Peik Korhonen

# Ensuring IEC 60947-3 Conformity: Impedance Profiling of Buck-Boost Transformers for Test Setup

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# Abstract


Author: Peik Korhonen


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The International Standards Organization has a conformity assessment system with a list of requirements for each testing laboratory operating under it. This thesis work investigated a laboratory's ability to meet a requirement related to a switch standard for a test setup that tests the switch's ability to make and break. At the test setup, the prospective short-circuit current of the source must be 10 kA while the voltage is +5% of the switch's rated value. The best solution to increase the rated voltage by +5% was to use voltage adjusters, of which the laboratory already had three. Technically, this voltage adjuster is a Buck-Boost transformer.

The thesis focused on measuring the impedance across the voltage adjuster and calculating what the prospective short circuit current would be at the test point. Information about the nature of a short circuit for this type of circuit did not exist previously. Three different methods were chosen for measuring impedance: using an LCR meter, measuring voltage drop across the load, and using an installation tester. The starting point for the short-circuit current was already available up to the room's 3-phase wall sockets, and this information could be used as a reference.

As a result of the measurements, it was observed that the voltage adjusters were constructed differently, preventing the use of multiple phases at the test setup. The impedance of the voltage adjusters proved to be too high to achieve a 10 kA short-circuit current. The existing data from the testing room wall sockets began to be questioned as well. Although the desired result was not achieved with the laboratory's current equipment, the generated data can be used for other testing purposes. Solutions for achieving compliance with the test setup’s requirements have also begun to be explored.



Keywords: Standards, Short circuit current, Buck-Boost Transformer, IEC 60947

## Tiivistelmä

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Kansainvälisellä standardointijärjestöllä on vaatimustenmukaisuuden arviointijärjestelmä, jossa on lista vaatimuksista jokaiselle testauslaboratoriolle, jotka toimivat heidän alaisuudessaan. Opinnäytetyö selvitti testauslaboratorion kykyä toteuttaa kytkinstandardiin liittyvää vaatimusta testipisteelle, joka testaa kytkimen kykyä avata ja sulkea piiri. Testipisteessä lähteen prospektiivisen oikosulkuvirran täytyy olla 10 kA samalla, kun jännite on 5 % kytkimen nimellisarvoa suurempi. Paras ratkaisu nostaa nimellisjännitettä 5 % oli käyttää jännitteensäätäjiä, joita oli jo kolme kappaletta olemassa laboratoriossa. Tämä jännitteensäätäjä teknisesti ottaen oli Buck-Boost-muuntaja.

Opinnäytetyö keskittyi mittaamaan impedanssin jännitteensäätäjän yli ja laskemaan tulosten perusteella, mikä testipisteen prospektiivinen oikosulkuvirta olisi. Tietoa tämän tyyppisen piirin oikosulkuvirran luonteesta ei löytynyt entuudestaan. Kolme eri tapaa valikoitui impedanssin mittaamiseksi. Impedanssia mitattiin LCR-mittarilla, jännitteen putoamisen mittauksella kuorman yli sekä asennustesterillä. Lähtökohta oikosulkuvirrasta löytyi jo valmiiksi huoneen kolmivaihepistorasioihin asti, tätä tietoa voitiin käyttää apuna. Työssä sivuttiin myös standardointijärjestöä, oikosulkulaskentateoriaa ja kytkinstandardin avaamis- ja sulkemistestauspisteen vaatimuksia.

Mittausten tuloksena huomattiin, että jännitteensäätäjät oli rakennettu kukin eri tavalla, mikä esti useamman vaiheen käytön testipisteessä. Jännitteensäätäjien impedanssi osoittautui liian suureksi saavuttamaan 10 kA:n oikosulkuvirtaa. Lopulta lähtötietoja, jotka oli saatu testaushuoneen pistorasiasta, alettiin myös epäilemään. Vaikka haluttuun tulokseen ei laboratorion nykyisellä kalustolla päästy, tuotettua dataa voidaan käyttää hyväksi muussa testaustarkoituksessa. Ratkaisua, miten testipisteen syöttö saadaan vaatimustenmukaiseksi, on alettu myös selvittämään.

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|---|---|
| Avainsanat: | standardit, oikosulkuvirta, Buck-Boost-muuntaja, IEC 60947 |

**Contents**

## List of Abbreviations

CB: Certification Body

CBTL: Certification Body Testing Laboratory

CTF: Customer Testing Facilities

EUT: Equipment Under Test

FINAS: Finnish Accreditation Service

IEC: International Electrotechnical Commission

IECEE: IEC System for Conformity Assessment Schemes for Electrotechnical Equipment and Components

NCB: National Certification Body

## 1 Introduction

SGS Fimko Ltd is a testing and certification company that works under the International Electrotechnical Commission (IEC) System for Conformity Assessment Schemes for Electrotechnical Equipment and Components (IECEE). The IECEE is a system established by the IEC [1]. SGS Fimko has multiple testing laboratories and one of them is located in Takomotie 8, Helsinki. The laboratory in Helsinki has approximately one thousand standards in its IECEE Certification Body (CB) test and CB certification scope [2]. To obtain a standard within the CB scope, the IECEE assesses the laboratory's adherence to the standard, ensuring that personnel are experienced with it and capable of conducting all the required tests. The IECEE provides an equipment list for each standard, specifying the requirements for testing facilities and equipment in the testing laboratories that conduct tests according to the CB scheme. Some of the tests IECEE allows to be outsourced to another laboratory. Once the laboratory meets these criteria, it can test products according to the CB scheme and provide customers with CB certificates if their products align with the standard's requirements. [3.]

