NTNU
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Design of a Circuit for Making Test for Load Break Switches

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MASTER THESIS

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Preface

This master thesis was carried out during the spring semester of 2017 and is the final part of the two-year program of the Master of Science in Electric Power Engineering awarded by the Norwegian University of Science and Technology which is located in Trondheim, Norway.

The master thesis is a continuation of the specialization project with the same name that was carried out during the autumn semester of 2016. The idea of the project was brought up by SINTEF Energy Research and NTNU due to their collaboration with ABB Skien to carry out an extensive R&D program on medium voltage load break switches with air as the interrupting medium.

The objective of this master thesis is to review and select the most appropriate alternative to perform making tests to load break switches. This project involved simulations and laboratory work. Simulations were carried out by using the commercial softwares ATPDraw and Matlab, and the laboratory work was performed at the high-voltage laboratory at NTNU. The results are expected to be of large interest for the switchgear design teams at SINTEF and ABB Skien.

Trondheim, June 25, 2017

Alejandro Nahum Prieto Almanza

Acknowledgment

I would like to express my appreciation and gratitude to my supervisor Professor Kaveh Niayesh for his guide, orientation, patience and willingness to help and support me every time I requested it. You have been a tremendous mentor and your lectures were an inspiration for me to choose this topic.

I would also like to thank the PhD candidate Fahim Abid for his assistance in planning and conducting the laboratory work.

Not less important is my family. I want to thank my family for their support, especially my mother for all the calls I received from her from Mexico to encourage me to never give up when difficult moments came, my grandmother who takes care of me from heaven, my brother for his funny calls, and of course to my little daughter for being my biggest motivation. She is my engine and the reason I came to Norway.

I want also to thank my good friends Dr. Spencer Crozier and Sage Jonathan Hadley for helping me with proofreading this thesis.

A.N.P.A.

Abstract

A load break switch is a type of switching device extensively used in medium-voltage applications at distribution systems. For that reason, it is of great importance that it works properly, and for this to happen, it needs to pass several types of tests. This thesis focuses on one of the most important tests designed for load break switches and that is the so-called *making test.* A making test for load break switches needs to be performed with the help of a circuit known as a *synthetic circuit* due to laboratory capability limitations.

This master thesis explains what a synthetic circuit is and the impact that its components have on the correct performance of the making test. A deep study about important components of the making switch is expounded due to its great importance on the making operation, more specifically, a study of the voltage drop across the making switch and across the load break switch is performed. The making switch is the component in charge of applying current at the desired moment during the test to the load break switch, which is the test object. The study of the making switch was done in a laboratory environment while the study of the load break switch was fully simulation based. Positive results were found out for these components.

A synthetic circuit also contains passive elements like resistances, inductances, and capacitances. It is very important to choose the correct values of these elements since a correct making operation depends on these values. Results for minimum allowed values for these elements were also found.

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Chapter 1

Introduction

1.1 Motivation

Largely used in electric systems are several kinds of switching devices that can be part of a substation and are normally used to change the grid configurations and/or to disconnect faulty parts from the grid; therefore, the study and understanding the behavior of these components are crucial for good performance of the electric system and for an effective delivery of electrical service to the customers which can be large industries or in some cases other electric networks with lower voltage levels which bring energy to other smaller consumers.

Switching devices must also be able to close electrical connections when a fault current continues, or in other words, they must be able to carry short-circuit current for a few seconds when they are in closed position. For example, this situation can happen when a part of the system must be re-energized, and therefore there is a re-close operation of the switching device even though the fault persists. The ability of a switching device to close under short-circuit condition can be tested with the so-called *Making test*. This test is part of a list of types tests, a switching device must pass in order to assure correct performance and making is one of the most important functions besides fault current interruption. For this reason, this thesis puts emphasis in designing a test circuit in order to prove and assure the correct making operation of one kind of switching device which is known as a Load Break Switch (LBS) since they suffer more pronounced problems that other kinds of switching devices endure during a fault condition.

1.2 State of the Art

Overview of Switching Devices and Load Break Switches

Switching devices are largely used in electrical systems since they change the grid configuration by opening or closing electrical connections. As long as the switching device remains closed, its impedance is almost zero. In contrast, when it remains open, its impedance raises nearly to an infinite value. Switching devices switch the current by mechanically moving their contacts with an appropriate speed in order to make (close) or break (open) the current. The switching device is also exposed to mechanical, thermal and dielectric stresses during switching operation [1]. A load break switch is a type of switching device used for voltages in the range of 12 to 36 kV and is able to interrupt currents less or equal to the load current (the maximum current the system is rated for). Medium voltage load break switches are common in the distribution grid, and are a cheaper option than installing a circuit breaker [6], which are devices able to interrupt currents created because of a low impedance path through an electric arc between two electrically conducting parts at different voltage levels: *short-circuit currents*. Load break switches are often used as a component in compact metal-enclosed substations, and in series with a fuse, which interrupts fault currents [6].

Nowadays, sulfur hexafluoride (SF_6) has become a popular arc quenching medium due to its superior dielectric and arc quenching properties [7], but is the strongest greenhouse gas known, leaving behind oil and and vacuum technology as shown in figure 1.1.

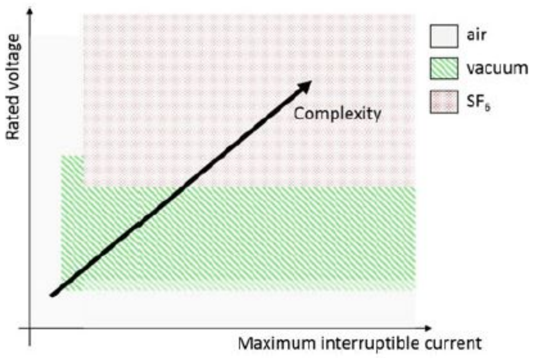

Figure 1.1: Insulating mediums of power switching devices for different rated voltages and maximum interruptible currents [1].

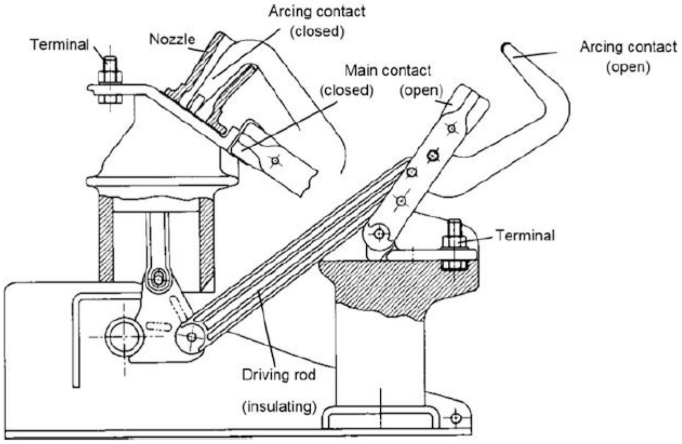

Figure 1.2: A LBS with Hardgas nozzle for 6-24 kV; both in closed and open position [1].

Figure 1.2 shows a representation of a load break switch using air as a interrupting medium. The main contacts are the last to mate when closing and the first to separate when opening. The nozzle is narrow and produces H_2 (Hardgas) when it is exposed to the arc making the interruption easier than if the arc burns in pure air [1].

Different Test Methods for Load Break Switches

According to the IEC Standard [5], there exists several types of tests for high-voltage switching devices to prove their ratings and characteristics, operating devices and auxiliary equipment. For convenience, the type tests shall be grouped like this:

Group	Types tests
1	Dielectric tests on main circuits Radio interference voltage test
2	Measurement of resistance of the manin current path Temperature rise test
3	Short-time withstand current and peak withstand current test Making and breaking test
4	Test to verify the degree of protection enclosures Tightness test (Where applicable) Mechanical test Environmental test Dielectric test and auxiliary and control circuits

Table 1.1: Example of grouping [5]

These tests shall be made on complete high-voltage switches, on their operating devices and on auxiliary equipment. At the beginning of the type tests, the mechanical characteristics of the switch shall be established, for example, by recording no-load travel curves. The mechanical characteristics will serve as the reference for the purpose of characterising the mechanical behavior of the switch. Furthermore, the mechanical characteristics shall not significantly differ in the different test samples used according to the manufacturer tolerances as defined in [8].

Among all of these tests mentioned above, one of the most important and relevant for this thesis is the *Making test* since this test applies high mechanical stresses to the switching device and guarantees high dissipation losses in the pre-strike, which can cause welding of its contacts. A making test simulates a closure operation of high-voltage switches during short-circuit condition, or in other words, it reproduces a closing operation for a switching device under faulty condition with the most possible accuracy.

Importance of Making Tests

A making test for load break switches requires huge amounts of power if the voltages and currents are obtained from one single source. Since that source must generate the voltage and currents at the same time, it is impossible to perform due to laboratory power limitations. A solution for this challenge is to obtain high-voltage and high-current from different sources where a *synthetic circuit* may be used to produce the required test voltage from one source and the rated making current from a second source.

Synthetic circuits become virtually important to switching devices, in this case to a load break switch, since this is the only method to perform making tests. Synthetic circuits are no longer considered an alternative to direct test (obtaining high-voltage and high-current from the same source) but as an equivalent to them. It is a fact that there is a necessity of synthetic circuits to test switching devices due to the capability limitations of laboratories.

What had been done and What remains

There have been several investigations about making tests using a synthetic circuit (synthetic making test) for switching devices. A very important part of a synthetic making test is a *making switch* which has the function of applying a high-current to a test object (switching device); therefore, most of the investigations are focused on the making switch and will also be treated in this thesis. Due to the low quality of the high-voltage chinese test levels, the chinese have increased their efforts in this field. For example, in [9], a new kind of fast making device was emphatically expounded, which is composed of a parallel-connected triggered vacuum switch and a fast vacuum circuit breaker with a permanent magnetic actuator. The research [10] went further and it was determined that the usage of a fast vacuum circuit breaker was actually suitable for the synthetic making test. In [11] and [12] an elaborated circuit was proposed for controlling the triggered vacuum switch. Research has also been done on the insulating medium of the making switch which normally uses a vacuum as a insulating medium (therefore is called Triggered Vacuum Switch or Triggered Vacuum Gap), There also has been a development [13] of a large current making switch using SF_6 gas as an insulation medium instead of vacuum. In [14], a rapid activated device intended on having the same function as a making switch was exposed and then manufactured, and fully complies with the requirements of the IEC Standard.

As a result of literature research on this field, it is concluded that researchers has been focused more on the making switch as it is an important component in a synthetic making circuit, but it seems they have put aside the impact that the rest of the components of the synthetic making circuit have on the performance of the making test. That is exactly what is studied in this thesis.

1.3 Objectives

The main objectives of this Master Thesis are

1. Designing of a synthetic circuit to perform a making test of load break switches in a laboratory environment.
2. Selecting of the most appropriate parameter of resistance, inductance, and capacitance on the synthetic circuit that successfully permits the applying of a high-current.
3. Taking into account all components of the synthetic circuit and their respective voltage drops, losses, time delays, and other relevant considerations to obtain more realistic results.
4. Following the IEC Standard limitations and requirements in order to perform a correct making operation.

1.4 Limitations

The main limitations for my study are physical and operational limitations. Physical limitations can be considered: the rated phase voltage of the load break switch, welding of contacts due to thermal stresses, maximum number of operations, closing velocity and distance gap of load break switches and time delays.

Operational limitations are reduced only to IEC Standard requirements in [2].

1.5 Structure of the Thesis

This thesis is divided in 5 chapters. The first chapter describes the motivation to do this work, a brief background on switching devices and its different types of tests, putting emphasis on the making test. The chapter continues with the objectives and limitations of the work.

The second chapter explains the making operation, the function of a synthetic circuit, and how it is composed and the standard requirements to perform a correct making operation. This chapter finishes with describing the synthetic circuit and the details that will be used in the simulation.

Chapter three is the longest chapter. Here the synthetic making circuit is analyzed and the results simulations are shown. The chapter also gives a brief introduction of voltage drop in a vacuum and in gas as a quenching medium. The results of the laboratory work and simulations are also demonstrated. The chapter concludes with the main results of the master thesis.

