapter 2.2 for all measured voltage forms.

The measured lightning and switching impulses may have superimposed oscillation on their rising front or at their peak. This oscillation is caused by the voltage generators inductances and capacitances, testing circuits inductive or capacitive components or the testing objects inductance or capacitance. These values react to the generated voltage front causing non ideal impulse shapes. The measuring system needs to have a high enough bandwidth to capture this oscillation to properly measure the impulse. The oscillation at the impulse peak especially is wanted to be measured in HV testing laboratories since it has been found to stress the frequency-dependent insulation. [11, pp. 10-11]

Since the generated waveform depends on the connected test circuit and the test object, the measurement system should be connected directly to the used test object [11, p. 23]. The used test voltage generation method also affects the measured test object parameters so either the test voltage generator has to be implemented in such a way that it affects the test object only on the wanted way or the unwanted effects have to be mathematically known so it can be compensated for after the measurements are done. When done this way the true voltage stress that effects the test object is recorded.

The combined voltage measurement systems need, according to standard IEC 60060-1, to be able to measure separately the voltage sources outputs of the combined voltage. This means that all relevant voltage components require separate measurement systems. Since the voltage stress in combined voltage testing takes place between the energized terminals of the test object, a direct measurement is hard to realize. Standard IEC 60060-1 allows therefore that the measurements are done for the voltage components available before the test object’s terminals. The measurements also should in these cases be done as close to the relevant terminal of the test object as possible and the effects of the coupling and test object on the measurements should be calculated. After the voltage components are measured the true voltage stress should be calculated as the difference separately. [2, p. 405] Figure 16 shows an example circuit layout for combined voltage measurement system that fulfils the requirements defined for combined voltage measurements according to standard IEC 60060-1. As the figure shows, the recorded voltage components of the combined voltage are recorded at the test object’s terminals. The evaluation software will then calculate the realized voltage stress on the test object after measurements.

As the composite voltages test circuits connect both test voltage generators in a same single terminal, which can cause them to disrupt each other’s operation as explained in chapter 3.1.3, the possible operational instability caused by this needs to be taken into account when carrying out the measurements [2, pp. 406-407]. For example, the triggering of an impulse generator can cause an HVAC voltage generators phase to shift, or HVDC test voltage generator may be affected by a voltage drop from triggering of an impulse generator.

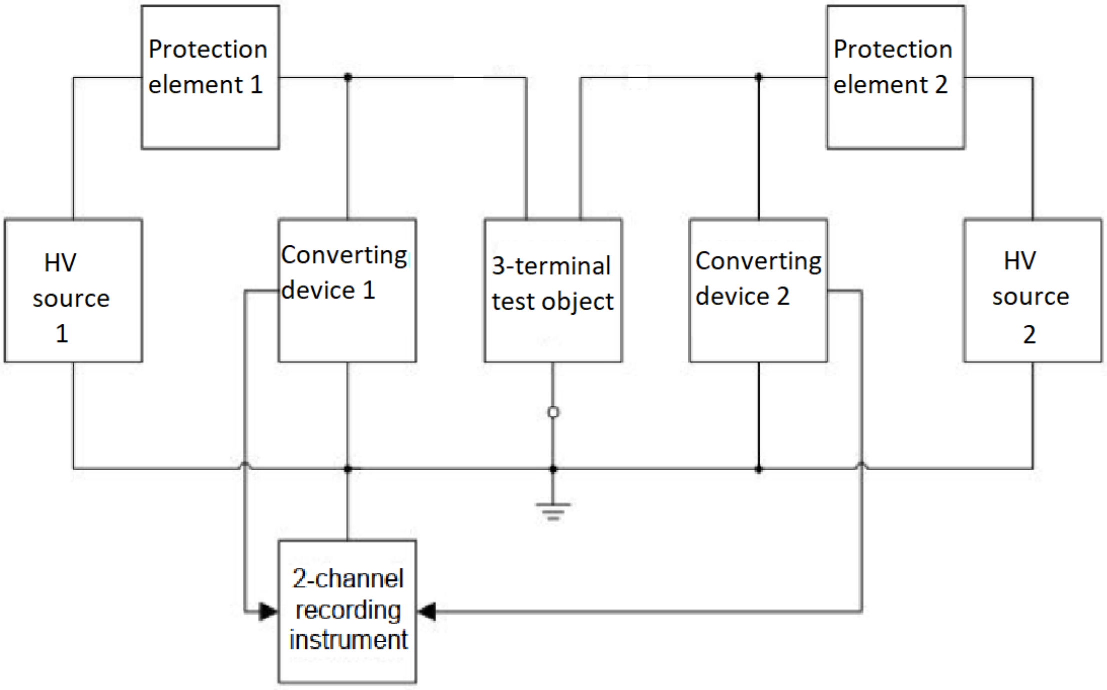

Figure 16: Combined voltage measurement system layout

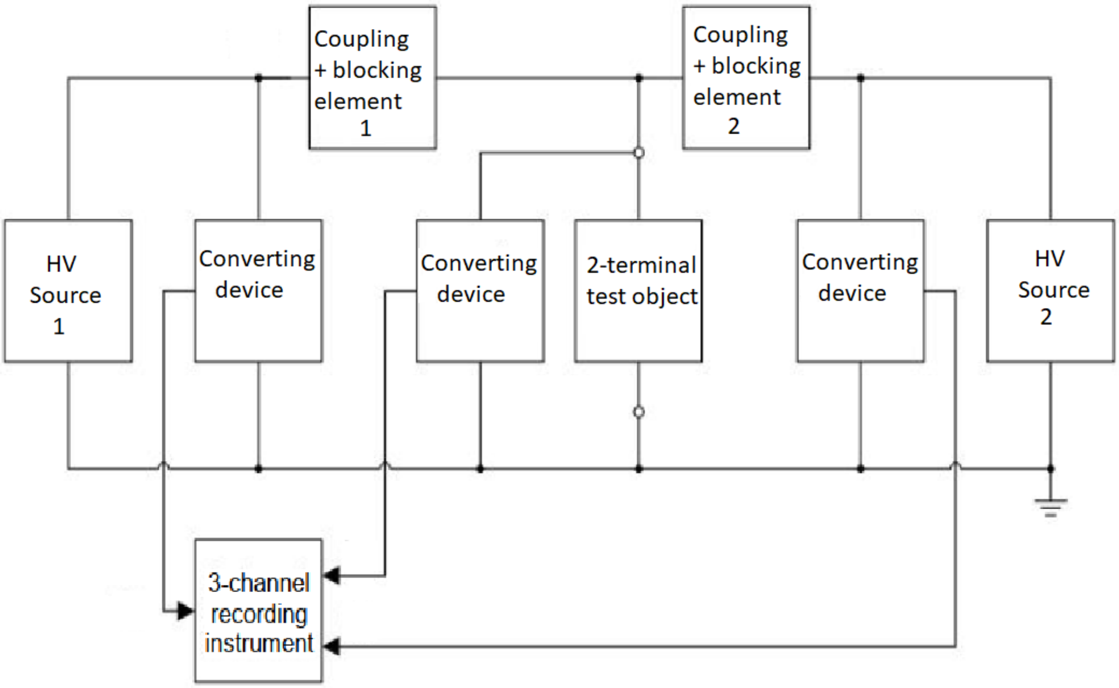

Figure 17: Composite measurement system layout

Figure 17 shows the recommended measuring system for composite voltages according to standard IEC 60060-1. The secondary measurements right after the HV sources are not mandatory for the measurements but taking them can help in the evaluation. The only mandatory measurement is the one connected right before the test object and the evaluation software is supposed to analyse this measurement.

For proper operation of a combined voltage measuring system all three voltage forms, the base components and the superposition should be measured simultaneously with the same time scale and recorded synchronously. The superposition shows the true voltage stress affecting the test object while the voltage components help in managing the voltage generators and in verifying the composite voltage. [2, p. 408]

Some of the important aspects of a high voltage measurement system are its linearity and to understand what effects the used measurement system has on the measurand and also isolate the measurement to only affect the wanted measurand at the wanted point [17, p. 29]. This way the measurement systems affects can be negated and more accurate measurements can be achieved.

HVDC measurements can be done in multiple ways. First, it is possible to do direct voltage measurements with the help of a resistor or by changing the measurement into a direct current measurement. Doing this allows the true measurement current to be minimal avoiding excess loading and stressing of the voltage source and measurement resistor. Problem with small measurement currents is that leakage currents can distort the measurement easily. When measuring the voltage with an ammeter, it is connected in series to the measurement resistor. When the voltage is measured with voltmeter with high internal resistance it is connected in parallel to a resistive divider which is connected in series to the measurement resistor. Electrostatic voltmeters can also be used to measure the HVDC voltage. [5]

HVDC ripple factor cannot be measured directly with ohmic resistive voltmeters. For this mixed voltage dividers must be used. Firstly, the direct voltage part of the voltage is measured with a resistive divider and the frequency depended part is separated from the direct voltage and measured separately with capacitive divider and a separate voltmeter. [5] With these measured values the ripple factor can be calculated as explained in chapter 2.2.1.

HVAC voltage measurements can be done with high voltage capacitors and they are used a lot for this job to make the measurable voltages small enough for the measurement instruments. The capacitor connection would reduce the current running through the measurement instrument. The accuracy of this measurement is limited by the earthing capacitance of the high voltage capacitor. [5]

Peak voltage measurements for HVAC systems can be done connecting rectifiers antiparallel after a capacitor and measuring the current running through one of the branches with a coil instrument. If the parameters of the capacitor and rectifiers are known, the peak voltage can be calculated with this measured current value. [5]

Capacitive voltage dividers can also be used to measure HVAC peaks and waveforms. In these measurement circuits a combination of low-, high voltage capacitors and rectifiers is used [5]. Basically, a HVDC test circuit is used to measure the peak values.