One standard that SGS Fimko has in the CB test scope is IEC 60947-1 *“Low-voltage switchgear and controlgear - Part 1: General rules”* [4] and its substandard IEC 60947-3 *“Low-voltage switchgear and controlgear - Part 3: Switches, disconnectors, switch-disconnectors and fuse-combination units”* [5]. Even though this standard is in the CB scope, some of the required tests cannot be carried out in the Takomotie’s laboratory and need to be done at an external laboratory, for example in a Customer Testing Facility (CTF). One of these tests that cannot be currently done in Takomotie’s laboratory site is related to the breaking and making capacities of switches. It is not desirable to conduct these tests in Takomotie since the full adjustable implementation of the test setup would be a very time-consuming project that would represent a significant financial investment. To keep personnel trained on testing according to the IEC 60947-3 and to demonstrate competence to customers, it would be important to have a single test setup for one type of switch that is fully built according to the IEC 60947-3 equipment list.

According to the IEC 60947-3 equipment list, the test setup for all switches rated up to 1 kA shall provide a 10 kA prospective short circuit current [6,2]. In addition to that, the voltage must be +5% of the switch's nominal voltage [5]. Switches are commonly rated for 230 V, 400 V, and 440 V, as these are widely used voltages. Because they are widely used voltages the lab is designed so that those voltages are obtained from the building's primary transformer. Therefore, the voltage must be increased before feeding it to the test setup. To raise the voltage while maintaining a high short circuit current, the best option was evaluated to be voltage adjusters. They are rated for 63 A and there is no galvanic isolation, therefore it was assumed that the impedance over them is the smallest out of all the available options.

This thesis focuses on finding the impedance of the buck-boost transformer and evaluating if the 10 kA short circuit current can be reached. The ideal outcome would be to determine that the test setup can be constructed using the laboratory's existing equipment without requiring additional investments. Three different methods of measuring impedance were studied and employed to determine the impedance. Additionally, these methods were compared to each other.

# 2 Understanding the Standard and Organizational Context

## 2.1 Being a CB Testing Laboratory in the IECEE

The IEC is a global non-profit organization, and its mission is to promote international co-operation on questions concerning standardization and conformity assessment. To further address this mission, the IEC has established four different conformity assessment systems. The IECEE is one of them and it is the conformity assessment system for electrical goods and components. The system is built upon mutual recognition of test results by its members to obtain certifications and approvals at the national level around the world. One of its slogans is "One test, one certificate" which sums up well the goal of the IECEE [1]. When selling products, compliance with the legal requirements is crucial. Testing and certifying a product instil confidence in its adherence to legal requirements. For many countries, it is necessary for an electrical product to be certified.

Accreditation for a testing laboratory means that it has been officially recognized by an accreditation body as competent to perform tests according to specific standards for which accreditation is sought. This recognition confirms that the laboratory meets the requirements for technical competence, impartiality, and reliability in conducting tests. Accreditation assures customers and regulatory bodies that the laboratory's test results are accurate and reliable. For a testing laboratory this means being recognized for its testing services and for a National Certification Body (NCB) it means being recognized for its certification services. [3.]

The Finnish accreditation organization is named “Finnish Accreditation Service” (FINAS). It operates under the Finnish Safety and Chemicals Agency which is administered by the Finnish Ministry of Labor and Economy. The testing laboratory of SGS Fimko in Takomotie is ISO/IEC 17025 ("General requirements for the competence of testing and calibration laboratories") accredited by FINAS [7]. SGS Fimko is also recognized IECEE CB testing laboratory (CBTL). Accreditation is not mandatory for an NCB or CBTL conducting CB scheme testing but it can be part of the IECEE assessment and will help a testing laboratory that is trying to join the IECEE. FINAS accreditation is a crucial quality assurance when other than CB-testing is conducted.

CB testing laboratories test products and verify that they fulfil the requirements of the relevant IEC standards, while NCBs then can certificate the products based on the test reports produced by the CB testing laboratories. CB testing laboratory operates under an NCB and the NCB is responsible for its actions. In the context of CB-testing, the IECEE’s peer assessment program holds great importance as it is mandatory to be part of it for a CB testing laboratory. Peer assessment program involves audits that are carried out by members of other CB testing laboratories and NCBs. Peer assessment program is meant to build confidence among its members leading to mutual recognition and raising the level above the ISO/IEC 17025. It uses those standards to evaluate but also several other IECEE’s own rules and procedures. To ensure the capability to carry out testing according to IEC 60947-3 also in the future and to better serve our customers, the test setup for the making and breaking capacities needs to be rebuilt. [3.]