Chapter four explains the synchronization between all the elements involved in the making operations. It gives explanations about all the steps from the moment of starting the making test until it finishes.

The last chapter explains in detail the conclusions and recommendations for further work.

Chapter 2

Synthetic making circuit

During a closing operation of the load break switch, its contact gap is subject to its rated voltage that it was designed for and after the moment of breakdown the load break switch is subject to a short-circuit current at power frequency.

When the contact gap of the load break switch closes with a rated voltage applied between them, an electric arc is ignited. This is called pre-arcing and happens before the mechanical touching of the contacts. Pre-arcing affects the capability of the switchgear to close and latch, owing to the welding of the contact surface because they absorb the power dissipation resulted from the arc. The dissipated energy can be calculated by

$$E_{dissipation} = \int_{t_0}^{t_{touch}} i_{SC}(t) \cdot u_{arc}(t)\, dt \tag{2.1}$$

Where $E_{dissipation}$ is the dissipated energy in the pre-strike during the making operation, t_0 is the moment when the breakdown occurs, t_{touch} is the moment when the contacts touch mechanically, i_{SC} and u_{arc} are the short-circuit current and arc voltage respectively. Excessive welding of contacts may prevent the switching device to appropriately respond to the next opening command if the operating mechanism does not provide an opening force sufficient to break the welded points [1]. The electric arc is generated due to an electric breakdown of the contact gap, when the dielectric withstand of the gap is less than the applied voltage, which means the current starts flowing before the mechanical touch, that is, several milliseconds earlier. Figure 2.1 shows the pre-strike phenomenon when contact gap suffers a dielectric breakdown.

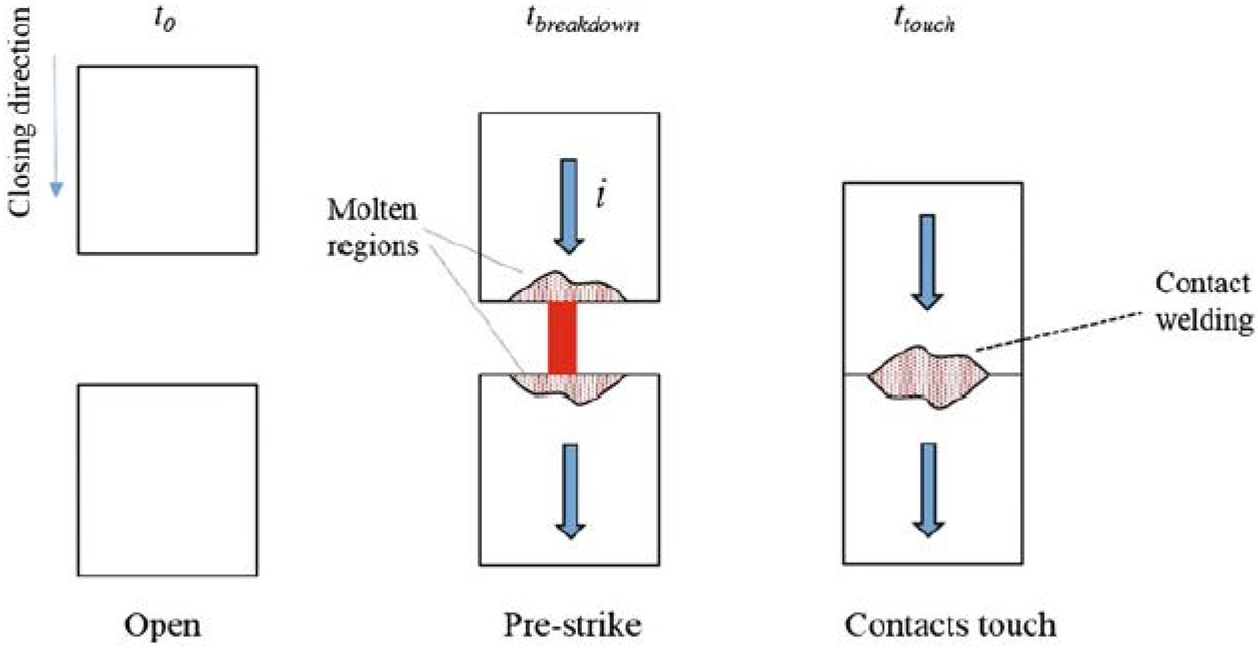

Figure 2.1: Different stages during making operation of a power switching device [1].

As mentioned in the preceding chapter, a synthetic circuit must be used to perform making tests. It is required that the synthetic making test shall adequately stress the load break switch. The adequacy is established when the test method meets the requirements in IEC Standard [2].

A typical synthetic making circuit has this configuration.

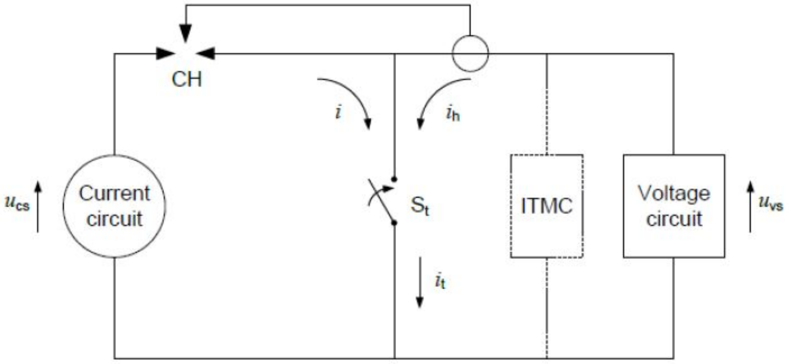

Figure 2.2: Typical synthetic making circuit for single-phase test: u_{CS} is the voltage of current circuit, CH is the making device, i is the power frequency current supplied by current circuit, S_t is the test object, i_h is the ITMC, i_t is the current in the test object, and u_{VS} is the voltage of the voltage circuit [2].

Synthetic circuits are made out of two circuits, the current-circuit and the voltage-circuit, located at the left and at the right in figure 2.2 respectively. Notice also the making device, which is normally a triggered vacuum switch. This device should ensure connecting the switching device under the test just after pre-strike from a high-voltage circuit to a high-current circuit with a very short time delay and must be designed to withstand the transient voltage and conduct a short-circuit current without excessive erosion [13]. During the time interval between the spark breakdown of the gap between contacts and the start of the passage of high amperage (short-circuit current), a transient activating current, generated by an Initial Transient Making Current (ITMC) device, should flow through the load break switch, ensuring continuous arcing between the contacts until the moment when the contacts are closed [14]. This transient current oscillates with a very high-frequency and only lasts during a few microseconds before the short-circuit current flows.

During the making process, it is possible to distinguish three different intervals [8]:

- *High-voltage interval*, which lasts from the beginning of the test to the moment of the breakdown across the contact gap. During this time the switching device is in open position. During this interval the switching device is stressed by the high-voltage circuit with a phase rated voltage.
- *Pre-arcing interval*, which is the time from the moment of breakdown across the contact gap to the touching of the contacts (closing stroke of the switching device). During this time the switching device experiences electrodynamic forces due to the current and deteriorating effects (welding of contacts) and due to arc-energy.
- *Latching interval*, which starts from the touching of the contacts to the moments when the contacts are fully closed, or in a latched position. During this interval the switching device closes in presence of the electrodynamic forces due to the current and contact friction forces; therefore during this interval the making current shall comply.

If close attention is paid to figure 2.3, it is possible to recognize these three intervals.

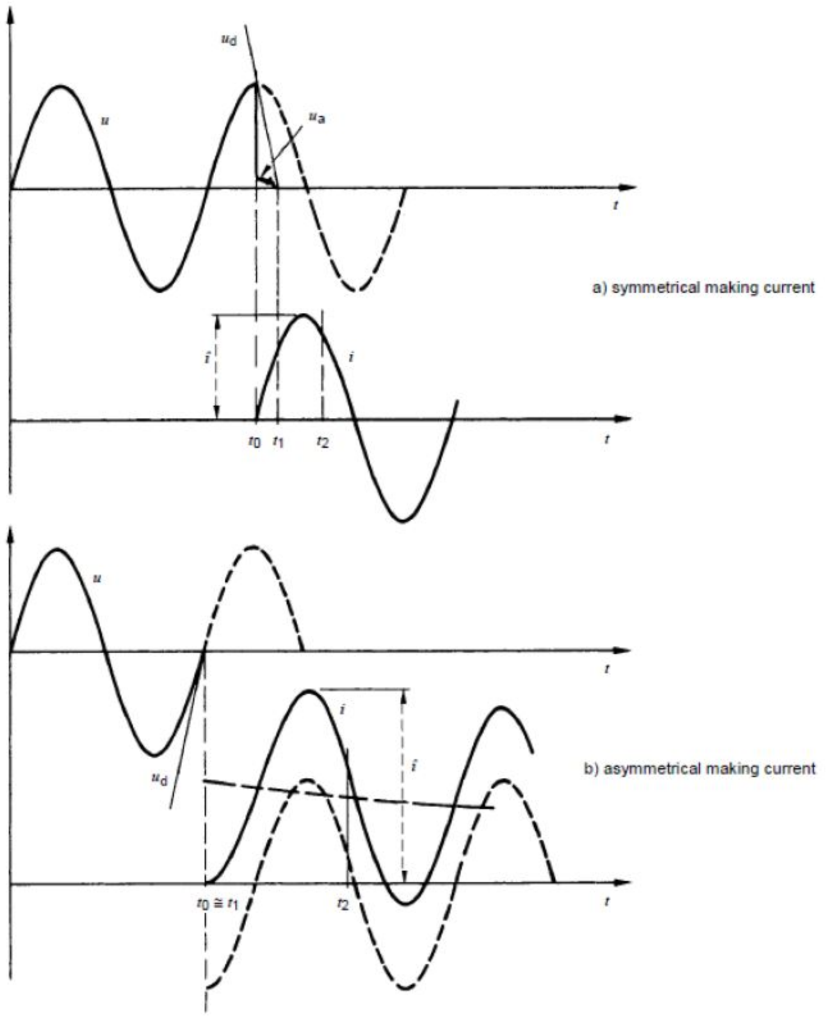

Figure 2.3: Making process and Basic time intervals: u is the power frequency voltage, u_d is dielectric closing characteristic, u_a is the arc voltage, i is the making current, î is the making current peak, t_0 is the instant of pre-strike, t_1 is the instant of contact touch, and t_2 is the instant of reaching fully closed position [2].

The load break switch shall be able to make a current with pre-arcing occuring at any time on the voltage wave. Two extreme cases are specified as follows [8]:

- *Making at the peak of the voltage wave*, leading to a symmetrical short-circuit current (this current shall be the symmetrical component of the rated short-circuit breaking current) and the longest pre-arcing time. The making shall occur with -30/+15 degrees of peak voltage.
- *Closing at the zero of the voltage wave*, without pre-arcing, leading to a fully asymmetrical short-circuit current (this current shall be the rated short-circuit making current which

is obtained multiplying the r.m.s. value of the A.C. component of the rated short-circuit breaking current with a factor given in clause 4.103 of [3]).

2.1 Voltage-Circuit

The voltage circuit supplies

- the applied voltage during the high-voltage interval,
- the ITMC during pre-arcing interval, by the discharge of the ITMC unit.

The Initial Transient Making Current (ITMC) can be obtained from a basic RLC circuit (see appendix B) and its governing equation depends on the roots of $\alpha \cdot C \cdot R^2 + R * C * \alpha + 1 = 0$; therefore, three different governing equations exist which are:

$$i_{hf}(t) = \frac{V_c}{L \cdot w_d} \cdot e^{-\frac{R}{2 \cdot L} \cdot t} \cdot \sin(w_d \cdot t) \tag{2.2}$$

$$i_{hf}(t) = \frac{2 \cdot V_c}{R} \cdot e^{-\frac{R}{2 \cdot L} \cdot t} \cdot t \tag{2.3}$$

$$i_{hf}(t) = \frac{V_c}{2 \cdot L \cdot w_d} \cdot e^{\alpha_1 \cdot t} - \frac{V_c}{2 \cdot L \cdot w_d} \cdot e^{\alpha_2 \cdot t} \tag{2.4}$$

Where $_{hf}$ makes reference to high-frequency, w_d is whether $w_d = \frac{\sqrt{4 \cdot L \cdot C - (R \cdot C)^2}}{2 \cdot L \cdot C}$ in case of equation (2.2) and (2.3) or $w_d = \frac{\sqrt{-4 \cdot L \cdot C + (R \cdot C)^2}}{2 \cdot L \cdot C}$ in case of equation (2.4), $\alpha_{1,2} = -\frac{R}{2 \cdot L} \pm w_d$; therefore the high-frequency current oscillating value can be obtained dividing w_d by 2π.