Electrostatic voltmeters are instruments which can be used to measure HVAC voltages. These instruments calculate the voltage values based on the force that effects electrodes. [5] Basically, if voltage value rises the force makes the electrodes distance shorten. A negative side to these measurement tools is that with high voltages, the need for space and costs are extremely high [5].

Voltage transformers can also be used in measuring alternating voltages up to ~100 kV. Since transformers reproduce the voltage waveshape of the primary winding extremely accurately on their secondary winding side, doing high accuracy measurements at lower voltage levels is easy with high voltage transformers. The problem is that the design that is used for testing, a normal transformer used in transmission networks should not be used since it would impose a high capacitive load on the voltage source. [5]

High voltage impulses are measured, and their impulse shape is recorded with a transient recorder, which can be a digital recorder, or a cathode-ray oscilloscope. The recorder is supplied with data with a measuring which is connected to a voltage divider connected at the wanted measurement point. [5] Transient recorders can also be used with any other high voltage type’s testing if the waveshape is wanted to be saved. The standard IEC 60060-1 requires this kind of recordings for high voltage evaluation. If only the peak value is wanted to be measured a direct measuring tool like voltmeter can be used. The whole impulse measuring system consists of the voltage divider, measuring cable, the recording instrument and of the evaluation software. [5]

Other important measurement done in HV applications in testing laboratories are breakdown discharge measurements and chopped wave tests for different insulators and their arrangements. The breakdown of insulation happens stochastically so the process needs to be measured with a statistical method which also means that the breakdown values are statistical nature. Typically, breakdown and withstand voltage tests are done by stressing the wanted component with varying voltage levels. The frequency of the breakdowns is then recorded and from these the relative breakdown frequency is found. [2, pp. 60-62]

3.2.1 Measurement system uncertainties

Measurement systems have many sources of uncertainty that need to be both acknowledged and quantified. Every measurement system has multiple uncertainty components which some are explained in standard IEC 60060-2. The uncertainty components depend on the used measurement system and there can be additional which are not explained in the relevant standard. The components are accordingly defined in relation to reference measuring system to make all measurements comparable. These components are explained shortly in this chapter.

There are eight main uncertainty components associated with measurement systems according to standard IEC 60060-2. First uncertainty source is the so-called non-linearity contribution on the measurement system calibration value u_{B0}, which denotes how the measurement systems accuracy does not stay the same along its measurement range. The second one is the possible extended voltage range linearity factor u_{B1}, which describes the measurement systems linearity outside the calibration range or how linear the measurements are in the extended measurement range. Third one is called the dynamic behavior uncertainty u_{B2}, which describes the effects of how the measurement system acts dynamically differently amplitude or frequency response. Fourth one is called short-term stability uncertainty u_{B3} and the fifth one is called long-term stability uncertainty u_{B4}, which both describe how the measurement systems measurements change during a short or long period respectively. Sixth uncertainty component is called ambient temperature u_{B5}, which describes the effects that temperature has on the measurement system. Seventh one is called proximity effect u_{B6} and the last uncertainty component is the software effect u_{B7}. Proximity effect describes the effects that the measurement systems environment has on the measurement system, such as earthed walls and other energized appliances. The software effect is caused by the measurement evaluation software's uncertainty pertaining to its handling of the measurement data. Since the evaluation software is considered a part of the measurement system, its uncertainty is calculated as a part of the whole measurement systems uncertainty. The software's uncertainty for impulse voltage evaluation is calculated according to standard IEC 61083-2. The software's, which this thesis is based one, uncertainty is calculated and shown in chapter 6.2. [18] The measurement system uncertainty factors are gathered in Table 1.

Table 1: High-voltage measurement system uncertainty factors

Uncertainty factors:	

Non-linearity	u_{B0}
Extended linearity	u_{B1}
Dynamic behavior	u_{B2}
Short-term stability	u_{B3}
Long-term stability	u_{B4}
Ambient temperature	u_{B5}
Proximity effect	u_{B6}
Software effect	u_{B7}

It is important to regularly calibrate the measurement systems to fix them to standardized measurement values through calibration determined scale factors. The regularity makes sure that over time the measurement system’s changing parameters affect the measurements as little as possible. Calibration should be traceable to national standards.

There are multiple scales for uncertainty values. These scales can be presented with confidence levels or coverage factor k. Coverage factor is a value used to multiply standard uncertainty values to gain expanded uncertainties. Basically, it is a value which shows how confident the uncertainty value is. The standard coverage factor expects the uncertainty value to be based on standard deviation. The three usual values for the coverage factor k are $k = 1$ for confidence level of about 68 %, $k = 2.58$ for confidence level of 99% and $k = 3$ for a confidence level of 99.7%.

4. EVALUATION METHODS

High-voltage test waveform evaluation requires a lot of signal processing to make the raw data into workable form, since the raw data has a lot of noise in it which distorts the output signals parameters. Most of the signal processing methods that must be used are highly mathematical in nature. The evaluation programs are used to calculate voltage parameters from the measured signal. Since the evaluation program is part of the measurement system, the signal processing methods used in it need to fulfil the requirements given to it in the relevant standard IEC-61083-2 [19]. More on the standard IEC-61083 is explained in chapter 6.

This chapter goes through a couple of signal processing methods that were used for the high-voltage composite and combined voltage evaluation. These methods are filtering, least squares curve fitting for both double exponential and sine curve parameter determination. Lastly, in this chapter the styles of exponential curve modelling styles of exponential growth and exponential decay are explained and shown.

4.1 Curve fitting

Curve fitting is a signal processing method that allows signal parameter analysis from a noisy digitized data. In curve fitting a method like least-squares is used to fit an assumed mathematical expression to recorded data. There are two main methods to do this, firstly by interpolating and fitting a mathematical expression that fits the recorded data. Basically, finding a function that is true with all recorded data points. This method does not work with noisy data. Secondly, parametric curve fitting where initially chosen mathematic expression is fitted to the recorded noisy data by iterating data points that fit the closest to the recorded data. This method needs more data points than the interpolation to work accurately. [16, pp. 2-3]

Since the data this thesis work uses are real recorded data, which includes noise induced errors, the second method is used and therefore explained in more depth in this chapter. This method is called Least-Squares method. Least-Squares method tries to find the curve form with set parameters that fits the raw data best given the boundaries. Basically, the method tries to find the form that has the least difference with the guessed fitted curve and the raw data by making a choice for the curve parameters that minimize the residual curve [16, p. 5].

4.1.1 Basics

Curve fitting is a mathematical method where a mathematical curve function is fitted on top of an existing data set in an attempt to explain mathematically the data sets operation. With the generally used curve fitting methods both the curve style and some initial guess values for the curve's parameters should be known for the curve fitting method to work properly. The two curves that were used in this work were double exponential- and sine functions.

In double exponential curve fitting a double exponential superposition of an exponential growth and exponential decay with their respective parameters is fitted on top of an existing measured signal. This curve style is identical to an ideal standardised impulse used in high voltage testing.

In sine fitting a sinusoidal waveform is fitted atop raw data points with parameters that make the least amount of error between the fitted sinusoid and the raw data. Since the standardised AC waveform is a sinusoidal waveform with frequency between 45-60 Hz, it is logical to use this method. Some might think that it would be a simple matter to just take a waveforms amplitude and frequency from the given data set and then build the AC waveform from this, but due to distortions and other imperfections in the original data set, a fitting algorithm is more stable and robust for this.

There exist many curve fitting methods, most needing an initial guess for the curve form and parameters. Some examples of utilizing optimization methods are Newton-Rapson method and methods deriving from it. The main method used in this thesis work is Least-Squares and more specifically Levenberg-Marquardt algorithm due to the standard IEC 60060-1 requiring it for LI analysis. These methods are explained more in depth in chapters 4.1.2 and 4.1.3.

The mathematical modelling of impulses which is needed for the curve fitting of double exponential waveforms consists of two separate parts. The two parts are exponential growth and exponential decay. There are many applications using the models for exponential growth and decay, for example in cell growth. Exponential growth can be mathematically modelled with formula

$$U(t) = U_0 e^{\frac{t-t_0}{\tau}}, \qquad (3)$$

where U_0 tells the initial voltage value, t_0 the starting time, t is time moment, τ is the time constant which tells at which rate the exponent rises. From formula 3 can the formula for exponential decay be derived as

$$U(t) = U_0 e^{\frac{t_0 - t}{\tau}}. \qquad (4)$$

The curve fitting depends on the needed curve type. For example, for sine fitting, a sine function is fitted on the data and for double exponential fitting, a double exponential curve is fitted on the data. The curve fitting is therefore a flexible method that can be used with most data sets that can be mathematically simulated.