## 2.2 Customer Testing Facilities (CTF)

A CTF is a customer’s testing facility used by the NCB to test specified products. The CTF concept applies only to IECEE-related work. The testing facility has to comply with part of the requirements of ISO/IEC 17025, but the CTF does not need to be accredited. NCB or CB testing laboratory obtains the test data that are developed by the customer. Because the CTF operates under the NCB, the NCB is responsible for its actions. The responsibilities include ensuring that all personnel witnessing or performing the testing are competent and several other demands. [8.]

There are four different CTF stages. The stage of the CTF represents the trust from the NCB to the CTF and the higher stages give more flexibility to the CTF. For example, in CTF1, which is the lowest level, the testing is carried out 100% by the CB testing laboratory personnel in the client's facilities but in CTF3 only selected parts of each testing project are witnessed in the client's facilities, so that the client's personnel carry out the testing. In figure 1 there is a short description of all four stages. CTF is audited every year by CTF auditors and the testing in the CTF laboratory shall be at the same quality level as in CB testing laboratory. [8.]

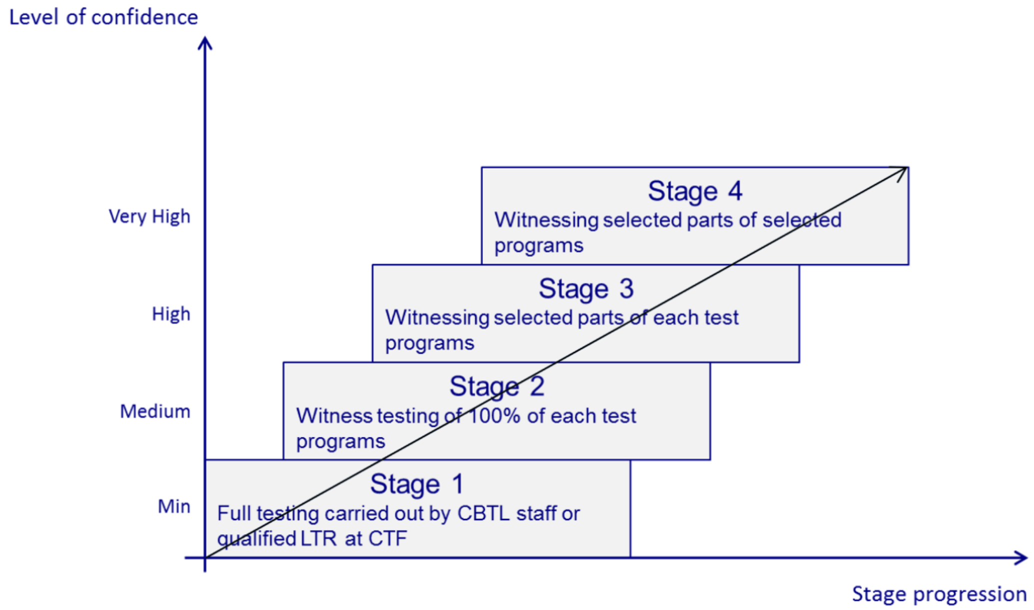


Figure 1. CTF stages [OD2048, s5]

### 2.3 IEC 60947-3 Switch's Making and Breaking Capacities

#### 2.3.1 Switch Categories

IEC 60947-3:2008 Cl 8.3.3.3 making and breaking capacities state a test that tests a switch's ability to close and open under specified conditions [5]. Breaking means opening the switch and making closing it. In this thesis, when referring to switches, switch disconnectors are discussed. A switch disconnector is a switch but with proper isolation and is therefore used in high power applications where it is necessary to manually do maintenance work [9]. In figure 2 there is the distinction between the switch and switch-disconnector symbols.

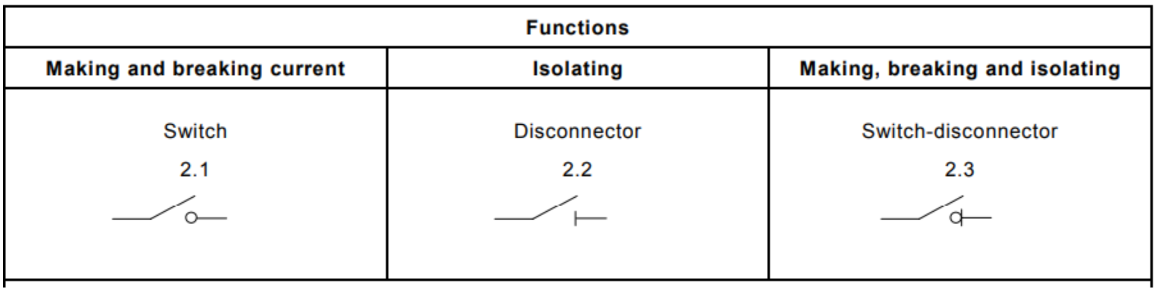

Figure 2. Distinction between switch disconnector and switch symbol [5,11]

Switches have various categories that indicate which kind of application they can be used for.  AC-23 for example is a switch category that can be used in very inductive circuits like a generator circuit, where the inductance can generate large electrical transients when a change happens to the circuit. Switches can have more than one AC rating but with different electrical ratings for each category. For example, a switch disconnector might have an AC-22 rating with 400 V, 125 A and an AC-23 rating with 400V, 90 A. Switches can also have ratings for DC conditions, but for the purposes of this thesis, those will not be considered [5,15].