The switching device is stressed with its phased voltage until the moment of breakdown that gives place to the injection of the short-circuit current.

2.2 Current-Circuit

Its main function is to supply the short-circuit (making) current during the pre-arcing and latching intervals. The short-circuit current has an A.C. and D.C. component depending on the value of the parameters of the high-current circuit and the time of closing the switching device (notice that if the switching device closes near the peak amplitude of the voltage wave, then it will give a symmetrical short-circuit current, on the other hand, if it closes near zero of the voltage wave, then it will give an asymmetrical short-circuit current).

The respective governing equation for the short-circuit current is (see appendix A).

$$i_{sc}(t) = \frac{R \cdot V_m \cdot (w \cdot t) + L \cdot w \cdot V_m \cdot \sin(w \cdot t)}{L^2 \cdot w^2 + R^2} + K \cdot e^{-\frac{R}{L} \cdot t} \tag{2.5}$$

Where K is a constant that depends on the closing time t_0 of the switching device according to

$$K = -\frac{R \cdot V_m \cdot \cos(w \cdot t_0) + L \cdot w \cdot V_m \cdot \sin(w \cdot t_0)}{L^2 \cdot w^2 + R^2} \cdot e^{+\frac{R}{L} \cdot t_0} \tag{2.6}$$

Equations (2.5) and (2.6) are valid for $t > t_0$. The first term of (2.5) equals to the A.C component of the short-circuit current and the second term equals to the D.C component which depends on the value of K in equation (2.6).

Currents with a D.C. component have more stress to handle for a switching device since the amplitude of the current becomes higher and also the arcing time becomes larger which results in a higher arching energy.

To demonstrate the effect of the D.C. component of the current, we will say that equation (2.7) defines a current without a D.C. component and equation (2.8) defines a current with a D.C. component.

$$i(t) = I_{max} \cdot \sin(w \cdot t) \tag{2.7}$$

$$i(t) = I_{max} \cdot \sin(w \cdot t) + D \tag{2.8}$$

It is clearly noticeable that the r.m.s. value of (2.7) is obtained by dividing the peak value by $\sqrt{2}$, but the r.m.s. value of (2.8) equals to

$$I_{eff} = \sqrt{\frac{I_{max}}{\sqrt{2}}^2 + D^2} \tag{2.9}$$

In equation (2.9) one can easily observe the augmentation of the r.m.s. value due to the D.C. component.

$$I_{eff} = \frac{I_{max}}{\sqrt{2}} \cdot \sqrt{1 + 2 \cdot \left(\frac{\%D.C.}{100}\right)^2} \tag{2.10}$$

Equation (2.10) is another way to express the relation between a current and its D.C. component in percentage and also shows that D.C. component contributes to increase the r.m.s. current value; therefore, this has more stress for the switching device. The D.C. component has to decay to zero as seen in figure 2.4.

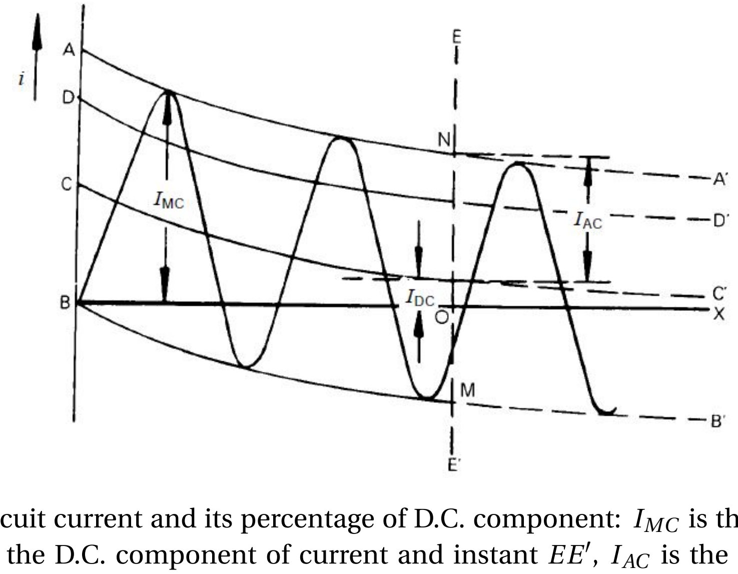

Figure 2.4: Short-circuit current and its percentage of D.C. component: I_{MC} is the making current, I_{DC} is the peak value of the D.C. component of current and instant EE', I_{AC} is the peak value of the A.C. component of current and instant, BX is the nominal zero line, CC' is the displacement of current-wave zero-line at any instant EE', and DD' is the r.m.s. value of the A.C. component of the current at any instant, measured from CC'. [3].

2.3 Specific Requirements

IEC Standard [2] regulates all relations with synthetic testing (breaking and making) and therefore shows the specific requirement to perform a successful making operation and that happens when

$$\beta + tm' + (90 - \mu) \leq 27° \tag{2.11}$$

Where

$$tm' = \frac{tm}{T} \cdot 360° \tag{2.12}$$

Where

- β is the phase displacement between the voltage source of the high-current circuit and the voltage source of the high-voltage circuit,
- tm is the time delay between closure of the making device and the gap breakdown, which has to be as short as possible, but in any case no longer than 300 μs,
- μ makes reference to the power factor of the high-current circuit ($cos\varphi$)and can be found with $\varphi = tan^{-1}\left(\frac{w \cdot L}{R}\right)$,
- T is 20 ms for 50 Hz or 16.7 ms for 60 Hz.

The condition described in equation (2.11) limits β to a value that depends on the time delay of the making device; thereby, a maximum phase displacement that permits a correct making operation is shown in figure 2.5

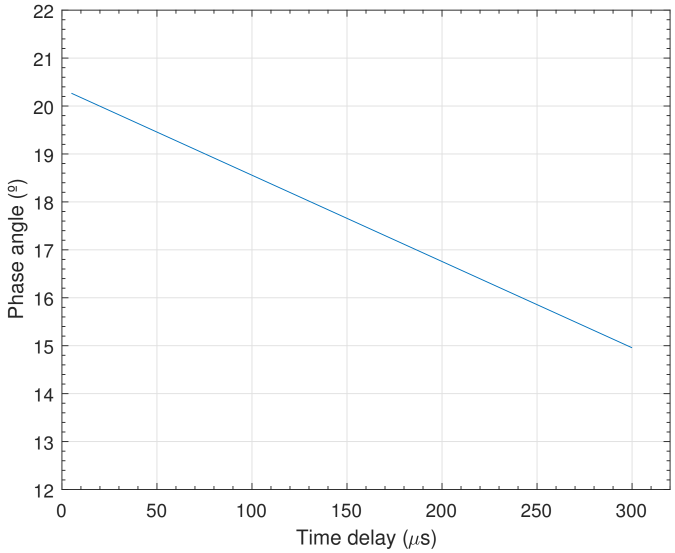

Figure 2.5: Maximum phase displacement allowed.

2.4 Actual Synthetic Making Circuit

The previous section described what a synthetic making circuit is and how it works. Now, we will be presented to the synthetic circuit that is going to be used for the simulations and experiments in the high-current laboratory at NTNU. The components of the synthetic circuit will also be described.

The current-circuit parameters are fixed which means they can't be controlled. There is a three-phase transformer which feeds the current-circuit with its secondary side and is connected to the grid at its primary side. There is also a current limiting impedance composed of a resistance and a reactance in series. The impedance has three different tap positions in order to control the limiting capability of the current, the first tap position gives lower values of reactance and the third gives higher values.

Component	Specifications
3-phase Transformer	$3MVA\,11.43/0.697kV$ $X_{SC} = 0.0037pu$
Limiting impedance	Tap 1: $R = 0.4741$ $L = 1.6\,mH$ Tap 2: $R = 0.07799$ $L = 3.17\,mH$ Tap 3: $R = 0.1350$ $L = 6.33\,mH$

Table 2.1: Components of the current-circuit

The voltage-circuit is a RLC circuit. The voltage source is a charged capacitor; therefore, the voltage also oscillates with a high-frequency value according to:

$$hf = \frac{1}{2\cdot\pi\sqrt{L\cdot C}} \tag{2.13}$$

The actual circuit that is going to be used has this configuration:

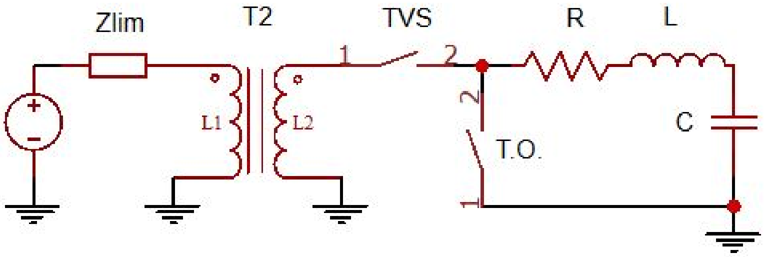

Figure 2.6: Actual synthetic making circuit

The values of R, L and C on the voltage-circuit on figure 2.6 will be defined according to the results of the simulations in order to assure a correct making operation. Those values also define the period of the high-frequency current, also called Initial Transient Making Current (ITMC), according to the inverse of equation (2.13) and its amplitude according to equations (2.2), (2.3) or (2.4). It is desired to have a shortest possible value of resistance, inductance and capacitance but in turn having large enough high-frequency current in order to apply the short-circuit current satisfactorily.

Chapter 3

Analysis of the synthetic making circuit

3.1 Working Principle

As explained in the previous chapter, the test object is first stressed with its rated voltage until a breakdown in the contact gap occurs which generates an electric arc. At this time a high-frequency current starts flowing through the test object followed by the short-circuit current after a time delay from the making switch; therefore, the current flowing through the test object is a combination of first, the high-frequency current and second, the short-circuit current.

To perform simulations, Matlab and a well-known Electromagnetic Transient Program (EMTP), ATPDraw, were used. Typical short-circuit currents using tap 1 on the limiting impedance (see table 2.1) and typical high-frequency currents are shown below in figures 3.1 and 3.2

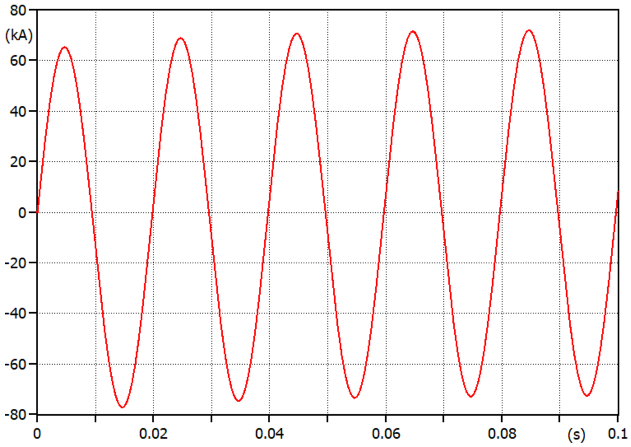

Figure 3.1: Typical short-circuit currents

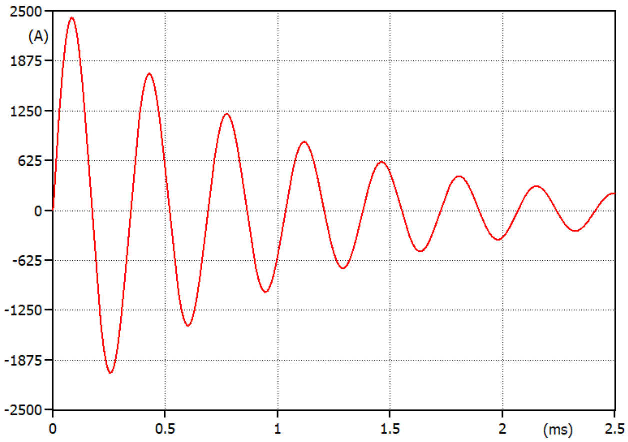

Figure 3.2: Typical high-frequency currents

The high-frequency current in figure 3.2 must be high enough at the moment of closing the making switch to permit the correct injection of the short-circuit current and thus avoid current-zero points.