4.1.2 Least-Squares method

When the given data is included with measurement errors caused by inherent faults in the measurement system, noise or some other source of error, a fitting method that can find the overall behavioural model of the data is needed while working past these errors. In these cases, there is no simple answer for the recorded data to fit a mathematical model where it stands that $y_i = x_i f(t)$, for all data points. So, finding a mathematical model that fits all data points is not possible. In these cases, an interpolating method must be used that finds the function closest to the where the earlier statement stands for all data points. [16, pp. 3-4]

In these cases, least-squares (LS) method can be used to minimize the collective error between the fitted curves values and the recorded data points. Since in least-squares there is no singular value for y_i, in these cases the calculations are based on formula

$$\min\|\boldsymbol{r}\| = min\|\boldsymbol{b} - A\boldsymbol{x}\|, \qquad (5)$$

where ***b*** is a vector of observation or recorded data points, *A* is a matrix of samples of the model function to be fitted and ***x*** is a vector of parameters to be fitted and ***r*** is the vector of residual left between the fit and the raw data. The vector ***b*** is usually used to mark all y_i in least-squares related literature. The aim of the formula 5 is to minimize the sum of squares in the residual that is left between the fitted functions parameters and the real recorded data. This is a linearized version of the least-squares problem. As the formula 5 shows, there is no exact answer x_j that fulfils the vector ***b***, but the answer is at a pseudo vector ***b**** that is closest to ***b***. This means that the vector ***r*** of residual components is the smallest possible sum of its component's absolute values. The vector ***b**** mentioned above can be stated as $\boldsymbol{b}^* = A\boldsymbol{x}^*$, where ***x**** is the vector of minimised fitted parameters. [16, pp. 25-27] The absolute values can be changed to a sum of squares in formula 2 [16, p. 5]. Basically, the Least-Squares method tries to define chosen model function parameters in such a way that the overall error compared to the noisy erroneous signal is minimized. Therefore, there is no exact answer, but the answer is closest approximation to it. Depending on the used least-squares algorithm and the accuracy of the function to be fitted compared to the true mathematical model that the measured data follows, the residual error ***r*** explained in formula 5 may also include measurement errors and errors between the mathematical models. For the least-squares algorithm to work properly, the ***r*** should be exactly equal to the measurement errors. [16, p. 5] The measurement errors include both noise and internal errors caused by the measurement system. The proper working of the least-squares method assumes that all of the data points are independent, and the noise is white noise. This would mean that the mean error is zero and the variance is identical between points. [16, pp. 5-6]

Least-Squares method is not an ideal method. Firstly, since the method does not give an exact answer but an approximation that mostly fits the recorded data [16, p. 27] it does not necessarily find the correct global minimum explained in formula 2, but a minimum which would distort the final output of the algorithm based on the initial parameters of A. Also, if the data matrix A is not fully known, for example if the true mathematical form of the data is not known, can cause random errors on the full least-squares method [16, p. 136]. These errors would happen for example if the assumed mathematical form does not match the true form of the data which would lead to a wrong fitting.

4.1.3 Levenberg-Marquardt algorithm

Levenberg-Marquardt (LM), or damped least-squares (DLS), is a specialised least-squares algorithm that is usually used in different software applications to solve nonlinear curve fitting problems iteratively. The LM algorithm is an iterative method which combines both Gauss-Newton method and gradient decent based algorithms. It is especially suited for fitting square or exponential functions. [20, pp. 297-298]

The LM algorithm is Gauss-Newton algorithm that has fixed the problem it has with the possibility where its Hessian matrix is not inversible. This means that the LM algorithm is a newton's updated method which optimizes its performance. The Hessian matrix a matrix multiplication between the wanted curve's Jacobian matrix and its transpose $H = J^T J$, where the J are the wanted functions Jacobian matrix and its transpose. To overcome this issue, in LM algorithm an eigen matrix the size of the hessian matrix that has been multiplied with μ. This effectively causes the LM algorithm to use a damped version of the Hessian matrix as $G = H + \mu I$. The value of μ is increased until for every vector in the Hessian matrix it stands that $(\lambda_i + \mu) > 0$ for every *i* and where λ_i are the eigen vectors of the Hessian matrix. If this statement holds true, the expanded Hessian matrix is always inversible. This modification leads to the Levenberg-Marquardt algorithm

$$x_{k+1} = x_k - \lfloor H(x_k) + \mu I \rfloor^{-1} J(x_k)^T, \tag{6}$$

for all $x_{k.}$ Levenberg-Marquardt algorithm optimizes the Newton’s methods performance index. [20, pp. 302-303] Each iteration of the Levenberg-Marquart algorithm a new value is inserted in λ_i. The value for μ is gotten from the linearization of the wanted curve forms function. Basically, in LM algorithm, the values of λ_i are defined by Gauss Newton method and the μ is gotten from gradient decent method. As the value of the μ increases, the LM algorithm acts like a gradient decent method [20, p. 304].

Levenberg-Marquardt algorithm has a problem where it finds a local minimum which is not necessarily the global minimum of the true fitted curve. This means that in order to work properly, it needs a proper initial guess for the wanted values for the fitted curve so that it is reasonably close to the true parameter values of the true fitted curve to arrive at the correct minimum.

4.2 Filtering

Filtering is used in signal processing to remove unwanted frequency components from the sent or received signal. The basic process is to reduce the noise effects and unneeded distortion from the signal.

Lowpass filter is a filter that only allows low frequency components pass through it and mitigates the effects of the high frequency components. For the purposes of the thesis work, only digital filtering is considered since the filter would be applied only on the recorded data not on the signal being recorded.

For the case of composite and combined voltage evaluation standard IEC 60060-1 requires lowpass filtering for lightning impulse evaluation [6]. This is done to make sure the analysed signal is acceptable for testing purposes so the noise power would be needed to be removed from the final signal. Basically, for lighting impulse evaluation lowpass filtering is done to have a smoothing function to attenuate oscillations and overshoots to make the parameter analysis as consistent as possible. Initially, the lowpass filtering for lightning impulse voltage evaluation was planned to be done to either the full received impulse or the overshoot of the impulse. [13] The current method for the impulse evaluation according to standard IEC 60060-1 has the lowpass filtering done to the overshoot of the evaluated lightning impulse [6].

The filter used in accordance with IEC 60060-1 is zero phase infinite impulse response (IIR) filter. The filter can be designed both forward and backwards. The forward filter equation and its coefficients are

$$y(\mathrm{i}) = b\big(x(i) + x(\mathrm{i}-1)\big) + a_1 y(\mathrm{i}-1), \qquad (7)$$

$$b = \frac{x}{1+x},$$

$$a_1 = \frac{1-x}{1+x},$$

$$x = tan\left(\frac{\pi T_S}{\sqrt{a}}\right),$$

where *a* is the -3dB K-factor filter point or $2.2 \cdot 10^{-12}$, T_S is the sampling interval of the recorded signal, *x*(*i*) is the input sample array and *y*(*i*) is the filtered output sample array of the filter. The filter shown in formula 7 will perform better if the filter is applied twice first forward and then backwards on the recorded signal. [6]

4.3 Downsampling

Downsampling is a signal processing method where the sampling rate of a given data set of a recorded signal is decreased for faster or easier evaluation. There are two main processes that can be used to downsample a signal after recording. Firstly, low pass filtering with the aim of removing most of the high frequency components of the signal. Secondly, downsampling by an integer factor, also called decimation, where every N$^{\text{th}}$ sample is only kept on the final used signal. The general definition or decimation is that for example one in ten is removed but in signal processing decimation means that in the same case nine in ten are removed. Decimation by the order of 1/1000 would mean that for every 1000 samples only one is saved.

One way is to first use a low-pass filter on the given signal, after which the signal is down sampled by the order of N. This way with low frequency signals, the least amount of useful information carried in the signal is lost and only noise power is lost.

The main reason why downsampling would be done is to make signal shorter. There are times where the excess length of a signal causes the signal processing methods to take too excessive amounts of time, or they became impossible due to electronic memory issues. In these cases, downsampling may be used if the loss of information is considered acceptable.

5. THE EVALUATION SOFTWARE

The main practical task of this thesis work was to produce an evaluation software that could determine all the parameters defined for high-voltage combined- and composite voltage waveforms as explained in chapter 2.2. The overall evaluation software was split into three main parts. There exists separate parts for composite and combined waveform analysis and another one for impulse evaluation. The main reason why this was done, was due to the composite and combined evaluations needing different amounts of initial data sets according to their measurement standard’s, as defined in chapter 3.2. The composite and combined waveform evaluation operates differently from each other, where combined voltages need to be artificially superimposed and then analysed, while the composite voltages can be analysed as they are but must be artificially separated to access component voltage forms.

This chapter explains the initial conditions, how and what different parts of the evaluation software was made to do and where the software was used. The chapter also goes through the reasonings on why the software was made to do the parameter evaluation in the chosen ways.

The three main parts of the final evaluation software are CombinedEval1, CompACeval1 and ImpulsEval1. All of these are tasked with analysis of different parts of the composite and combined voltages. CombinedEval1 is tasked with the combined waveforms, CompACeval1 with the composite AC waveforms and power frequency voltages and lastly ImpulsEval1 is tasked with composite DC and SI and LI voltage evaluation.