### 2.3.2 Requirements for Testing Making and Breaking Capacity

The equipment list provided by the IECEE for IEC 60947-3 specifies that to test the making and breaking capacities, the laboratory must have a required capacity of 10 kA at the power supply point of the test table [4]. This thesis aims to investigate the feasibility of meeting this requirement. The test values for the test are drawn from the IEC 60947-3 clause 7.2.4.1, table 3 which can be seen in figure 3. It shows that the making and breaking current change significantly depending on the switch category. For AC-23 rated switches the making capacity is 10 times the operational current and for the AC-22 only 3 times higher. In table 3, there is also the requirement for raising the voltage by 5% of the switch’s nominal voltage. Currently, this is the hardest requirement to accomplish while still maintaining the 10 kA short circuit current in the test setup with the available equipment. [5,20.]

| Utilization categories | Rated operational current | Making [a] | | | Breaking | | | Number of operating cycles [c] |
|---|---|---|---|---|---|---|---|---|
| | | $I/I_e$ | $U/U_e$ | cos $\phi$ | $I_c/I_e$ | $U_r/U_e$ | cos $\phi$ | |
| AC-20A [b] – AC-20B [b] | All values | – | – | – | – | – | – | |
| AC-21A – AC-21B | All values | 1,5 | 1,05 | 0,95 | 1,5 | 1,05 | 0,95 | 5 |
| AC-22A – AC-22B | All values | 3 | 1,05 | 0,65 | 3 | 1,05 | 0,65 | 5 |
| AC-23A – AC-23B | $0 < I_e \leq 100$ A | 10 | 1,05 | 0,45 | 8 | 1,05 | 0,45 | 5 |
| | $100 \text{ A} < I_e$ | 10 | 1,05 | 0,35 | 8 | 1,05 | 0,35 | 3 [d] |

$I$ = making current
$I_c$ = breaking current
$I_e$ = rated operational current
$U$ = applied voltage
$U_e$ = rated operational voltage
$U_r$ = operational frequency or d.c. recovery voltage

[a] For a.c. the making current is expressed by the r.m.s. value of the periodic component of the current.
[b] The use of these utilization categories is not permitted in the USA.
[c] One switching operation without current between each making and breaking operation is allowed, providing it does not alter the time interval between the prescribed operations as defined in 8.3.3.3.1.
[d] In order to cover both AC-21 and AC-22 categories, an increase in the number of operations for AC-23 from 3 to 5 is allowed with the agreement of the manufacturer.

Figure 3. Extract of the table 3 from IEC 60947-3 Cl 7.2.4.1 [5,20].

In table 3 the AC-23 switches have different make and break values, unlike the other switch categories. Because the test current for making and breaking is the same for other than AC-23 categories, it is easy to test the make and break capacity for them in one take since the load does not need adjustment, but for AC-23 switches the load has to be adjusted between the tests if make and break capacity is wanted to be tested in one take. The table 3 also states that the number of make-break operating cycles and the Cl 8.3.3.3 states that the time interval between the close-open cycles is 30 s ± 10 s. The switch needs to be in the closed position only for a period long enough to let the switching operation be completed, the test current value to be established and allow the moving parts to stop. [5,35.]

The test circuit for the test setup is given in the IEC 60947-1 Cl 8.3.3.5.2 and it has 4 different circuits from single-pole equipment to four-pole equipment. The test circuit consists of a supply source, Equipment Under the Test (EUT) and the load circuit. It is specified that the load circuit must consist of resistors and air-cored reactors in series. The air-cored reactors in any phase also must be shunted by resistors, taking approximately 0.6% of the currents that flow through the reactor. Shunting essentially means just placing the resistor in parallel with the coil in means of installation. [4,93.]

Figure 4 shows the simplest test circuit for a single pole switch. Standard states that the circuit must be grounded only from one point, with all other components typically linked to the protective earth in the EUT, such as the enclosure, being insulated from it. During the test, a metallic screen, e.g., metallic woven wire mesh is placed on top of the switch in all the places that are likely to be a source of external phenomena capable of producing a breakdown. The fusible element F in the circuit is called a detecting circuit and it is there for the detection of the possible breakdown of material during the test. The fault current limiting resistor in the circuit is used to adjust the fault current to 1.5 kA unless otherwise specified. Standard recommends using a copper wire 0.8 mm in diameter that is at least 50 mm long as the fusible element. If the fusible element is blown, the switch's material is not sturdy enough and the test fails. [4,93-94.]