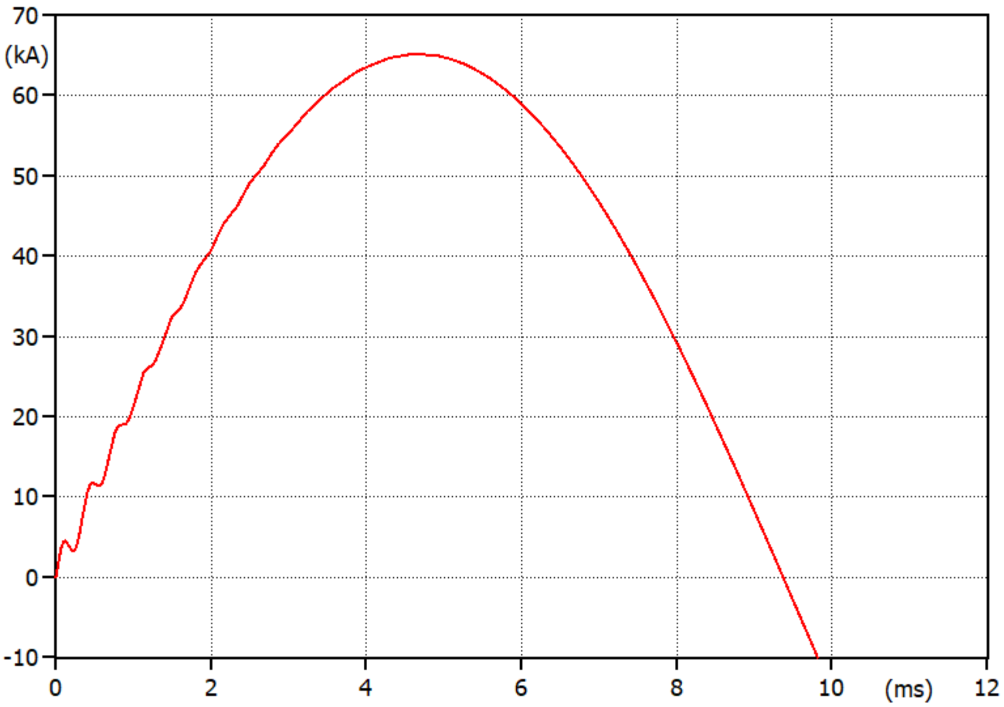

Figure 3.3: Typical making current

Figure 3.3 shows a typical successful making current which is composed by high-frequency current and short-circuit current.

3.2 Practical Considerations

During the performance of simulations, it is necessary to take into consideration the voltage drop across the making switch (Triggered Vacuum Switch) as well as the voltage drop across the test object (Load Break Switch). It is important to have a very low voltage drop across the making switch since the voltage on the secondary side of the transformer is only some hundreds volts, and at the same time our goal is to get the highest possible current through the test object.

3.2.1 Background on Low Pressure Switching Arc

An arc can very well live in the vacuum. In fact, the arc voltages in a vacuum are considerably lower than those that develop in other mediums [15]. An electric arc on a triggered vacuum switch is a low pressure switching arc using a vacuum as insulation and arc quenching medium among the main contacts [16]. Arcs in vacuum occur in two main forms: the diffuse mode and the constricted mode.

Diffuse and Constricted Vacuum Arc Voltage

A *diffuse mode vacuum arc* is the mode which a vacuum arc adopts for a current range covering a few kilo-amps. When the temperature on small areas of the cathode exceeds the melting temperature of the cathode material, micrometer-sized (5 to 10 μm [15]) foot points better known as *cathode spots* are formed [1]. The cathode emits into the contact gap, via one or several cathode spots, a globally neutral plasma made up of electrons and of high speed ions. The cathode spots and the plasma are specificities of the arc in the diffuse mode [15]. In addition, the cathode spots emit a weak powerful light source in the contact gap and move very fast all over the contact surface; therefore, the arcing in the diffuse mode tends to occupy the entire available surface of the cathode [15]. Due to this the arc is not well-defined. The diffuse arc voltage is characterized by low contact erosion, easy current interruption due to the fast recovery of the switching gap after current zero, independence of the arc voltage on the distance between the contact and the current magnitude, and a very low arc voltage [1].

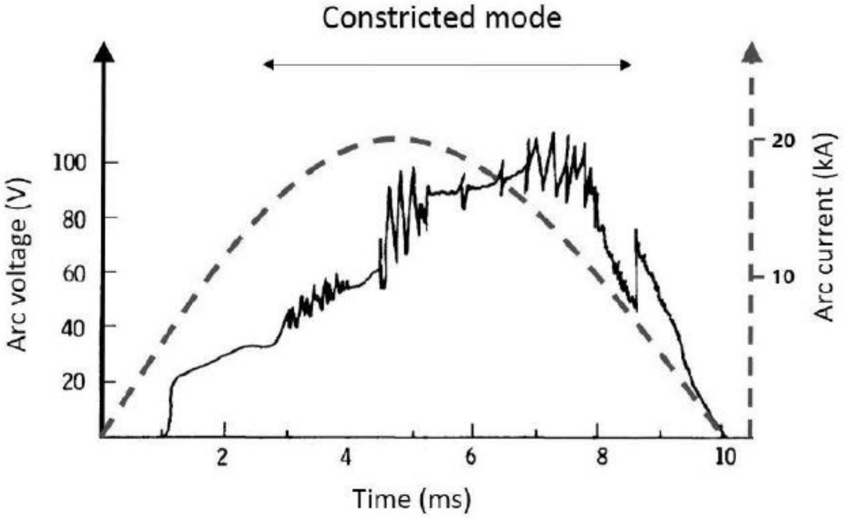

Figure 3.4: Arc of vacuum interrupter at different currents [1].

In case of higher currents (around 10 to 15 kA [1]) the arc behavior change drastically. A constriction of the plasma column takes place making the current concentrated on a more limited area of the anode called *anode spot* which is in the region of 1 cm^2 and spills considerable amount of vapour [15]. This contraction effect on the anode side leads to a contraction on the cathode side creating a preferential path: A cathode spot corresponding to an anode spot is established and a well-defined *constricted vacuum arc* forms in the contact gap which looks similar to a typical arc formed in gaseous medium (high pressure switching arc). A constricted arc voltage is characterized by a large molten cathode and anode surfaces, a high contact erosion, a slow recovery of the switching gap and a higher arc voltage than the one in a diffuse mode but which changes sporadically (see figure 3.4) [1]. The appearance of constricted arc limits the interruption performance of the vacuum switches [17]. The control of arc in vacuum switching devices means to distribute the dissipated energy homogeneously over the whole contact surface to prevent large melting areas [1], harmonize thermal-electrical stress on the contact surface and therefore reduce erosion effects [18]. The interaction of an axial magnetic field (AMF) with the vacuum arc delays the transition from a diffuse to a constricted arc form [17].

3.2.2 Voltage Drop across the Making Switch (Triggered Vacuum Switch)

The making switch is located on the current-circuit just after the secondary side of the transformer. The making switch is a Triggered Vacuum Switch (TVS), inside of it, an arc burns in vacuum conditions, which is a low pressure switching arc. The triggered vacuum switch is a new switching device combining vacuum switch technology with electrode spark technology, using a special designed trigger electrode to control switching for quick making [16].

It is important to understand the working conditions of a triggered vacuum switch. Specifically, it is desired to know how possible is to trigger it, how large the time delay is, how possible is to measure it and, how large the voltage drop is when there is an electric arc.

A triggered vacuum switch uses a special designed trigger electrode to control switching for quick making. It has several advantages, such as wide working voltage range, great through current capacity, triggering simply, rapid media recovery, compact structure, high working reliability, long life time, low price, and so on [16].

The actual triggered vacuum switch that will be used in the synthetic making circuit is from a manufacturer called "VEI-A VIS Ltd" and the type is "RVU-63(TVS-63)". This making switch is used to discharge a capacitor bank through a load. The working principle of this triggered vacuum switch is explained as follows: The triggered vacuum switch has two metallic flanges to which the main electrodes are attached. The cathode flange is the one with a triggering electrode input, being the remaining flange, the anode flange. The triggered vacuum switch includes a triggering unit which applies a positive triggering pulse to the input of the triggering electrode (cathode flange). The triggering unit triggers with a control signal applied, it generates a triggering voltage pulse and breakdown occurs at the triggering gap letting the current flow through the main electrodes for only a half period.

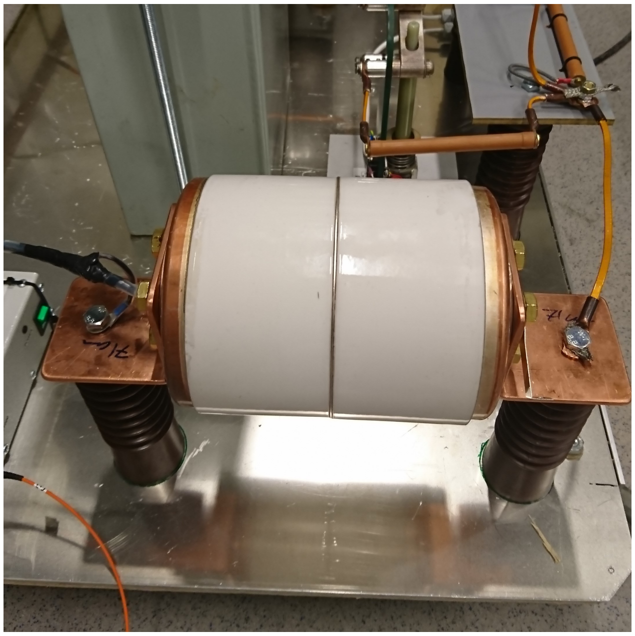

Figure 3.5: Triggered Vacuum Switch (TVS).

Testing of the Actual Triggered Vacuum Switch

Before using the TVS in a synthetic making circuit, it needs to be tested in a test circuit to know how great the voltage drop is across it and how large approximately its time delay is.

The test circuit is formed by a transformer, diodes rectifiers, a resistor, an inductance, and of course the triggered vacuum switch with its triggering unit. Figure 3.6 shows a schematic of the test circuit whereas table 3.1 shows the value of the different components that form the test circuit.

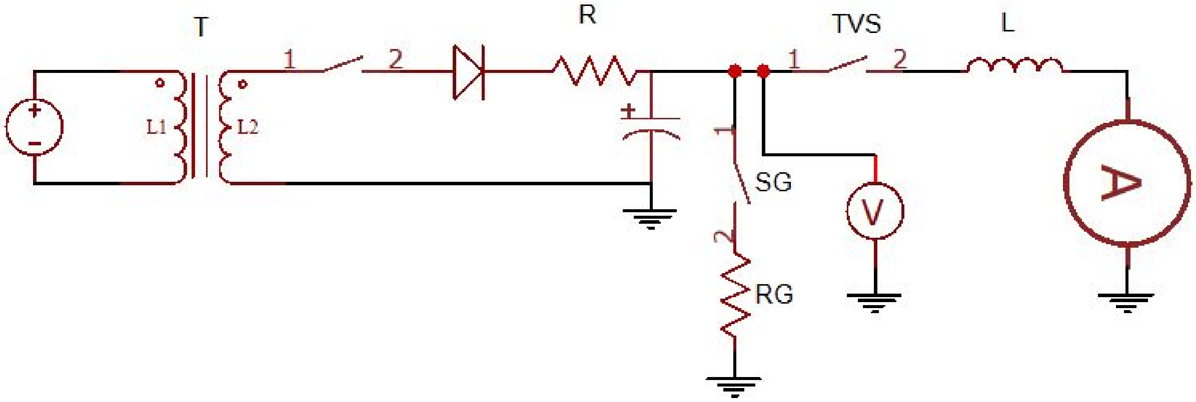

Figure 3.6: Schematic of the test circuit for the TVS.