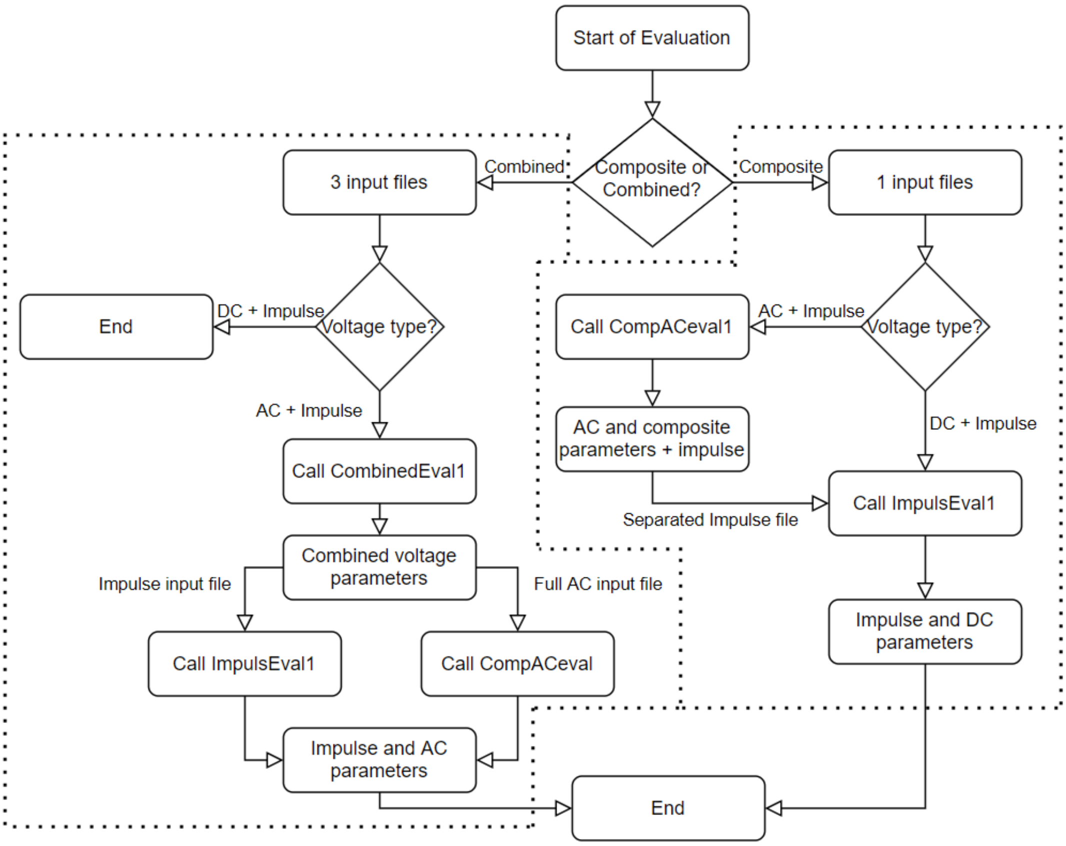

Figure 18: Flowchart of the evaluation software's operation

The software design of the final evaluation software is explained and shown in a compressed way in Figure 18. The composite voltages need only a single input file which is directed depending on the base component voltage to either CompACeval1 or ImpulsEval1. The output or separated impulse from CompACeval1 is also required to be send to ImpulsEval1 to get the impulse parameters. For the combined voltages, three input files are required. Only AC + Impulse combined voltages are analysed since DC + Impulse voltages were deemed unnecessary to evaluate. The AC + Impulse combined voltages are sent to CombinedEval1 and the component voltages to CompECeval1 and ImpulsEval1.

5.1 Initial conditions

Initially the work was started with an existing software LIVeval4.c provided by VTT MIKES programmed on C++ programming language. The existing program was produced initially by A. Korhonen and modified by J. Hällström. The existing base program could evaluate LI pulses according to IEC 60060-1 standard and was produced in accordance with its annexes A and B. The program effectively could evaluate both base lighting impulses and composite lighting impulses with DC offset. The composite lighting impulse with DC offset evaluation capabilities were only the ability to evaluate the lighting impulse with DC offset and to calculate the DC offset value. It was not capable of evaluating the DC component more deeply, neither did it evaluate any of the combined or composite voltage specific parameters.

The initial software LIVeval4.c calculated the DC offset parameter from the 20 first data points before the analysed impulses origin. This value is a good initial guess to normalize the data, but it is not necessarily the accurate true DC value depending on the DC ripple frequency. This data normalization is done according the IEC 60060-1 standard’s annex B to find the correct lightning impulse values and to help make double exponential curve fitting process possible.

The initial evaluation software mainly followed standard IEC-60060-1:2010 LI evaluation directives from annex B. Therefore, the software calculated all the LI parameters required by the standard shown in chapter 2.2.3 using the LM algorithm for curve fitting and waveform purification of excess noise. Since the annex B requires the normalization of the voltage values, it also calculates the offset DC voltage value for composite DC/LI voltages as a by-product. The parameters calculated by LIVeval4 are shown in Table 3.

5.2 Test pulses

The organizations that provided composite and combined voltage test pulses for HV-com^2 were international technical universities, national metrology laboratories and high voltage test equipment manufacturers. The provided test pulses were all measured with different measurement systems.

The test pulses used in HV-com^2 project for combined and composite voltage evaluation consisted of composite AC-Impulse and DC-Impulse measurements as well as combined AC-Impulse measurements. No AC-DC composite or combined pulses were used as test pulses or any DC-Impulse combined voltage pulses since they were deemed un-needed.

The combined voltage test pulses consisted of two different types. Firstly, measurements with separate impulse and base voltage measurements with differing measurement frequencies. Secondly, of separate measurements with impulse and base voltage with a separate measurement of the base waveform with the same sampling rate and timing as the impulse measurement.

Table 2: HV-com^2 test pulses

Type	Waveshape	Filename
Combined	AC/LI+	COMB_1_LI.txt COMB_1_AC.txt
	AC/LI-	COMB_2_LI.txt COMB_2_AC.txt
	AC/SI+	COMB_3_SI.txt COMB_3_AC.txt
	AC/SI-	COMB_4_SI.txt COMB_4_AC.txt
	AC/LI+	COMB_5_LI.txt COMB_5_AC_LI.txt COMB_5_AC.txt
	AC/LI-	COMB_6_LI.txt COMB_6_AC_LI.txt COMB_6_AC.txt
	AC/SI+	COMB_7_SI.txt COMB_7_AC_SI.txt COMB_7_AC.txt
	AC/SI-	COMB_8_SI.txt COMB_8_AC_SI.txt COMB_8_AC.txt
Composite	LI+DC-	COMP_1.txt
	SI+DC+	COMP_2.txt
	AC/SI+	COMP_3.txt COMP_3_low_sample_rate.txt
	AC/LI-	COMP_4.txt COMP_4_AC.txt COMP_4_LI.txt
	DC-/LI+	COMP_5.txt COMP_5_short.txt
	DC-/SI-	COMP_6.txt COMP_6_short.txt
	AC/SI+	COMP_7.txt COMP_7_low_sample_rate.txt

All the test pulses used in HV-com^2 are shown in Table 2. The contents are listed based on what kind of test voltage it is based on, composite or combined, the type of ‘mixed’ voltage is used and the file names. The type of ‘mixed’ voltage used describes the voltage components the ‘mixed’ voltage consists of. The files containing the test pulses depended on the test pulse case. Firstly, the combined test voltages 1 to 4 were initial test cases which contained separate pulse measurement and AC measurement with different sampling rates. These test pulses were decided in the middle of the project to not be used in the project. The next four combined test voltages from 5 to 8 were the finalized cases where a separate measurement was recorded for the impulse, AC and one for AC measurement with the same sampling rate as with the impulse measurement. This can be seen from the Table 2.

The composite voltage test pulses contained only single files since the composite voltage evaluation should operate with a single measurement data set. The additional files for measurements that are shown in Table 2 for composite 3, 5, 6 and 7 test pulses are cases where the file length is downsampled. The composite 4 test pulse has separate measurements provided for its voltage components, but those were not used in the evaluation.

5.3 Downsampling

Sometimes the input data is unnecessarily large for high-voltage waveform evaluation. In these cases, downsampling was used to make the data evaluation more realistic. There were also cases where the input file was too large, and the used algorithm could not reserve enough memory to operate properly. Both styles of downsampling are explained in chapter 4.1.

The main use was simple decimation to make extremely large files reasonable to process. Decimation was done for files that had data points in millions. Lowpass filtering was also used in the program. Firstly, the LI evaluation according to standard IEC 60060-1 requires this to be done. However, its main function is to reduce noise effect on the signal parameters.

Since the used LM algorithm cannot handle data sets with more than million data points, the data sets must be downsampled when the input file is too large. This problem manifested with the impulse evaluation software where most of the file would have to be used for double exponential fitting. If the file is more than one million lines long the program forcibly reduces the line count to one million. Having to do this means that some information is lost in the downsampling which can change the calculated impulse parameter values. This loss of information is accepted to have the software work properly.

The loss of information is accepted since normal switching impulses are ~3ms long in duration and lightning impulses are not longer than ~0.1ms. This would mean that for the impulse evaluation, the lost information is only marginal and in most cases measurement errors and noise but it’s effects should be noted.

5.4 Impulse analysis

The parameters that needed to be analysed and evaluated from the raw data for both lightning- and switching impulses were explained in chapters 2.2.3 and 2.2.4. The impulses have different parameters that need to be evaluated according to the current standard version IEC 60060-1:2010, but it was decided that switching impulses would be also evaluated according to the same parameters as defined for lightning impulses in order to see the differences between parameters and for the future iteration of the standard that is assumed to be one where switching impulse’s parameters are the same as lightning impulses.

The lighting and switching impulse analysis was in the end combined into one singular program capable of analysing both impulse types. This was effectively done by expanding the initial LIVeval4.c and made to calculate SI parameters for the input waveforms. There are already existing examples of using formula 2 to represent SI test voltages since they are already understood ideally as double exponential voltages. For example, Hylten-Cavallius have explained in their book “The Measurement of High Impulse Voltages and Currents” switching impulses as double exponential impulses [21, pp. 10-11]. Therefore, the SI evaluation was tested with the same evaluation method as LI evaluation is required to be done according to the standard IEC 60060-1.