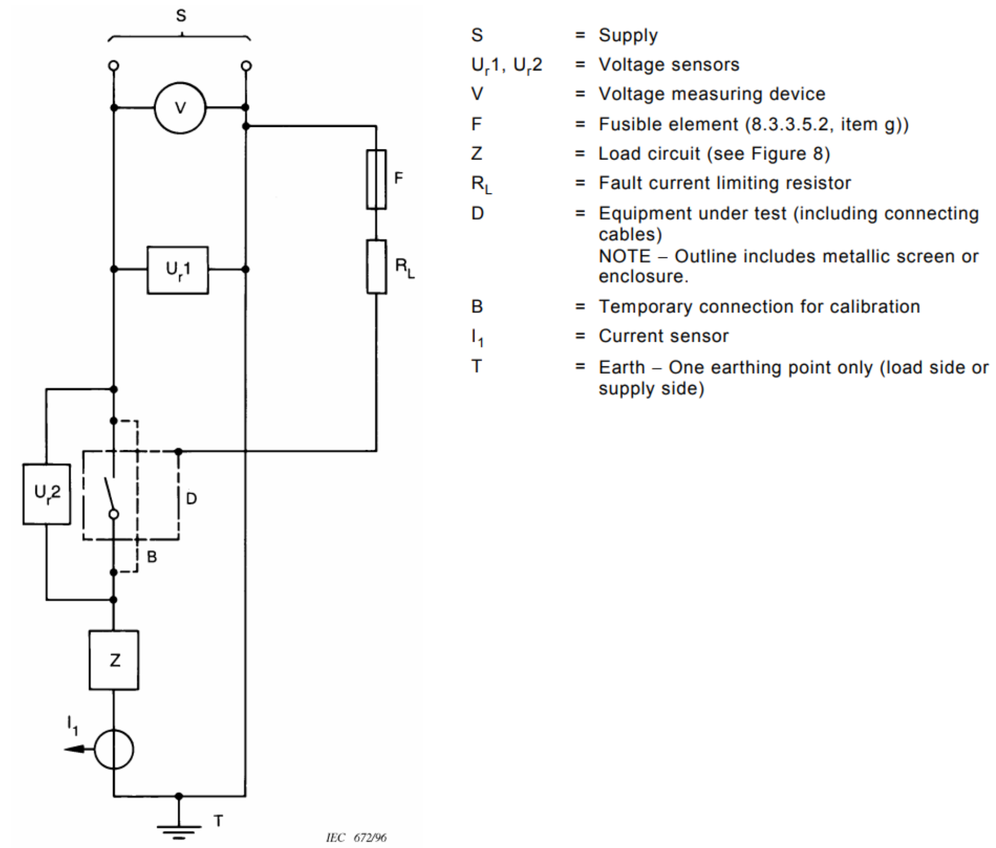


Figure 4. Circuit diagram for testing the making and breaking capacity for single pole equipment on single phase AC or on DC [4,121].

For AC-22 and AC-23 switches, after opening the switch, a transient recovery voltage must be applied to the circuit. It simulates the conditions of inductive circuits like motor loads. The frequency of the recovery voltage depends on the breaking current and rated operational voltage. The circuit for that purpose also has capacitors and resistors parallel to the reactors for adjusting the frequency. IEC 60947-1 Annex E presents two different ways of adjusting the load circuit. For training purposes, this kind of setup needs more planning and investing than a simpler setup like in figure 4. [4,93-95.]

# 3 Test Point Analysis

## 3.1 Test Place of Choice

The test room 227/228 was chosen for the possible test setup. In the test room 227/228 there are programmable robotic tables that are used to test plugs and couplers like appliance inlets. The test setup needs a robotic actuator to open and close the switch and therefore it was the only choice. Other benefits of the room are that it has a digital interface for controlling the supply voltages, high available output current up to 125 A, and programmable loads that could be used in the test bench to control the current. Figure 5 shows the interface and the wall sockets of test room 227/228.

When the testing room was built short circuit calculations were calculated by a company in the electrical industry called PJC. PJC used Siemens Simaris design software to calculate the approximations for minimum and maximum impedances and different fault currents, as such as three-phase short circuits and L-N short circuits. PJC handed the results from the Simaris design in Excel form. The extract of the results can be seen in Appendix 1 table 3. These calculations are used as base information and as an aid when calculating the test bench short circuit current.

Figure 5. Testing room 227/228 125 A wall sockets and the control interface

## 3.2 Transformer Circuit Analysis

In the test room 227/228 there are three voltage adjusters ordered from Watford. These devices are buck-boost transformers with a variable transformer to adjust the voltage. The voltage adjusters comprise an autotransformer with a voltage tap to lower input voltage which then goes into a variable transformer that is wired as an autotransformer [10]. The variable transformer includes an autotransformer with a center tap and a brush, manually adjustable via a wheel located on top of the transformer.

An additional winding, positioned adjacent to the input-output winding, exists between the center tap and the brush. The magnitude of voltage and its polarity depends on the brush position, inducing voltage into the input-output winding. This way the voltage adjuster's output can be altered between ±15% of the input voltage. The voltage adjuster utilizes a three-phase cable and connector, where two lines remain connected directly from input to output, while only one line passes through the voltage adjuster. Adjusting two or three phases requires the use of additional voltage adjusters.