Component	Value
Transformer	$220V/45000V$
Switch	N/A
Diode	N/A
Resistor	350 $k\Omega$
Capacitor	4.8 μF
Grounding switch	N/A
Grounding resistor	10 $k\Omega$
TVS	N/A
Inductor	41.4 mH

Table 3.1: Components of the test circuit

The testing of the TVS follows this sequence:

1) The capacitor is charged with a test voltage.
2) The capacitor discharges through the load by triggering the triggered vacuum switch manually by using an optical pulse shaper.
3) Current and charging voltage waveform are read from the oscilloscope.

The primary side of the transformer is connected to the grid through a variac (variable auto-transformer). The charging operation is performed through the transformer which charges the capacitor with a D.C. voltage (due to the diode rectifier and the resistor) by closing $S1$. When the capacitor is charged to a desirable value, S1 opens and the discharging operation is ready to start. By triggering the triggered vacuum switch the discharging operation starts. The triggered vacuum switch lets only one half cycle of the current flows through the inductor.

In order to obtain the different waveforms on the oscilloscope, transmitters were used to receive the analog signal from the voltage and current probes and they transmit them to the oscilloscope by using fiber optical signals. Transmitters work also as isolator between equipment exposed to high-voltage and measuring instrument. The current probe is located after the inductor and the voltage probe is located between the anode flange of the triggered vacuum switch and ground as it is showed in figure 3.6. Figure 3.7 shows the test circuit from two different perspectives.

Figure 3.7: Test circuit

The result of the voltage drop across the triggered vacuum switch was obtained by combining real measurements and a mathematical approach. It was like this due to measurement equipment limitations. The mathematical approach is described in detail in appendix C and gives a result of a voltage drop across the triggered vacuum switch of **50 volts**. It was also found a triggered time delay (time different from the moment when the trigger voltage waveform starts rising to the moment when the main current start raising smoothly [16]) about **50 microseconds** (See figure 3.8).

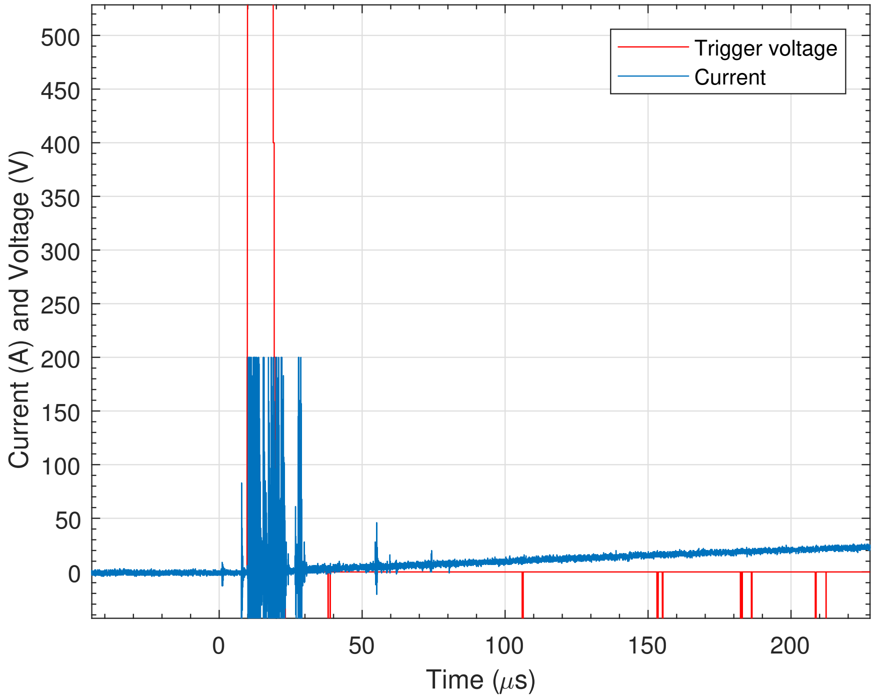

Figure 3.8: The trigger time delay waveform

The voltage drop obtained across the triggered vacuum switch is clearly in a diffuse mode and agrees with results obtained in other relevant works. In [19], the arc column voltage drop was calculated for different applied axial magnetics fields giving results from 10 to 27 volts. In [20], the voltage drop across a triggered vacuum switch in a enabled state was 50 to 100 volts. A similar result was found in [15], where the author sustains a distribution of voltage in the arc as first, 20 volts in the immediate area of the cathode; and second, few volts in the plasma which increases with the distance and the current.

3.2.3 Background on High Pressure Switching Arc

The electric arc across the test object (Load Break Switch) is a high pressure switching arc since the arc burns freely in a gas as a quenching medium without using an interruption chamber. An arc of this type can be whether *static* if a D.C. circuit is used to generate the arc, or *dynamic* if the current varies with the time. Dynamic arc is always a duty for A.C. switchgears and that is why it will be treated in this thesis leaving apart the static arc voltage.

Dynamic Arc Voltage

This type of arc appears in case of A.C. current flowing through the arc due to the rapidly oscillation of the current; therefore, the temperature of the arc and its cross-section are not capable to adjust to the new current value because the temperature can not change instantaneously. Due to this, the arc has a thermal inertia. The thermal inertia causes the arc to remember the amplitude of the current that just passed for a short period of time [21]. Thermal inertia can be exemplified with a step function current, giving the result an arc voltage that starts with a high value and gradually decreases to a value corresponding to the static arc characteristic. In other words, the voltage waveform has an exponential decay as seen in figure 3.9.

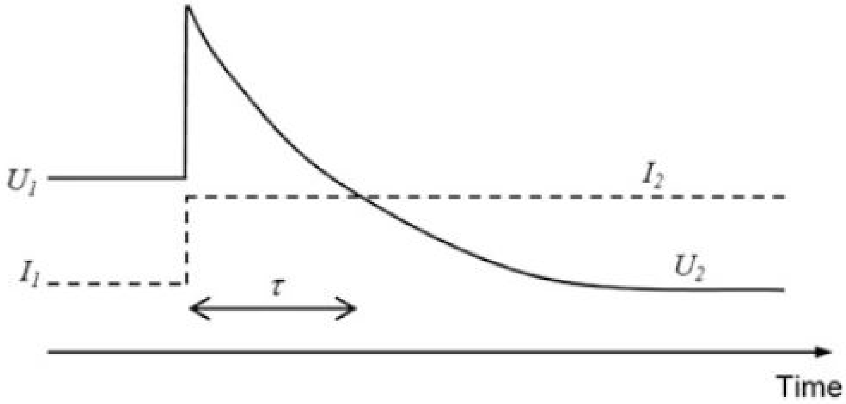

Figure 3.9: Voltage drop (solid line) of an arc exposed to a current that follows a step function (dashed line) [1].

The voltage drop is proportional to the step in the current. The time constant changes from gas to gas and depends on the test conditions, the method of measurements and the magnitude of the current [1]. A gas with a low time constant is faster to cool. The time constants of SF_6 gas is 0.8 μs whereas the time constant corresponding to air is 80 μs. The dynamic arc characteristic, which is the relation between voltage drop and current between the contacts in a dynamic arc, changes with the frequency as shown in figure 3.10. The greater the frequency is, the more the curve narrows.

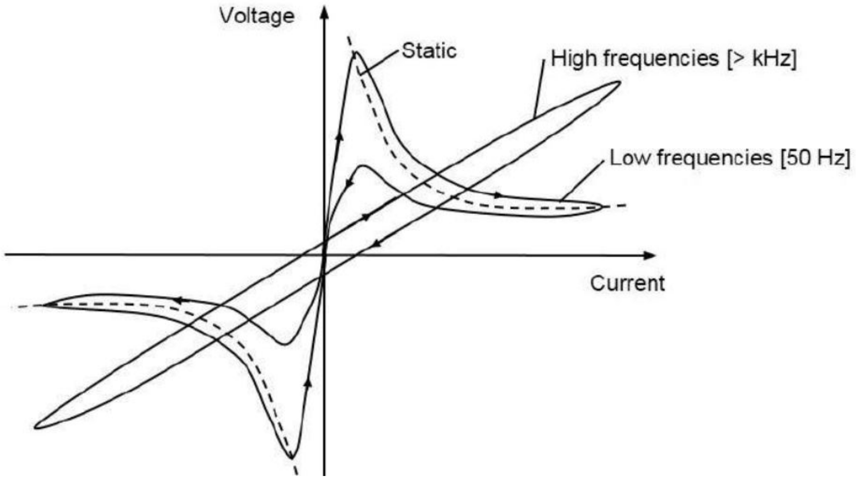

Figure 3.10: Arc characteristic for a static arc, low (typically 50 kH) and high frequencies (several kH) [1].

3.2.4 Voltage Drop across the Test Object (Load Break Switch)

The test object is a load break switch (LBS) and inside of it, an arc exposed to gas (air) extinguishes, this is a high pressure switching arc.

When the contacts of a load break switch approach with a rated voltage applied between them, an electric arc is ignited, which means that current starts flowing before the mechanical touching of the contact gap. The electric arc is generated due to an electric breakdown of the contact gap (when the dielectric withstand of the gap is less than applied voltage). The voltage drop along the arc is approximately constant and much lower than the rated power network voltage. The arc voltage depends on the design, the materials of the switching device, and on the interrupting medium among other factors.

As an initial approach, a switching device could be acceptable to model as an ideal component in case of the network voltage being much greater than the arc voltage. But in case of understanding the interaction between arc voltage and components of the surrounding network, an arc model needs to be used.

Different methods have been developed in order to understand the behavior of the arc voltage. In 1901, one of the most significant scientists was Hertha Ayrton. She discovered that the resistance of an arc of a given length must depend solely on the cross-section of the carbon mist, since the mist practically carries the entire current; therefore, the whole resistance of the normal arc diminishes quicker than the current increases [22].

Hertha Ayrton also developed an equation for the arc voltage based on a shape of a hyperbola. This equation accurately gives the law connecting voltage, current and apparent length of the arc in [23]

$$V_{arc} = \alpha + b \cdot l + \frac{c + d \cdot l}{i_{arc}} \tag{3.1}$$

Where V_{arc} is the arc voltage in volts, α, b, c and d are constants that depends on the hardness of the contacts and on their size, l is the length of the arc (or the length of the contact gap) in meters and i_{arc} is the arc current in amperes. Since i_{arc} normally is very high, the last term of the equation (3.1) can be removed and a simplified version is achieved

$$V_{arc} = \alpha + b \cdot l \tag{3.2}$$

The length of the arc changes with the time, that means there is an elongating arc whose voltage changes accordingly to the equation (3.2). The length of the arc is following a lineal motion described by

$$l = d = d_o - v \cdot t \tag{3.3}$$

Where d_0 is the breakdown distance of the contact gap in meters, v is the closing velocity of switching device in $\frac{m}{s}$ and t is the time in seconds. If equation (3.3) is inserted in equation (3.2), then

$$V_{arc} = \alpha + b \cdot d_0 - b \cdot v \cdot t \tag{3.4}$$

If $K_1 = \alpha + b \cdot d_0$ and $K_2 = b \cdot v \cdot t$, the arc voltage can be expressed in terms of these two constants. Therefore the above equation becomes

$$V_{arc} = K_1 - K_2 \cdot t \tag{3.5}$$

Which is only valid for $t_{BD} < t < t_{touch}$, being t_{BD} and t_{touch} the time when the breakdown happens in the contact gap and the time of mechanical touching respectively. Equation (3.5) describes the arc voltage as a straight line from the peak of the arc voltage towards 0 volts. That is the simplest way to describe the arc voltage behavior using Hertha Ayrton's research.