The algorithm Levenberg-Marquardt, which the standard IEC 60060-1:2010 suggests for the lightning impulse evaluation’s curve fitting, requires initial guesses for the parameters of the fitted base curve, see formula 2. The initial guesses need to be reasonably close to the true values of the wanted impulse waveforms parameters to find the true global minimum. For this, the program needed to calculate both front and tail time constants, τ_2 and τ_1, values from the input waveform. The initial guess values provided in the standard IEC 60060-1 Annex C of $\tau_1 = 70\mu\mathrm{s}$ and $\tau_2 = 0.4\mu\mathrm{s}$ [6] are suitable for lightning impulse evaluation which were used in the initial LIVeva4l.c, but using these with SI voltages does not return the correct base curve since the LM algorithm found an incorrect minimum in these cases. To provide better initial guesses for the LM algorithm concepts of both exponential decay and exponential growth were utilized. The exponential growth was used to calculate an initial value for the time constant of the raising side of the impulse between the values of 0.3 and 0.9 of the impulses maximum value. The tail time constant was calculated from between the times of the maximum value and the half value of the tail.

The time constants τ_2 and τ_1 were calculated with the help of formulas 3 and 4 for the double exponential fitting formula 2. Using formula 4 and defining the time frame form between 30% and 90% of the recorded impulses maximum we get a formula

$$9 = 3e^{\frac{t_{3/9}}{\tau_1}}, \qquad (8)$$

where $t_{3/9}$ is the time between the impulse takes to rise from its 30% value to 90% value. From this formula 8 a value for the first time constant can be calculated as

$$\tau_1 \approx 0.9102 t_{3/9}. \qquad (9)$$

With the formula 3 for exponential decay, and taking the times the impulse takes to decay from its absolute value to its half value we get a formula of

$$\frac{1}{2} = e^{-\frac{t_{1/2}}{\tau_2}}, \qquad (10)$$

where $t_{1/2}$ is the time the impulse takes to reduce to its half value. From this formula 10 a value for the second time constant can be calculated as

$$\tau_2 \approx 1.4427 t_{1/2}. \qquad (11)$$

Using the approximate formulas 9 and 11 the initial guesses for the time constant values for LM algorithm using formula 2 could be calculated for every standard form impulse. The values got from formulas 9 and 11 for time constants are not accurate as can be seen from them being approximation. At the same time, the values do not need to be accurate since they are taken from a noisy signal and are initial guesses taken for the Levenberg-Marquardt algorithm to make sure the algorithm finds the correct minimums independently of the pulse size and form. The one negative side to using double exponential curve fitting for SI evaluation, the evaluation of pulse forms that are not of standard form is less accurate and may cause errors on the final parameter analysis. At the same time, when the LM algorithm is used with non-standard LI voltages, the parameter analysis is less accurate. For this reason, the negative effect of using LM algorithm with SI voltages is negligible. The LM algorithm used was done according to formula 3.

Table 3 shows the differences between the initial lightning impulse evaluation software's capabilities and the impulse evaluation software's evaluation capabilities towards calculating composite DC+LI voltages. The switching impulse voltage specific parameters are not included in the table since the initial software was not made to calculate those. As was explained before, the impulse evaluation software does not calculate composite voltage Δt values, since they would always be zero when used with the impulse evaluation as explained in chapter 2.2.6. Aside from the LI parameters, the

ImpulsEval1 also evaluates all SI parameters compared to the initial software. One big difference is also the fact that the initial LIVeval4 was incapable of evaluating switching impulses at all, since the initial guesses for the time constants were initialized for lightning impulses.

Table 3: Differences on what the initial LIVeval4 and ImpulsEval1 calculate

	Lightning Impulse:				DC:			Composite:	
	Ut	T1	T2	β'	U	∂U	∂f	Value	dt
LIVeval	x	x	x	x	x				
ImpulseEval	x	x	x	x	x	x	x	x	

The ImpulsEval1 program has both input and output parameters. The input parameter is a text file containing a recording of the wanted impulse as two columns, where the first column contains the time components and the second column, separated with a space, contains the respective voltage components. The input text file's name is given to the program executable as a parameter when the program is run.

Table 4: Output parameters of ImpulsEval1.

Parameter	Unit	Parameter	Unit
U_p	V	U_{DC}	V
T_{AB}	s	Ripple f	Hz
T_1	s	Ripple Amp	V
T_2	s	Ripple Fact	%
T_{2s}	s	t_0	s
T_p	s	t_{0s}	s
T_e	V/s	bm	V
U_{ext}	V	rbm	%
U_{ext0}	V	Δt	s

The output of the software are three text files which the program generates based on the input text file's name. The first output file contains the impulse evaluation help curves explained in chapter 2.2.3. The help curves are in the first output file 'input file name'-res provided in the same format as the input file. The columns on the first output file contain the time vector, the offset compensated recorded curve, test voltage curve, base curve, residua curve and the filtered residual curve, respectively. The second output file 'input file name'-par contains the parameters of the impulse and the DC components explained in chapters 2.2.1, 2.2.3 and 2.2.4. Table 4 shows all the parameters and their units that the program returns in the second output file in order starting from U_p downwards and continuing from the second column from top to bottom. The third output file 'input file name'_coef contains the results of the double exponential curve fitting result parameters. These parameters are the parameters shown in formula 2 or the impulse amplitude U, time constants τ_1 and τ_2 and the time delay t_d.

5.5 DC analysis

Part of the DC evaluation was initially part of the initial LI evaluation program. It was decided that there would not be any need to expand the DC evaluation to be part of the combined voltage evaluation but to keep it only for the composite voltage evaluation. This way, by expanding the initial lightning impulse evaluation software to also analyse the DC parameters explained in chapter 2.2.1 the composite DC/LI or DC/SI evaluation could be achieved at the same time.

Compared to the initial impulse evaluation software's operation, the DC offset parameter evaluation was changed for the composite evaluation software. The DC offset was calculated in this iteration from start of the inserted data set to the origin of the impulse quantified by the software. To analyse the rest of the DC parameters of the given signal, the software would take every data point before the quantified start of the impulse and do the analysis for these data points.

DC offset was calculated as the mean value of data points between chosen time values. In the program it was implemented in impulse evaluation to both normalize the impulse's voltage values and to analyse the composite DC voltage values. The mean value was calculated as the arithmetic mean

$$U_{DC} = \frac{1}{n}\sum_{i=1}^{n} U_i, \qquad (12)$$

where n is the amount of data points and U_i is a voltage value in the data set. Formula 12 was implemented in the software and used to calculate the DC offset of composite DC-impulse voltages. The DC offset was calculated in two separate instances, first to normalize the impulse to help in finding the "true" origin of the impulse and second time with all data points before the true origin to find the true DC offset. In the software, n is a number for how many data points in the received data are used from the start of the received data on the DC voltage value calculations. At first to get an initial guess for the DC voltage value it is 20, but for the more accurate DC offset calculation, n is an integer pointing to just before the impulse's origin.

DC ripple evaluation is done on the DC offset compensated part of the input impulse data set. First the DC offset is removed after which the initial part is separated from the data set. This data is then supplied to a fast Fourier transform (FFT) algorithm which calculates the frequency components in the given data set. The effectiveness of this varies based on how long in time duration the initial part of the impulse data set is. If it is too short, there is no feasible way to differentiate ripple frequency from measurement noise. To be able to for example evaluate ripple frequency of 1kHz the DC part would have to be of length of at least 1ms which is longer that most lighting impulses in time duration. The DC ripple frequency was decided as the frequency component with the biggest contribution aside from possible DC component or if no calculated frequency component has any strong presence in the normalized frequency spectrum. If the calculated ripple frequency spike is recognized as noise, the program will mark it as a negative value to show it is a non-applicable value.

Ripple amplitude was calculated as half of the difference between the maximum and minimum values of the DC offset compensated DC part. The software finds both the absolute maximum and absolute minimum of the initial DC part of the given impulse and then calculates their difference and halves it. This calculated value is then shown as the ripple amplitude.

5.6 AC analysis

AC analysis was done in the software in order to find the AC parameters defined in chapter 2.2.2 for the HV composite and combined evaluations. Since both composite and combined waveform evaluation require that the AC parameters are evaluated if power frequency signal is part of the ‘mixed’ waveform, it was required to evaluate the AC parameters. For combined voltage evaluation analysis as it was enough, but composite voltages required that the AC signal is removed as perfectly as possible from the composite signal to analyse the impulse separately.

According to how combined waveforms are measured, (shown in chapter 2.2.6), the AC signal is measured and analysed separately from its component voltage. This separate AC waveform is then separately evaluated with ACeval to gain all the needed alternating power frequency voltages parameters.

The r.m.s value of the AC voltage was calculated over a single fundamental frequency cycle using formula 1 ideally. Since it cannot be assumed that the received data has the impulse start only after a single full fundamental frequency cycle, the received data could not be used for the calculation. Instead, the fitted AC parameters would be used to find and calculate the r.m.s value over a single AC cycle or the whole data set would be used, whichever is smaller.

Figure 19 shows an example of the difference between analysing the composite or combined voltage’s AC component from the start or the end of the received data. Comparing the cases, it can be seen that the AC voltage cannot be perfectly removed from the composite voltage and there stays a distortion on the separated impulse. Since the impulse may cause a phase shift on the AC voltage source, the distortion is either after the impulse when AC is evaluated from the start of the recorded data or before the impulse when the AC is evaluated from the end of the recorded data. Since the important parameters of the impulse are received from the start and the impulse evaluation is done by finding the rising front of the impulse, it is preferred and chosen that the AC parameters are evaluated from the start of the recorded data before the impulse to lessen the distortion to the impulse evaluation.