The voltage adjuster has a measuring circuit that is used to measure voltage, current, and frequency. It also has a varistor between the output and neutral for overvoltage protection and circuit breakers on the output and neutral line for overcurrent protection. The schematic of the voltage adjuster is in figure 6.

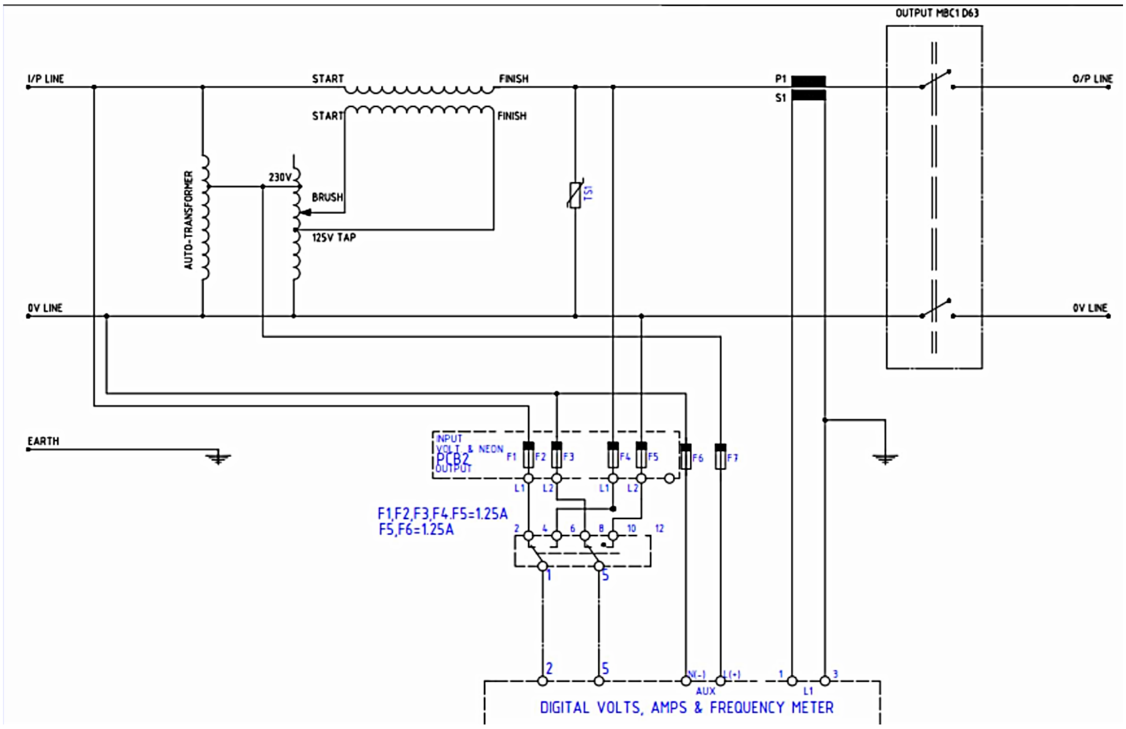


Figure 6. Voltage adjuster schematic

No information was found on how this kind of circuit would behave in a short circuit situation so presumptions must be made. Because the input-output is not isolated but in galvanic connection, it is assumed that in a short circuit the input-output impedance would be just the reactance of the winding being the same as the reactance of a coil while only a small portion would go through the adjustment circuit. Reactance of a coil is expressed as:

$$X_L = \omega L \tag{1}$$

$\omega$ is the angular frequency. It defines the duration of one complete cycle of the signal. $2\pi$ in radians is one complete period of a signal. The duration of one period is dependent on the frequency $f$ and therefore the angular frequency is expressed as:

$$\omega = 2\pi f \tag{2}$$

In practice, coils have parasitic components, and the impedance can be better described as the circuit in figure 7. Coil’s conductor is a long wire and therefore it has resistance as well. Coils also have capacitance between each loop of wire wrapped around the transformer's iron or ferrite core. The reactance that the capacitance forms at low frequencies like the mains frequency of 50 Hz is negligible and can therefore be ignored [12,13].

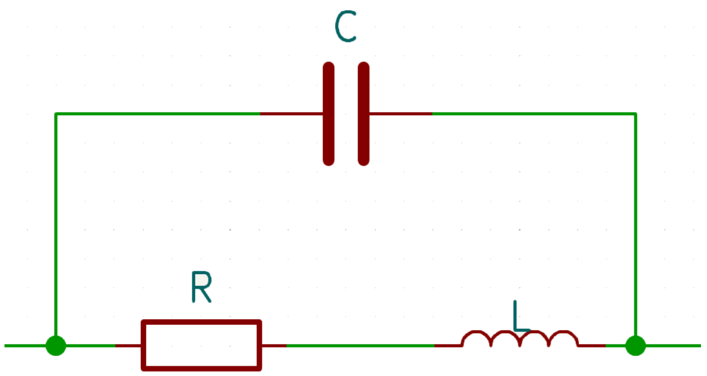


Figure 7. Coil with its parasitic components

# 4 Short Circuit Calculation Theory

## 4.1 Overview

When estimating short circuit currents, there are several different methods for calculating them. Short circuit calculation has many changing variables and therefore requires precision. Software that are designed specifically for calculating short circuit currents are used in the industry, e.g., Simaris design that PJC used. They provide reliable and consistent estimations that are faster to make and have smaller room for error than calculating by hand. Short circuits are commonly termed as “faults” since they are unintended and undesirable in electrical networks.