3.3 Parameter Simulations

It is possible to obtain a minimum value for the inductor and the capacitor of the voltage-circuit for different time delays. According to equation (2.13) the frequency and obviously the period of the high-frequency current can also be controlled by changing inductance and capacitance values. It was decided that in order to have large enough high-frequency current at the moment of short-circuit current injection, the time delay of the triggered vacuum switch must be less than a quarter of the period of that current. That condition can be expressed as

$$w_d \leq \frac{\pi}{2 \cdot t_d} \tag{3.6}$$

Using this condition, several combinations of minimum values of inductance and capacitance for different time delays can be achieved. Figure 3.11 shows these combinations.

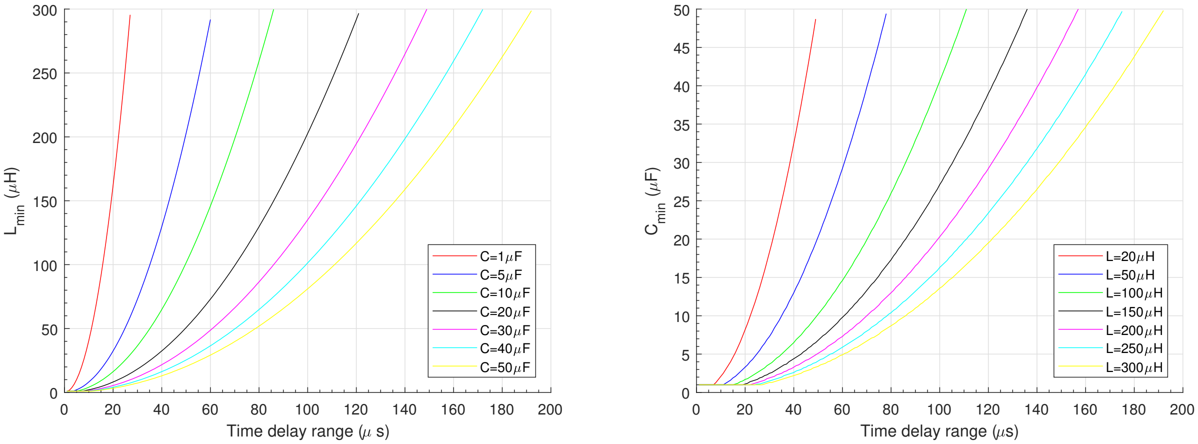

Figure 3.11: Minimum L and C values on the voltage-circuit for different times delays [4].

As the time delay of the triggered vacuum switch is 50 microseconds, several combinations of values can be listed for that time delay and are exposed in table 3.2.

L (μH)	C_{min} (μF)	C (μF)	L_{min} (μF)
20	No value	1	No value
50	20.3	5	202.7
100	10.2	10	101.4
150	6.8	20	50.7
200	5.1	30	33.8
250	4.1	40	25.4
300	3.4	50	20.3

Table 3.2: Minimum capacitance value for each inductance value and minimum inductance value for each capacitance value for a time delay on TVS equal to 50 μs.

Now only the minimum value of the resistance on the voltage-circuit needs to be found. Notice that the resistance value controls the amplitude of the high frequency current according to equation (2.2) and also damps the current waveform; therefore, a minimum value of resistance must exist to obtain a great enough current level of high-frequency current at the moment of short-circuit current appliance. Any value greater than this also works, but it may have a higher cost.

This minimum value of resistance also assures the non-existence of current-zero points in the making current, which is the combination of a high-frequency current and a short-circuit current. Figure 3.12 shows these minimum resistance values.

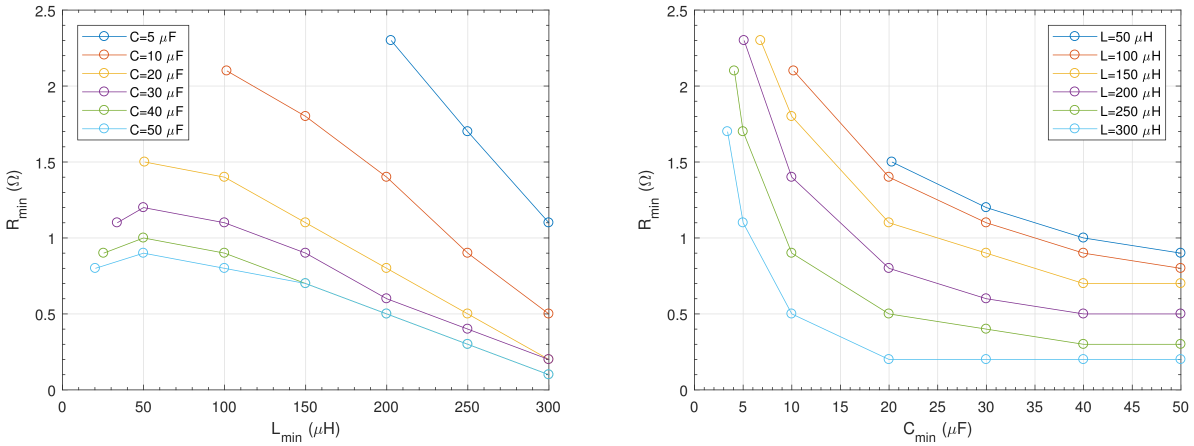

Figure 3.12: Minimum R values on the voltage-circuit for a time delay equal to $50\mu s$.

It is important to mention that the inductor has an internal resistance that is directly proportional to its own value. The proportionality factor depends mainly on the length of the coil wire, its radius, number of turns, cross-section area of the coil and wire. This internal resistance is not great enough to damp the waveform, that is why an external resistance needs to be added in order to reach the minimum value on figure 3.12.

As explained in the preceding chapter, the arc voltage across the load break switch is modeled following Hertha Ayrton's research. According to Ayrton's experiment, the arc voltage mainly depends on the breakdown distance of the contact gap and on the closing velocity of the switching device. By fixing the breakdown distance of the contact gap to 10 mm and letting variable the closing velocity from 1 to 5 meters per second, the voltage drop across the test load break switch varies and therefore the amplitude of the current waveform varies as well. The quicker the closing velocity is, the lower the voltage drop is and the higher the amplitude of the current is. Figure 3.13 shows how the amplitude of current waveform changes with the closing velocity.

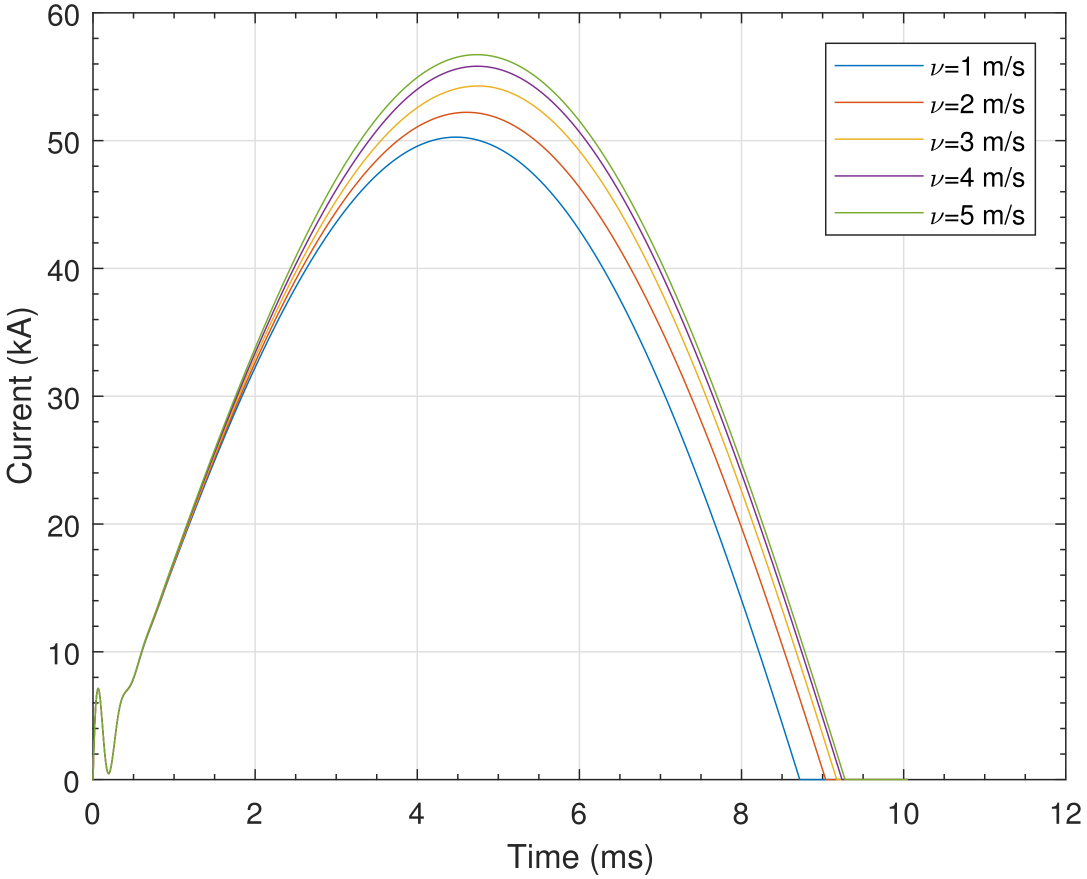

Figure 3.13: Making current amplitude for $R = 1.5\,\Omega$, $L = 100\,\mu H$, $C = 20\,\mu F$, breakdown distance gap of 10 mm, and closing velocity from 1 to $5\,\frac{m}{s}$.

By choosing the right resistance, inductance, and capacitance values on the voltage-circuit it is possible to guarantee a good performance of the current appliance and therefore having a making current without a current-zero point.

Chapter 4

Synchronization

In the previous chapters all the background and all the paramaters to perform a making test to load break switches were explained and defined in order to obtain a correct making operation. A making test simply begins by pushing a button, this action starts a structured sequence of combinations of time delays of different devices until the moment of latched position of the contacts. In other words, a certain *synchronization* must exist between all these actions that are going to take place. The starting point is defined by the phase voltage across the load break switch at the moment of pushing the button, this initiates the start of the making test. This parameter is totally random and starts an algorithm that finds the peak of the voltage as shown in figure 4.1.

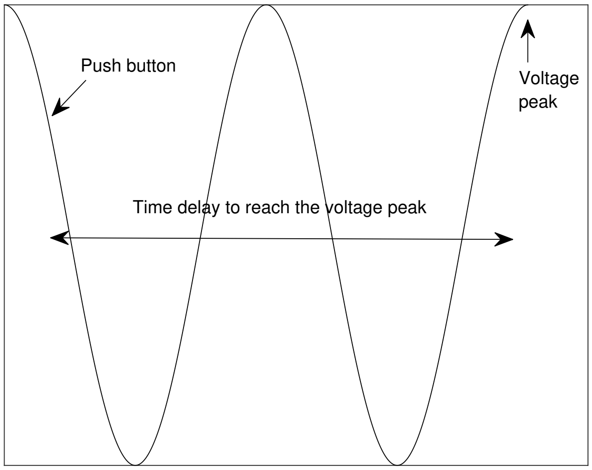

Figure 4.1: Time delay to reach the voltage peak in order to start a closing operation of test object.

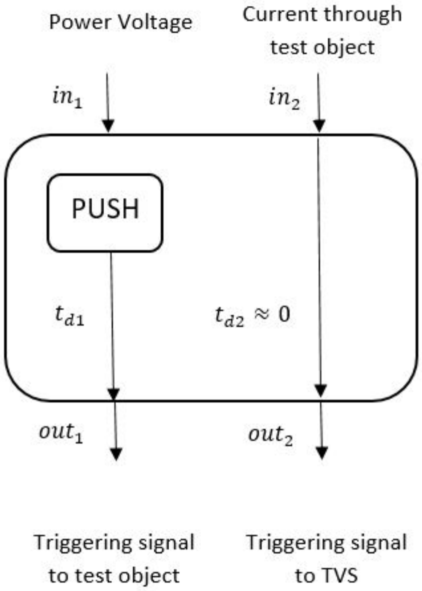

Figure 4.2: Representation of a synchronization unit.

The so-called *synchronization unit* (see figure 4.2) is a physical component in charge that all these actions happen in the correct order. This unit is composed of two input signals and two output signals. The input signals are the power voltage across the load break switch and the current through it. The output signals are the triggering signal to the load break switch and the triggering signal to the triggered vacuum switch.