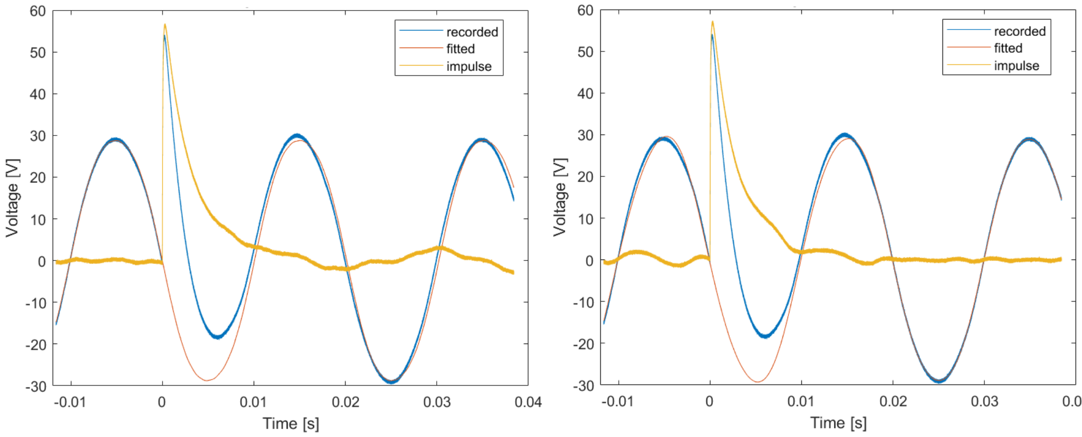

Figure 19: Example of difference between analysing AC from the start or the end of the received data. Evaluated from Composite data COMP_6. Parameters taken from the beginning on the left and, parameters from the end on the right.

The approximate AC analysis was done in both combined and composite voltage evaluation with curve fitting method. This was done to analyse the AC parameters as well as possible since the possible harmonic components in the AC waveform may distort the waveform therefore a simple fundamental frequency AC evaluation is not enough. Using curve fitting approximates the closest fitting AC parameters allowing for the evaluation of the remaining curve or the harmonics evaluation. This is especially useful for the composite AC + impulse evaluation since the pulse can be separated from the recorded waveform for pulse evaluation. The program looks for the three most prolific harmonic components aside from the fundamental frequency.

5.7 Combined waveform

The combined waveforms are analysed as based on three separate provided measurements. The measurement data files to be provided for the evaluation software are at least a single wavelength of the power frequency voltage at low sampling rate, impulse voltage at high sampling rate and power frequency voltage at the same sampling rate as the impulse with the exact timing as the impulse measurements.

The calculated combined voltage measurement provided by the software was done by subtracting the impulse measurement from the power frequency measurement. The power frequency measurement used in the combined voltage calculation was the one with the same sampling rate and timing as with the impulse measurement. Combined voltages were thus calculated as

$$U = U_1 - U_2, \qquad (13)$$

where U_1 is the base AC or DC voltage measurement and U_2 is the impulse voltage measurement [6]. Formula 13 is made with the assumption that the combined voltage generated over the test object happens between two terminals in a three-terminal system which means that the voltage stress that manifests in the test object would be the difference of the component voltages between the two energized terminals.

The main parameters that the combined waveform evaluation program evaluates are it's time delay Δt between the voltage component maximums and the peak value of the combined voltage. The peak voltage value is evaluated from the combined data set and does not consider the separate full AC waveform data set.

The combined voltage evaluation program calculates the combined voltage specific parameters for AC + impulse combined waveform data sets, explained in chapter 2.2.5. It also calculates the combined waveform from the correct input files according to formula 13 and returns the calculated voltage. The output parameters are therefore the time-delay Δt and the value of combined voltage. The other output for the CombinedEval1 is the calculated combined waveform for visual analysis.

5.8 Composite waveform

The composite voltage evaluation uses two softwares depending on the composite voltage composition. Composite AC + impulse would use the CompACeval1.c to evaluate the composite parameters and the AC parameters and to find the impulse from the input data. This found impulse would then be evaluated through ImpulsEval1.c for the impulse parameters. Composite voltages of impulse + DC would only need to use the ImpulsEval1.c for the analysis since the program is able to analyse both plain impulse and composite impulse + DC data.

Table 5: Output parameters of CompACeval1

Parameter	Unit	Parameter	Unit
U_{AC}	V	f_3	Hz
U	V	f_4	Hz
U_{rms}	V	THD	%
f	Hz	Δt_{fund}	s
U_{e0}	V	Δt_{true}	s
f_2	Hz		

Table 5 shows the output parameters for the composite evaluation software CompACeval.c. It does not include impulse parameters since the software provides the subtracted impulse from the input data. The impulse evaluation software would need to be used for the impulse evaluation.

Unlike with combined voltages, composite voltages are measured directly as they are. Still the composite voltage is calculated when separated following the formula

$$U = U_1 + U_2, \qquad (14)$$

where the U_1 and U_2 are the component voltages of the composite voltages [6]. This means that when using the formula 14 for analyzing the composite voltages, simply removing one of the voltage components U_1 or U_2 would return the other.

Considering the definition for the time delay Δt explained in chapter 2.2.6, it allows for the time delay to be calculated in two different ways. The difference arrives from whether the AC maximum time instant is taken from the AC fundamental's maximum or from the true AC voltages maximum where both fundamental and harmonics are considered. As can be seen from Table 5, the CompACeval1.c calculates both instances.

Examples of the differences between the time delay values that can be calculated with different methods are for COMP_4 test pulse with the true full AC maximum of 408.9µs and with the fundamental AC maximum of 204.2µs. For the COMP_3, time delay gets values of 4.75ms with the fundamental AC and 4.36ms with the true full AC maximum.

6. UNCERTAINTY ESTIMATES

Since the aim of this thesis is to produce an evaluation software for combined and composite voltages the uncertainties and output of the software need to be also evaluated. There are multiple ways to estimate the uncertainties of a mathematical software and the accuracy of its output. One way is to compare the output to already existing reference values, such as in the combined and composite high-voltage evaluation software's pulse case to IEC 61083-2. The accuracy of the software can also be evaluated by comparing the evaluated parameters to other evaluation softwares answers. For example, in the case of HV-com^2 comparing the partner organizations evaluated parameters using the test pulses explained in chapter 5.2 to the answers from the thesis software.

6.1 General

System error sources that the program cannot affect are a couple that need to be stated. Firstly, noise that will always affect the signal causes possible errors in the evaluated parameters. The curve fitting method which is used in the evaluation software minimises the effects of noise power in the evaluated parameters, but if the noise is random enough the curve fitting may also be erroneous.

Secondly, errors are also caused by the measurement system used in taking the measurements. The errors caused by this are related to the performance of the measuring system and the bandwidth available for the measurements in the measurement system. No matter what, doing true continuous measurements is impossible, so between measurements is always a time gap. Also, the measurement points are not floating points in true measurement but have a chosen resolution to them as well. This means that not all information is recorded, and some is lost.

6.2 Software

The software's proper operation was to be verified by the standard IEC 61083-2 "Instruments and software used for measurement in high-voltage and high-current tests – Part 2: Requirements for software for tests with impulse voltages and currents test data generator". The test data generator delivered with the standard generates waveforms that the software would evaluate, and the output parameters would have to be within uncertainty limits defined in the standard IEC 61083-2 [22]. The standard uncertainty (k=1) that can be calculated with the help of the standard IEC 61083-2 is the software uncertainty effect u_{B7} introduced in chapter 3.2.1.

There are two parts to the standard IEC 61083-2. Firstly, any used evaluation software needs to be able to calculate the impulse parameters of the test data within pre-set acceptance limits which depend on the test pulse. The second part is the uncertainty effect u_{B7} that can be calculated based on the deviation from the reference parameters. All the parameters for evaluation for both LI and SI voltages have their own acceptance limits and uncertainty effects. For all test pulses generated by the test data generator, the standard IEC 61083-2 has reference values for the evaluated parameters, against which the software's evaluation answers are then compared to. LI voltages have 29 full LI pulses that can be generated with the test data generator while for SI voltages only five full SI pulses are available. [22] The reference values and their deviations are based on values given by different calibration laboratories evaluation softwares' values after which the reference values are chosen based on these answers.

The LI test data generated with the test data generator was used with 12-bit resolution and 200 MS/s sample rate. This was done to make the final uncertainty values comparable with the LIVeval4 software's uncertainty values. The SI test data was generated with 12-bit resolution and sample rate of 10 MS/s.

The standard IEC 61083-2 defines that evaluation software's uncertainty contribution can be calculated aside from acceptance limits of reference test pulses parameter evaluation by calculating the uncertainty contribution of the software with this information in two parts. First uncertainty contribution parameter can be calculated with formula

$$u_{B71} = \frac{1}{\sqrt{3}} \max_{i=1}^{n} \left| \frac{x_i - x_{REF,i}}{x_{REF,i}} \right|, \qquad (15)$$

where x_i is the calculated value for the chosen parameter and $x_{REF,i}$ is the reference value gotten from IEC 61083-2 for the parameter. For β' the first uncertainty component is calculated as

$$u_{B71} = \frac{1}{\sqrt{3}} \max_{i=1}^{n} \left| \beta_i' - \beta_{REF,i}' \right|. \qquad (16)$$

The secondary standard uncertainty component is gotten from formula

$$u_{B72} = \frac{1}{2} \max_{i=1}^{n} U_{x,i}, \qquad (17)$$

where $U_{x,i}$ are the expanded uncertainties for $x_{REF,i}$. The expanded uncertainty components $U_{x,I}$ are given in the standard IEC 61083-2. When combining the uncertainty components calculated with formulas 15, 16 and 17, the standard uncertainty of an evaluation software can be calculated with formula

$$u_{B7} = \sqrt{u_{B71}^2 + u_{B72}^2}. \qquad (18)$$

[22]

When using the formulas 15 and 16 on the evaluated parameter values of the test impulses errors, the first uncertainty component can be calculated. In case of the secondary uncertainty component shown in formula 17, the evaluation software can not affect its value.