A common calculation method is presented in IEC 60909-0 utilizing Thevenin theorem and symmetrical components, which this thesis does not go into explaining [12,13]. The method is applicable up to 230 kV and the standard introduces a way to calculate minimum and maximum short circuit current. Using symmetrical components sometimes might be even required for instance when phase-to-earth short circuit current must be calculated, it requires the use of a zero-sequence component that is introduced in symmetrical component theory. [12,25.]

Calculation of short circuit current using the impedance method can be used to calculate short circuit currents at any point of an installation with good accuracy. The impedance method can be considered an easier approach to implement mathematically than the IEC 60909 method which is harder to use without a software tool. There are various formulas for calculating the short circuit impedances for various parts in the system like rotating machines. All impedances up to the fault point are added together and the total impedance is then calculated. Short circuit current then is calculated by simply using Ohm’s law: [12,12.]

$$I = \frac{U}{\Sigma(Z)} \tag{3}$$

where,
*I* is the current,
*U* is the voltage,
*Z* is the impedance

## 4.2 Fundamental Concepts and Principles in Short Circuit Analysis

When a short circuit happens, it usually consists of more than one component and the root means square value of it keeps changing until it reaches a steady state. How the current evolves depends mostly on how far the fault location is from a generator. Hence, a distinction between "fault away from the generator" and "fault near the generator" can be made. The distance is not the physical distance from the generator but the relation between the impedance of the generator and the link impedance to the fault location. In power distribution networks, the situation is typically characterized to be fault near the generator, where the impedance is predominantly inductive. In both of these instances, there is not a clear boundary, yet this defined line makes it easier to distinguish between them, particularly in scenarios involving faults away from the generator, where fewer factors are to be considered. In the test setup where there is the voltage adjuster and additional wiring, the link impedance will most likely be high enough to classify as fault away from the generator scenario although it does not matter since only the steady state short circuit current was of interest. [12,9.]

Transient conditions in fault away from the generator are a result of a voltage applied to an inductor-resistor circuit. The fault current *i* consists of a periodical component $i_a$ and an aperiodical component $i_{dc}$ which both can be seen in figure 8. Fault near the generator consists of three alternating components subtransient, transient and steady-state and one decaying aperiodical component, all seen in figure 9 [12,12]. The transient conditions in power distribution primarily rely on the synchronous machines. These machines have low reactance at the start of the fault, but the reactance rises gradually when time goes on. [13,172.] The term steady state current means a state where all transients have vanished [12,9].

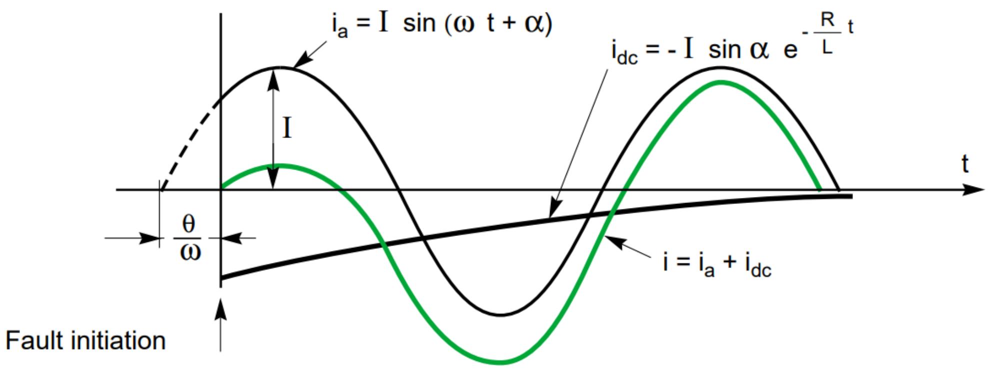


Figure 8. Graphical presentation and decomposition of a short-circuit current occurring away from the generator [12, 9].