It is important to describe all the actions that take place during the synchronization process. These actions follow a chronological sequence that is described below whilst figure 4.3 shows a time-line of these actions.

1) Push the button to initiate the start of the time which is a random parameter.
2) Based on the start of the time, there is a time delay to reach the peak of the voltage waveform. (t_{d1})
3) Test object closing operation starts.
4) Electric breakdown of the contact gap takes place.
5) High-frequency current start flowing through the test object.
6) Detection of current flow through test object.
7) Time delay to close the triggered vacuum switch (50 μs) plus time delay of the synchronization unit which is almost zero (t_{d2}).
8) Short-circuit current starts flowing through the test object.
9) A making current, which is a combination of two different currents (high-frequency current and short-circuit current), flows through test object.

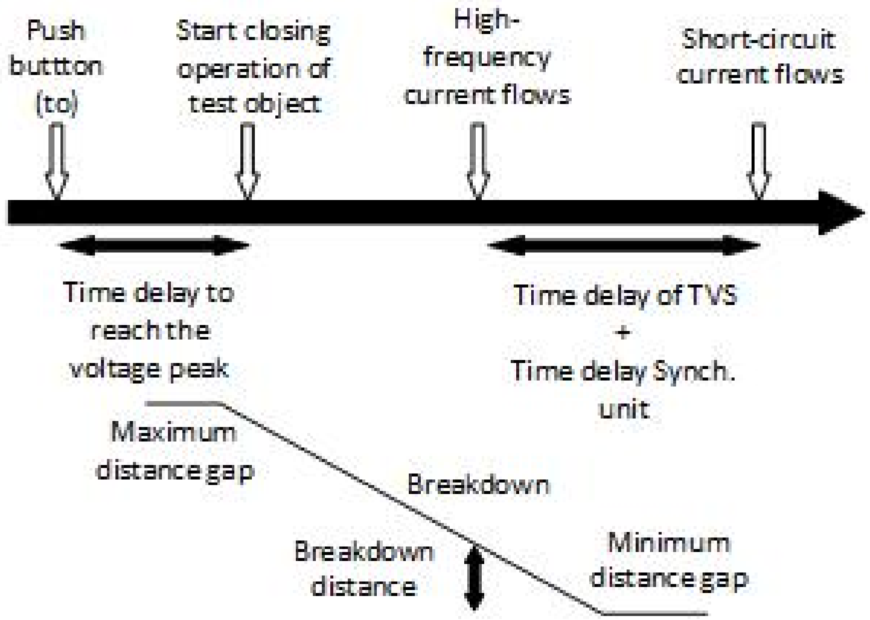

Figure 4.3: Making operation steps.

It is important to make the current as closest as possible to the peak of the voltage wave in order to get a symmetrical short-circuit current, longest pre-arcing time, and a greater current peak.

Chapter 5

Summary and Recommendations for Further Work

5.1 Summary and Conclusions

A synthetic circuit for making test for load break switches was explained and designed in this master thesis following the IEC standard requirements. The governing equations of the current-circuit and the voltage-circuit that compose the synthetic circuit were deeply studied. Also the voltage drop across the triggered vacuum switch and across the test object were taken into consideration in order to get more realistic results. The triggered vacuum switch was tested on a test circuit in laboratory environment where results of voltage drop and time delay were found; however, the voltage drop across the load break switch was calculated theoretically, giving a positive result.

By having proper values for voltage drops it was possible to find several appropriate combinations of minimum values of resistance, inductance, and capacitance that make a satisfactory making operation possible.

The ending results were positive and showed that the making operation was made correctly for a load break switch rated for 24 kV with closing velocity from 1 to 5 $\frac{m}{s}$ and a triggered vacuum switch with time delay of 50 μs. The making current was in the range of 50 to 60 kA without any high-frequency crossing-zero points as expected.

5.2 Discussion

When testing the triggered vacuum switch in the laboratory, it was unreliable to measure the voltage drop across the triggered vacuum switch by direct connection of the voltage probe across it since the result showed several undesirable oscillations at the beginning of the arc. These oscillations could be either because of the triggering unit, which was connected to one side of the voltage probe, or because the voltage probe must have a reference to ground. That is the reason why it was opted to connect the voltage probe only to the anode flange of the triggered vacuum switch, and from that result, get the voltage across it by using a mathematical approach based on RLC circuit equations, the measured values of the current peak through the triggered vacuum switch, and the charging voltage of the capacitor. The value obtained was low and reasonable as expected, but a more realistic value can be obtained by connecting a voltage probe directly across the triggered vacuum switch.

During the same test, the transmitters were saturated when they reached 5 volts. This was not a problem at all for the transmitter connected to the current shunt since the current waveform reached around 50 amps; however, it was a deal for the transmitter connected to the voltage probe that measured the charging voltage of the capacitor. This is the reason the charging voltage of the capacitor was limited to 5000 volts since the voltage probe has a ratio of 1000V/1V. More accurate results could be obtained with a wider saturation rating range on the transmitters.

On other hand, it is possible to control the current peak by changing the tap position of the limiting reactance.

5.3 Recommendations for Further Work

An appropriate mechanism to synchronize high-current and high-voltage source is necessary. Synchronization part of the making test was only covered briefly in this thesis, so further experiments must be performed on this topic. A synchronization unit or control device for synthetic making test based on pre-arcing current detection, and phase control must be developed and built. This unit can be built by the electronic department.

Further experiments should be done by realizing the making test with different configurations on the transformer that is located on the current-circuit. It is important to choose the configuration that gives a greater voltage on the secondary side. The model of the voltage drop across the load break switch can also be improved either by selecting other parameters on the arc voltage equation designed by Hertha Ayrton or by selecting other appropriate models.

A possible extension to this work is to perform making tests by using different synthetic making circuit schemes. The usage of a series arrangement is a potential extension of this work since in this thesis it was opted to use a parallel arrangement. In addition to this, further investigations can be done to improve the performance of the making switch either by parallel-connecting a fast vacuum switching breaker to the triggered vacuum switch or by opting to give a chance to other types of devices designed for this purpose that are commonly available.

Appendix A

Current-Circuit Equation Development

The short-circuit current can be calculated taking this circuit as base:

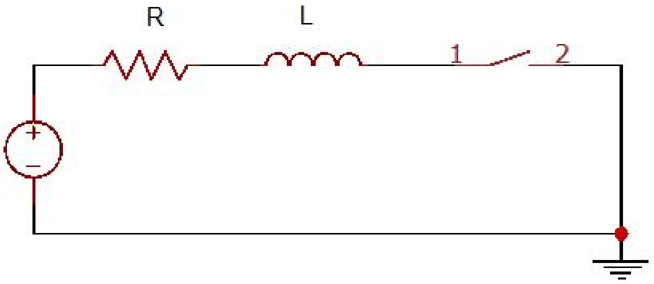

Figure A.1: Base circuit to calculate a short-circuit current

This circuit is a first-order circuit since there is only one energy storage element, therefore one initial condition exists which is:

$$i_L(t = t_{0-}) = i_L(t = t_0+) = 0 \tag{A.1}$$

Applying KVL to the circuit on figure A.1 the next equation is achieved

$$V_m \cdot \cos(w \cdot t) = L \cdot \frac{d}{dt} i_L + R \cdot i_L \tag{A.2}$$

Equation (A.2) is a differential equation and its solution is in this form

$$i_L^{AC}(t) = A \cdot \cos(w \cdot t) + B \cdot \sin(w \cdot t) \tag{A.3}$$

and deriving

$$\frac{d}{dt} i_L^{AC}(t) = -A \cdot w \cdot \sin(w \cdot t) + B \cdot w \cdot \cos(w \cdot t) \tag{A.4}$$

Replacing (A.4) and (A.3) on (A.2)

$$V_m \cdot \cos(w \cdot t) = L \cdot (-A \cdot w \cdot \sin(w \cdot t) + B \cdot w \cdot \cos(w \cdot t)) + R \cdot A \cdot \cos(w \cdot t) + B \cdot \sin(w \cdot t) \tag{A.5}$$

Comparing both sides of (A.5)

$$V_m = L \cdot B \cdot w + R \cdot A \tag{A.6}$$

$$0 = -L \cdot A \cdot w + R \cdot B \tag{A.7}$$

From (A.6) and (A.7) it is possible to know that $A = \frac{R}{L^2 \cdot w^2 + R^2} * V_m$ and $B = \frac{L \cdot w}{L^2 \cdot w^2 + R^2} * V_m$.

The complete response from a short-circuit current is

$$i_L(t) = i_L^{AC}(t) + K \cdot e^{-\frac{R}{L} \cdot t} \tag{A.8}$$

Inserting (A.3) into (A.8) with the values of A and B

$$i_L(t) = \frac{R \cdot V_m \cdot \cos(w \cdot t) + L \cdot w \cdot V_m \cdot \sin(w \cdot t)}{L^2 \cdot w^2 + R^2} + K \cdot e^{-\frac{R}{L} \cdot t} \tag{A.9}$$

For finding K, initial conditions on (A.1) are applied, therefore

$$K = -\frac{R \cdot V_m \cdot \cos(w \cdot t_0) + L \cdot w \cdot V_m \cdot \sin(w \cdot t_0)}{L^2 \cdot w^2 + R^2} \cdot e^{+\frac{R}{L} \cdot t_0} \tag{A.10}$$

Equations (A.9) and (A.10) are valid for $t > t_0$.

Appendix B

Voltage-Circuit Equation Development

The voltage-circuit is in charge of applying a rated voltage to stress the switching device before making operation and to supply the high-frequency current at the moment of breakdown of the contact gap. The Initial Transient Making Current (ITMC) can be achieved from a basic RLC circuit as follow:

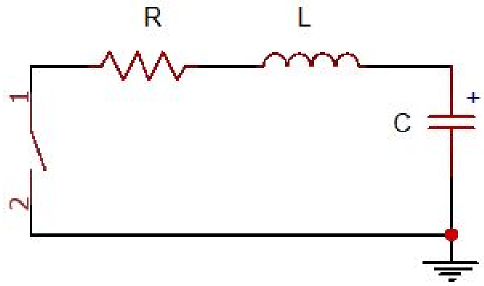

Figure B.1: Base RLC circuit to obtain a high-frequency current

This circuit is a second order circuit since there are two energy storage elements and therefore two initial conditions exist which are:

$$i_L(t = t_{0-}) = i_L(t = t_{0+}) = 0 \tag{B.1}$$

$$\frac{d}{dt} i_L(t = t_{0-}) = \frac{d}{dt} i_L(t = t_{0+}) = \frac{V_c}{L} \tag{B.2}$$

Applying KVL to the circuit on figure B.1 the next equation is achieved

$$R \cdot i + L \cdot \frac{d}{dt} i + \frac{1}{C} \int i dt = 0 \tag{B.3}$$

Deriving and multiplying times C

$$R\cdot C\cdot \frac{d}{dt}i + L\cdot C\cdot \frac{d^2}{dt^2}i + i = 0 \tag{B.4}$$

The solutions of the differential equation on (B.4) depends on the roots of

$$\alpha\cdot C\cdot R^2 + R\cdot C\cdot \alpha + 1 = 0 \tag{B.5}$$

The roots are

$$\alpha_{1,2} = \frac{-R\cdot C \pm \sqrt{(R\cdot C)^2 - 4\cdot L\cdot C}}{2\cdot L\cdot C} \tag{B.6}$$

If the term inside the radical is negative, then there are two complex conjugate solutions in the form of $\alpha_{1,2} = -\frac{R}{2\cdot L} \pm j\cdot w_d$ where $w_d = \frac{\sqrt{4\cdot L\cdot C-(R\cdot C)^2}}{2\cdot L\cdot C}$.

The solutions of the differential equation on (B.4) in this case is

$$i(t) = e^{-\frac{R}{2\cdot L}\cdot t}\cdot (A\cdot \cos(w_d\cdot t) + B\cdot \sin(w_d\cdot t)) \tag{B.7}$$

Finding A and B the initial conditions on (B.1) and (B.2) are replaced on (B.7). The result is $A = 0$ and $B = \frac{V_c}{L\cdot w_d}$. Thereby, equation (B.7) can be written as

$$i(t) = i_{hf}(t) = \frac{V_c}{L\cdot w_d}\cdot e^{-\frac{R}{2\cdot L}\cdot t}\cdot \sin(w_d\cdot t) \tag{B.8}$$

(B.8) being the governing equation of the high-frequency current when the term inside the radical on (B.6) is negative.