How the software's operational accuracy has changed can also be checked by comparing it to the initial software for lighting impulse evaluation. The switching impulse evaluations accuracy can also be compared with already existing switching impulse evaluation software's uncertainties [23].

Table 6: LIVeval4 uncertainty components (LI)

No noise	U_t	T_1	T_2	β'
u_{B7}	0.02 %	0.35 %	0.05 %	0.07 %
u_{B71}	0.01 %	0.24 %	0.04 %	0.06 %
u_{B72}	0.015 %	0.25 %	0.03 %	0.04 %

Table 6 shows the uncertainty components of the initial evaluation software. For comparison the impulse evaluation software's uncertainty components for lightning impulse evaluation are shown in Table 7. When comparing these two tables, it can be seen that the software's accuracy u_{B7} has not changed greatly for parameters U_t, T_1 and β', but the uncertainty estimate for time to half-value has lowered from the initial value. The most probable reason for this is the change to the DC offset calculations which changes the calculated voltages half value changing the calculated time.

Table 7: ImpulsEval1 uncertainty components (LI)

No noise	U_t	T_1	T_2	β'
u_{B7}	0.02 %	0.35 %	0.04 %	0.07 %
u_{B71}	0.016 %	0.240 %	0.024 %	0.062 %
u_{B72}	0.015 %	0.25 %	0.03 %	0.04 %

Table 8 shows the uncertainty components calculated for the impulse evaluation for switching impulses. The parameters that have uncertainty components according to standard IEC 61083-2 are U_p, T_p and T_2. The uncertainty components were calculated with the help of formulas 16, 17 and 18.

Table 8: ImpulsEval1 uncertainty components (SI)

No noise	*Up*	*Tp*	T_2
u_{B7}	0.085 %	3.378 %	1.128 %
u_{B71}	0.056 %	2.723 %	0.521 %
u_{B72}	0.065 %	2.000 %	1.000 %

The uncertainty components shown in Table 8 are high for time to peak values and time to half-values. This is somewhat acceptable since the two measured test pulses for switching impulse testing are not of standard form. Even their expanded uncertainties for all parameters are high and they even have higher acceptance limits than the standard form analytical test pulses. Since the measured test data waveforms SI-M1 and SI-M2 do not represent impulses that are suitable for calibration purposes due to excessive noise and distortion, it is justifiable to calculate the uncertainty values with only the analytical waveforms A1-A3 [23].

Table 9: ImpulsEval1 uncertainty components (SI) analytical waveforms SI A1-A3

No noise	*Up*	*Tp*	T_2
u_{B7}	0.004 %	1.267 %	0.012 %
u_{B71}	0.003 %	0.777 %	0.007 %
u_{B72}	0.002 %	1.000 %	0.010 %

Table 9 shows the uncertainty components derived for the ImpulsEval1's SI evaluation when the measured waveforms of IEC 61083-2 are not used. When comparing these uncertainty values to the ones shown in Table 8 the effects of the measured signals are apparent especially towards the time to peak and time to half-values. The uncertainty components for time to peak values are still relatively high.

The reference values for SI voltage evaluation uncertainty components were gotten from VTT MIKES' older switching impulse evaluation software which uncertainty values were shown in publication “Reference Switching Impulse Voltage Measuring System Based on Correcting the Voltage Divider Response with Software”. The existing system does not utilize the curve fitting method that LI evaluation is required to use, so the comparison between the systems is useful also in this way. [23] The reference uncertainty components for switching impulses are shown in Table 10.

Table 10: Reference uncertainty components for VTT MIKES' SI evaluation software [23]

	U_p	T_p	T_2
u_{B7} A1-A3	0.04%	2.32%	0.06%
u_{B7} A1-A3, M1-M2	0.16%	4.94%	2.28%

When comparing the values shown in Table 10, Table 9 and Table 8 it is noticed that the curve fitting method used with SI evaluation is operational and with higher accuracy compared to the normal evaluation method. Both calculated uncertainty components for the SI evaluation are higher for the reference evaluation system than for the ImpulsEval1.

The second way to evaluate the accuracy of the evaluation software is to compare the evaluated parameter values of the test pulses shown in chapter 5.2 to the evaluated parameter values of the other partners of HV-com^2. This is more expansive than using the standard IEC 61083-2 since it can be used for wider range of voltage shapes.

Reference data was recorded for most HV-com^2 test pulses shown in Table 2. Only the composite 3, 4 and 7 test pulses had no reference values provided since most project partners decided to not evaluate these voltage shapes. Voltage shapes in question were AC + impulse composite voltages. For all other HV-com^2 test pulse parameters, reference values were evaluated by the project’s partner organizations. The calculated values, variance, and average values between calculated parameters for combined and composite test pulses in HV-com^2 calculated by the different partner organizations are shown in appendixes A and B. Appendix A contains the values for combined voltages of the test pulses and Appendix B contains the values for composite voltages. In the appendixes, the different opinions for polarities, time delay and ‘mixed’ voltage maximums are ignored and only the overall values of these are compared.

When comparing the evaluated values for composite and combined voltages using the test pulses shown in appendixes A and B, the accuracy of the produced evaluation software compared to reference programs can be evaluated. Most of the evaluated values are withing 1 % range from the average evaluated value. The only major differences are the AC peak value shown in Appendix A with difference of 2-3% from the average and time to peak value shown in Appendix B with difference of 8 % from the average. When comparing these differences from the average, they are still lower than the standard deviation between partner organizations for the AC peak value and for most of the other values. The only one with major differences from the average compared to the standard deviation is the time to peak value evaluated from COMP_6 test pulse shown in Appendix B where the standard deviation was 6.1 %.

There are some differences between the calculated values based on how some parameters definitions are understood. For example, if Δt for composite and combined voltages is always positive or if one of the voltage components is the main one and the Δt can be therefore negative. Second example is whether the combined voltage value is always positive or can be negative. The choices made for the program created for this thesis were that the time delay is absolute value of the time difference, and the combined voltage value is either positive or negative based on the maximum potential difference. These values have high variance between partners due to differing opinions on how the values are calculated.

The other value that has high difference between partner organizations evaluations is the time to peak T_p of the switching impulses. There are multiple reasons for this, firstly, the calculation method for this value is not well standardised as was explained in chapter 2.2.4 which is why it is planned to be left out from the next iteration of the standard. Secondly, even the reference uncertainty values shown above are comparatively uncertain according to the standard IEC 61083-2.

The uncertainty components and values related to composite and combined voltages are typically higher than for their voltage components when calculated on their own. This is because the impulse distorts and causes interference on the other voltage component on the composite or combined voltage, and vice versa.

7. FUTURE WORK

The problems that arose in the process of this thesis are recommended to be investigated. Most are related to the shortcoming and obscurities of the standing definitions for test voltages in standard IEC 60060-1.

There is a problem in the standard IEC 60060-1, since it does not define how long a composite or combined voltage is analytically. The ‘mixed’ voltage length obscurity affects the maximum value of the ‘mixed’ voltage. Since for example with composite AC + Impulse voltages, the maximum value can be taken from either the AC part before or after the impulse or the impulse maximum, depending on whether the ‘mixed’ voltage duration is only the superposition of the two voltage components or some amount of time around the superposition. Duo to vague definition for the length of composite and combined voltage multiple differing values from different points of the ‘mixed’ voltage can be achieved. For this reason, the definition should be focused and investigated.

As explained and shown in chapter 5.8, the standard IEC 60060-1 does not define accurately from which maximum the time delay point is to be calculated from AC voltage for both combined and composite waveforms. So, the definition either needs to particularize from which waveform the AC maximum time is calculated from or the time delay value can be calculated with ~0.5 ms accuracy. For future study, the maximum time difference between possible acceptable AC voltages with maximum acceptable harmonic components should be investigated. With this information it could be investigated and standardised whether the AC maximum should be taken from the fundamental frequency component or from the whole waveform, or if precision values are chosen based on the maximum possible time difference.

The tolerance of lightning impulse front time and time to half-value errors is excessively huge. The error values that standard IEC 60060-1 accepts are for front time 30 % from the standard value and 20 % from the standard value for the time to half-value [6]. For calibration purposes the value accuracy is not desirable. However, the reason why this rather large variance is accepted in the standard is the costs required to build an accurate time to half-value and front time achieving circuits for various test objects. The choice is therefore what to prioritize, measurement accuracy or measurement availability.

The evaluation software leaves some room for future improvement. The first improvement is the addition of combined DC + Impulse voltage evaluation, which the current software is not able to do so as shown by the flowchart shown in Figure 18. Other future improvement could be the overall compatibility of the software, where the software could detect which kind of test voltage data was supplied to it. The parameters calculated for SI voltages should also be changed in accordance with the new version of IEC 60060-1 standard.

The AC + Impulse composite voltage analysis should be evaluated and investigated. The accuracy of the chosen method of using curve fitting algorithms to separate the voltage components could not be investigated due to the lack of reference data. The power frequency component could not be perfectly separated from the composite voltage which could be seen from Figure 19 leaving distortions to the impulse waveform affecting the impulse parameter evaluation accuracy. Therefore, in the future if reference data can be gathered, the usability of the chosen method and the accuracy of the software on this front should be reviewed and upgraded if deemed necessary.

8. CONCLUSIONS

The conclusive operation of the program is shown in the flowchart shown in Figure 18. From this flowchart it can be seen that the software is not intended to operate combined voltage evaluation with Impulse + DC voltage shapes. The second thing that can be seen, is that the combined and composite evaluation require different amounts of input files. While composite evaluation requires only one input file, the combined evaluation requires three input files. It was shown that the program is designed for composite voltage evaluation and can also be used to evaluate the component voltages of the combined voltage for full combined voltage evaluation.

The method of evaluating switching impulses with lightning impulse evaluation methods according to IEC 60060-1:2010 was deemed to be acceptable. The tests to see how accurate values this method gave for SI evaluation was shown in chapter 6.2. The evaluated SI parameters fulfil the accuracy requirements of standard IEC 61083-2 and is even more accurate than the reference system. It is concluded that there is no metrology reason to not evaluate the SI voltages with the same LM algorithm as LI voltages and the effects of doing so are positive. This method achieved uncertainty components for peak voltage U_p of 0.004 %, time to peak T_p of 1.27 % and time to half T_2 of 0.01 % which were within acceptable ranges according to standard IEC 61083-2 and an improvement compared to the reference systems values shown in Table 10.

The upgrade of LIVeval4 to evaluate Impulse + DC composite voltages, was able to keep the accuracy of the software for LI voltages mostly the same, decreasing the uncertainty component for time to half from 0.05 % to 0.04 %. The aim of the software development was not to make the software more accurate and some increase in the uncertainty of the evaluated components would have been acceptable. For this reason, the achieved uncertainty values are a positive outcome. Even if the change is negligible in effect.

The use of curve fitting to remove AC voltage data from composite voltages was deemed to be a successful method. As explained in chapter 7 the AC component voltage separation is not perfect and the accuracy depends on the length of the AC component before the impulse. Regrettably, the accuracy of using the curve fitted AC separation could not be realistically compared.

Overall, the evaluation of both combined and composite voltages according to relevant standards was successful and the chosen methods operate acceptably. The accuracy of the software is acceptable for the parameters that could be evaluated. The software and the evaluated parameters done with it help in assessing uncertainties related to composite and combined voltage evaluation softwares in project HV-com^2. Thus, the program achieves its intended goals.

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APPENDIX A: COMPARISON OF CALCULATED COMBINED VOLTAGE EVALUATIONS WITHIN THE HV-COM2 PROJECT PARTNERS

Combined Pulse+AC	Comb [V]	Average	STDEV
COMB_5	1113,70	1113,80	0,00 %
COMB_6	-1113,96	-1113,98	0,00 %
COMB_7	732,81	735,40	1,00 %
COMB_8	-799,27	-802,8	-1,00 %
AC peak [kV]		Average	STDEV
COMB_5	206,50	206,70	0,20 %
COMB_6	206,00	206,20	0,10 %
COMB_7	192,50	197,00	3,70 %
COMB_8	191,80	196,80	4,20 %
AC rms [kV]		Average	STDEV
COMB_5	145,99	146,00	0,00 %
COMB_6	145,60	145,60	0,10 %
COMB_7	136,67	136,90	0,80 %
COMB_8	136,29	136,58	1,00 %
THD [%]		Average	STDEV
COMB_5	0,00	0,20	0,00 %
COMB_6	0,00	0,20	0,00 %
COMB_7	0,00	0,03	0,00 %
COMB_8	0,00	3,79	0,00 %
f [Hz]		Average	STDEV
COMB_5	49,99	50,00	0,00 %
COMB_6	49,98	49,99	0,00 %
COMB_7	49,82	50,12	0,70 %
COMB_8	49,79	50,12	0,80 %
Δt [µs]		Average	STDEV
COMB_5	46,07	46,00	0,20 %
COMB_6	18,65	18,65	0,00 %
COMB_7	34,37	35,10	2,80 %
COMB_8	71,26	70,70	1,20 %
U_t [kV]		Average	STDEV
COMB_5	934,07	934,10	0,00 %
COMB_6	-934,16	-934,20	0,00 %
COMB_7	565,10	565,20	0,00 %
COMB_8	-635,20	-635,40	0,00 %
T_1 [µs]		Average	STDEV
COMB_5	1,45	1,44	0,00 %
COMB_6	1,45	1,44	0,60 %
COMB_7	165,10	165,10	0,10 %
COMB_8	165,00	165,00	0,00 %
T_2 [µs]		Average	STDEV
COMB_5	55,90	55,89	0,00 %
COMB_6	55,94	55,94	0,00 %
COMB_7	2539,00	2540,00	0,00 %
COMB_8	2544,00	2543,25	0,10 %
β' [%]		Average	STDEV
COMB_5	0,00	0,00	0,00 %
COMB_6	2,99	3,37	9,70 %
COMB_7	0,01	0,17	25,40 %
COMB_8	0,02	0,19	30,40 %
U_p [V]		Average	STDEV
COMB_5	0,00	0,00	0,00 %
COMB_6	0,00	0,00	0,00 %
COMB_7	567,30	565,66	0,20 %
COMB_8	-638,10	-636,00	0,20 %
T_p [µs]		Average	STDEV
COMB_5	0,00	0,00	0,00 %
COMB_6	0,00	0,00	0,00 %
COMB_7	245,50	248,50	0,10 %
COMB_8	250,60	249,50	1,20 %
T_{2s} [µs]		Average	STDEV
COMB_5	0,00	0,00	0,00 %
COMB_6	0,00	0,00	0,00 %
COMB_7	2509,19	2510,00	0,10 %
COMB_8	2515,07	2513,76	0,10 %

This appendix shows the evaluated parameters of project HV-com^2 in a table for combined voltages with three input files. The shown parameters are evaluated parameters for combined impulse + AC voltages. The first shown value in a column is the value evaluated with the thesis works evaluation software. The next column holds the average evaluated value between all project partners and the last column hold the standard deviation between project partners evaluated values.

These values were calculated based on the evaluated values that the project partners provided for the test pulses. The average value was calculated as the average of all provided values and standard deviation as the standard deviation between the provided values. Some modifications were done to the data. Since the definition for combined voltage value was deemed vague, some project partners calculated the combined voltage value as an absolute value while some calculated the highest voltage value. For this reason, the different calculated values were modified to be the same polarity for more accurate comparisons. Secondly, the time difference Δt's definition was also deemed vague on whether it is always positive absolute value or can be negative based on which voltage component is taken as the base voltage. For this reason, the polarity of the time difference was ignored for the comparison analysis.

APPENDIX B: COMPARISON OF CALCULATED COMPOSITE VOLTAGE EVALUATIONS WITHIN THE HV-COM2 PROJECT PARTNERS

Composite Pulse+DC	Comp [V]	Average	STDEV
COMP_1	-525,65	-524,91	-0,20 %
COMP_2	936,30	935,50	0,10 %
COMP_5	163,70	162,70	0,50 %
COMP_6	-138,20	-137,80	-0,20 %
DC [V]		Average	STDEV
COMP_1	-524,17	-524,20	0,00 %
COMP_2	522,87	522,86	0,00 %
COMP_5	-38,24	-38,23	-0,10 %
COMP_6	-38,22	-38,24	-0,20 %
Ripple Amp [V]		Average	STDEV
COMP_1	1,71	1,71	0,00 %
COMP_2	1,75	1,75	0,00 %
COMP_5	0,67	0,67	0,00 %
COMP_6	0,91	0,91	0,00 %
Ripple f [Hz]		Average	STDEV
COMP_1	0,00	0,00	0,00 %
COMP_2	1000,00	1000,00	0,00 %
COMP_5	0,00	0,00	0,00 %
COMP_6	952,90	952,90	0,00 %
U_t [V]		Average	STDEV
COMP_1	886,92	886,93	0,00 %
COMP_2	412,30	412,20	0,10 %
COMP_5	200,40	200,30	0,00 %
COMP_6	-99,42	-99,68	-0,40 %
T_1 [µs]		Average	STDEV
COMP_1	4,41	4,41	0,20 %
COMP_2	147,40	147,30	0,30 %
COMP_5	1,25	1,25	0,90 %
COMP_6	166,60	166,80	0,20 %
T_2 [µs]		Average	STDEV
COMP_1	46,72	46,72	0,00 %
COMP_2	2697,00	2699,00	0,10 %
COMP_5	72,23	72,23	0,00 %
COMP_6	1713,00	1701,00	1,70 %
β' [%]		Average	STDEV
COMP_1	1,26	1,26	0,4 %
COMP_2	0,00	0,00	0,00 %
COMP_5	2,07	2,52	10,10 %
COMP_6	0,00	0,00	0,00 %
U_p [V]		Average	STDEV
COMP_1	0,00	0,00	0,00 %
COMP_2	413,50	412,40	0,10 %
COMP_5	0,00	0,00	0,00 %
COMP_6	-99,98	-99,71	-0,40 %
T_p [µs]		Average	STDEV
COMP_1	0,00	0,00	0,00 %
COMP_2	225,60	225,00	0,40 %
COMP_5	0,00	0,00	0,00 %
COMP_6	257,40	238,80	6,10 %
T_{2s} [µs]		Average	STDEV
COMP_1	0,00	0,00	0,00 %
COMP_2	2671,00	2678,00	0,40 %
COMP_5	0,00	0,00	0,00 %
COMP_6	1696,00	1670,00	1,80 %

This appendix shows the evaluated parameters of project HV-com^2 in a table for composite voltages. The shown parameters are evaluated parameters for composite impulse + DC voltages. The first shown value in a column is the value evaluated with the thesis works evaluation software. The next column holds the average evaluated value between all project partners and the last column hold the standard deviation between project partners evaluated values.

These values were calculated based on the evaluated values that the project partners provided for the test pulses. The average value was calculated as the average of all provided values and standard deviation as the standard deviation between the provided values. Some modifications were done to the data. Since the definition for composite voltage value was deemed vague, some project partners calculated the combined voltage value as an absolute value while some calculated the highest voltage value. For this reason, the different calculated values were modified to be the same polarity for more accurate comparisons.