When the term inside the radical on (B.6) is zero, there is one real double solution in the form of $\alpha_{1,2} = -\frac{R}{2\cdot L}$. The solution for the differential equation on (B.4) is

$$i(t) = e^{-\frac{R}{2\cdot L}\cdot t}\cdot (A + B\cdot t) \tag{B.9}$$

Using initial conditions on (B.1) and (B.2) into (B.9) gives $A = 0$ and $B = -\frac{2 \cdot V_c}{R}$. For this reason (B.9) can be expressed as

$$i(t) = i_{hf} = -\frac{2 \cdot V_c}{R} \cdot e^{-\frac{R}{2 \cdot L} \cdot t} \cdot t \tag{B.10}$$

Equation (B.10) is the governing equation of the high-frequency current when the term inside the radical on (B.6) is zero.

When the term inside the radical on (B.6) is positive, two real and different solutions exist in the form of $\alpha_{1,2} = -\frac{R}{2 \cdot L} \pm w_d$ where $w_d = \frac{\sqrt{(R \cdot C)^2 - 4 \cdot L \cdot C}}{2 \cdot L \cdot C}$.

The solution for the differential equation on (B.4) is

$$i(t) = A \cdot e^{\alpha_1 \cdot t} + B \cdot e^{\alpha_2 \cdot t} \tag{B.11}$$

Using initial conditions on (B.1) and (B.2) into (B.11) gives $A = \frac{V_c}{2 \cdot L \cdot w_d}$ $B = -\frac{V_c}{2 \cdot L \cdot w_d}$; therefore equation (B.11) can be expressed as

$$i(t) = i_{hf} = \frac{V_c}{2 \cdot L \cdot w_d} \cdot e^{\alpha_1 \cdot t} - \frac{V_c}{2 \cdot L \cdot w_d} \cdot e^{\alpha_2 \cdot t} \tag{B.12}$$

Equation (B.12) is the governing equation of the high-frequency current when the term inside the radical on (B.6) is positive.

Equations (B.8), (B.10) and (B.12) are the three governing equations depending on the roots of (B.5).

Appendix C

Voltage Drop across the Triggered Vacuum Switch (Mathematical Approach)

The mathematical approach is based on a RLC circuit as shown in figure C.1

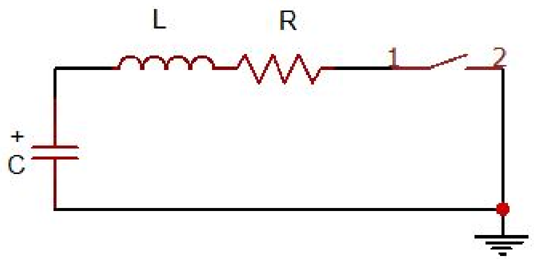

Figure C.1: Base RLC circuit to obtain a voltage drop across TVS

Applying KVL to the the circuit on figure C.1

$$\begin{aligned} V_L + V_R + V_{TVS} + V_C &= 0 \qquad (C.1) \\ \frac{d}{dt} i_L(t) = +R \cdot i_L + V_C &= 0 \qquad (C.2) \\ \frac{d^2}{dt^2} U_c + R \cdot C \cdot \frac{d}{dt} U_C + V_{TVS} + V_C &= 0 \qquad (C.3) \end{aligned}$$

The voltage across the capacitor is

$$U_C = (A \cdot \cos(w_d \cdot t) + B \cdot \sin(w_d \cdot t)) \cdot e^{-\frac{R}{2 \cdot L}} - V_{TVS} \tag{C.4}$$

where $w_d = \frac{\sqrt{4 \cdot L \cdot C - (R \cdot C)^2}}{2 \cdot L \cdot C}$. This circuit is a second order circuit since there are two energy storage elements and therefore two initial conditions exist which are:

$$\begin{aligned} U_C(t=t_{0-}) &= U_C(t=t_{0+}) = U_{charge} && \text{(C.5)}\\ \frac{d}{dt}U_C(t=t_{0-}) &= \frac{d}{dt}U_C(t=t_{0+}) = 0 && \text{(C.6)} \end{aligned}$$

Where = U_{charge} is the desired charging voltage of the capacitor. For getting A and B the initial conditions on (C.5) and (C.6) are replaced on (C.4). The result is $A = U_{charge} + U_{TVS}$ and $B = \frac{(U_{charge}+U_{TVS})\cdot R}{2\cdot L\cdot w_d}$.

From the circuit

$$\begin{aligned} i_L &= -i_C && \text{(C.7)}\\ (K_1\cdot\cos(w_d\cdot t)+K_2\cdot\sin(w_d\cdot t))\cdot e^{-\frac{R}{2\cdot L}} &= -C\cdot\frac{d}{dt}U_C && \text{(C.8)} \end{aligned}$$

Deriving equation (C.4) and inserting (C.8)

$$\begin{gathered} (K_1\cdot\cos(w_d\cdot t)+K_2\cdot\sin(w_d\cdot t))\cdot e^{-\frac{R}{2\cdot L}} = -C\cdot[(-A\cdot w_d\sin(w_d\cdot t)+B\cdot w_d\\ \cos(w_d\cdot t))\cdot e^{-\frac{R}{2\cdot L}}+(A\cdot\cos(w_d\cdot t)+B\cdot\sin(w_d\cdot t))\cdot e^{-\frac{R}{2\cdot L}}\cdot-\frac{R}{2\cdot L}] \end{gathered} \tag{C.9}$$

Inserting A and B and comparing both sides of equations can be found $K1$ and $K2$ which are

$$\begin{aligned} K1 &= 0 && \text{(C.10)}\\ K2 &= (U_{charge}+U_{TVS})\cdot\left[W_d+\frac{R^2}{(2\cdot L)^2\cdot w_d}\right]\cdot C && \text{(C.11)} \end{aligned}$$

Therefore

$$i_L = (U_{charge}+U_{TVS})\cdot\left[W_d+\frac{R^2}{(2\cdot L)^2\cdot w_d}\right]\cdot C\cdot\sin(w_d\cdot t))\cdot e^{-\frac{R}{2\cdot L}} \tag{C.12}$$

Notice that the current peak is equal to $K2$. The current waveform shown in figure C.2 was measured directly from the circuit with a current shunt. The waveform has an offset of 2 amps which has to be taken in consideration at the time of reading the current peak which is 49 amps. Now the only unknown remaining is U_{charge} which can be taken from the waveform on figure C.3 and its value is 4500 volts.

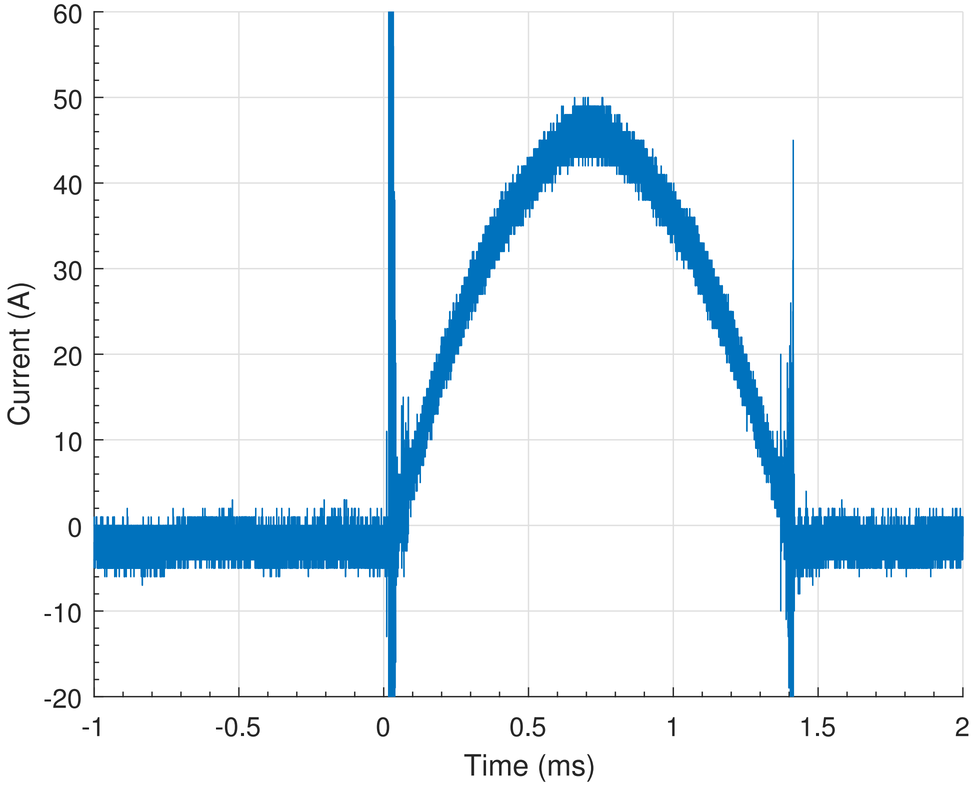

Figure C.2: Half cycle of a current waveform through the TVS in the test circuit.

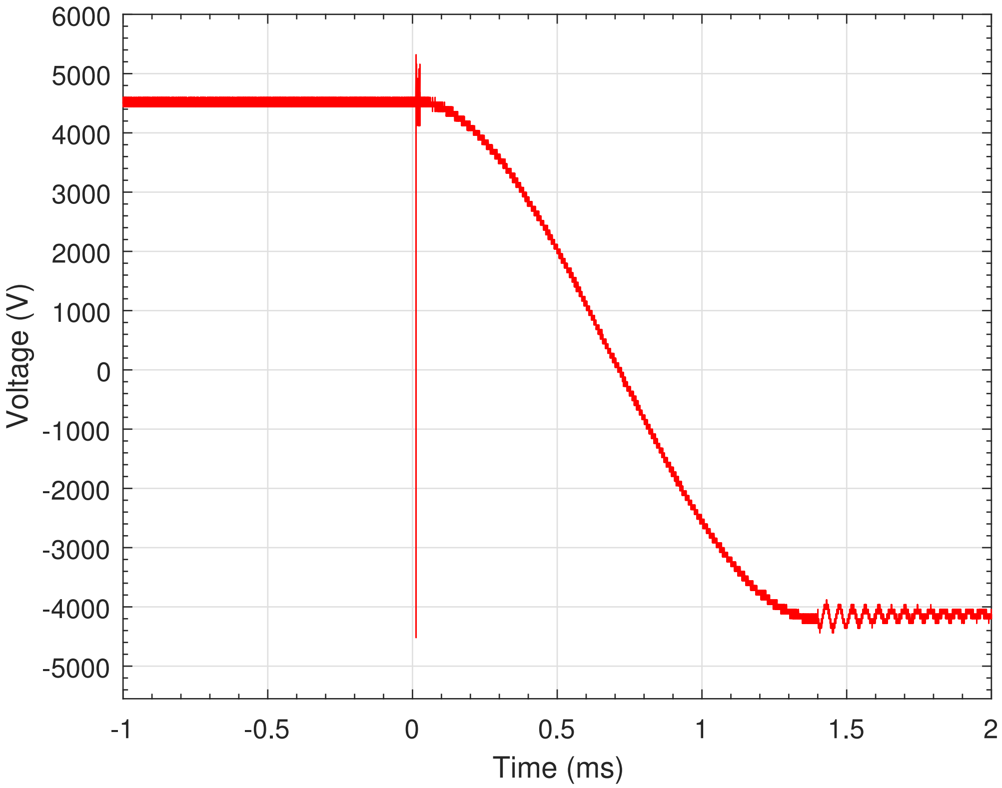

Figure C.3: Voltage waveform across the TVS in the test circuit.

Now it is possible to get U_{TVS} from equation (C.11) since the only unknown is precisely U_{TVS}. The value of the voltage drop across the triggered vacuum switch is then 49.16 volts which can be rounded to 50 volts.

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