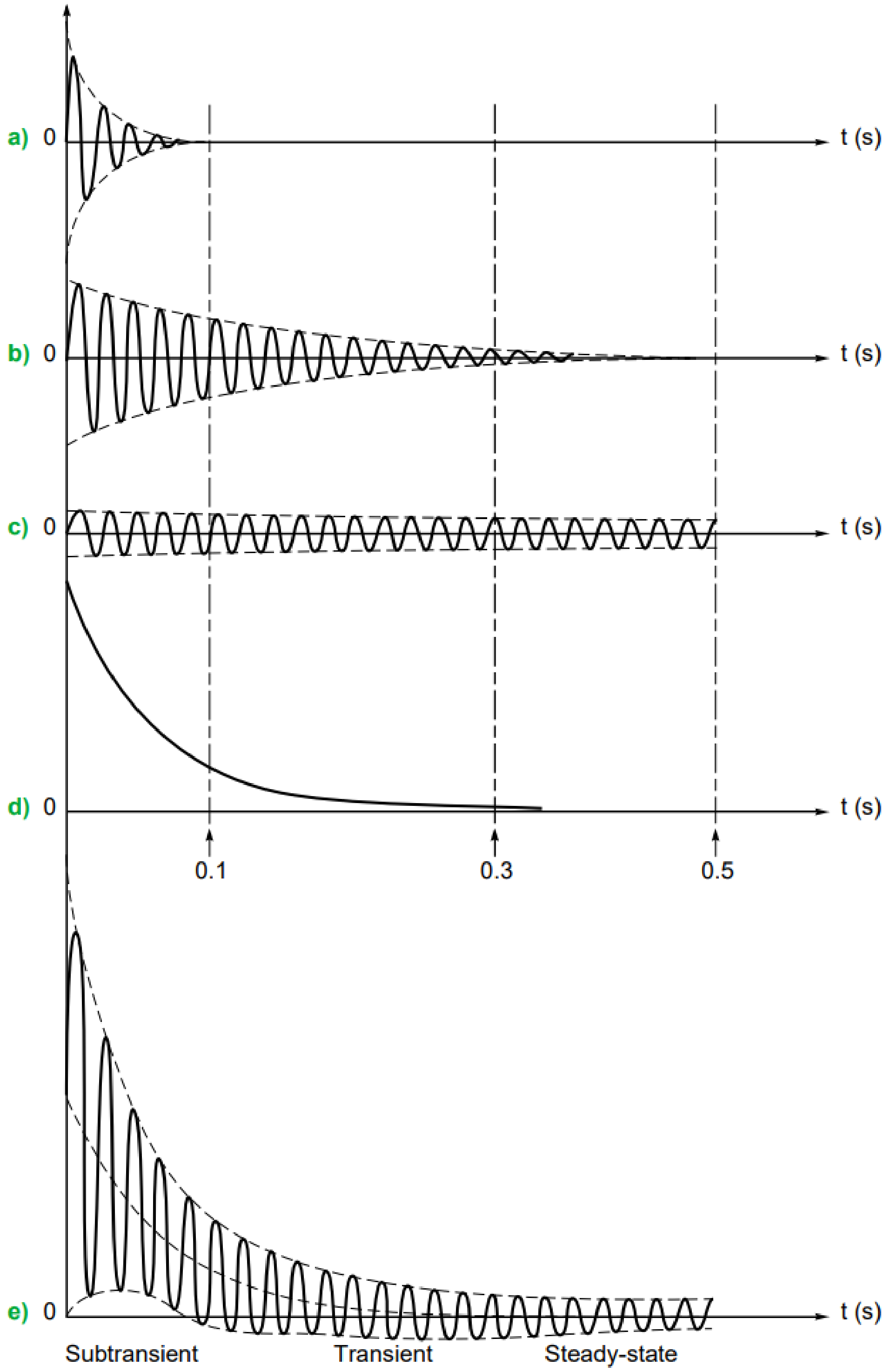


Figure 9. Graphical representation of unsymmetric fault near the generator and its different components, where
a) Subtransient, b) Transient, c) Steady state, d) aperiodic component, e) total short circuit current [12, 11].

The moment the fault takes place is defined by its timing in relation to the network voltage known as the closing angle α. Therefore, the voltage is expressed as [12,9]:

$$u = E\sin\left(\omega t + \alpha\right) \tag{4}$$

The short circuit current is expressed as [12,10]:

$$i = \frac{E}{Z}\left[\sin(\omega t + \alpha - \varphi) - \sin(\alpha - \varphi)\, \mathrm{e}^{\frac{\mathrm{R}}{\mathrm{L}}t}\right] \tag{5}$$

where,

*E* is the peak voltage value

*Z* is the impedance

*ω* is the angular frequency

*t* is the time

*α* is the closing angle

*φ* is the phase angle

*R* is the resistance

*X* is the reactance

Impedance and phase angle are derived from resistance and reactance. Impedance is expressed as:

$$Z = \sqrt{R^2 + X^2} \tag{6}$$

Phase angle the impedance forms:

$$\varphi = \arctan\left(\frac{X}{R}\right) \tag{7}$$

The first component in the brackets is the sinusoidal alternating component with a shift equal to *φ* with respect to the voltage and the second aperiodic decaying to zero as the *t* approaches infinity. In figure 10 two extreme cases can be seen where the *α* is equal to *φ* in the case of a symmetrical short circuit and where the α is equal to 0 where the peak is at its highest. When the *α* = *φ* ≈ *pi/2* the *α* and *φ* cancel each other, hence no aperiodic component and the peak value is just *E/Z* This kind of short circuit is said to be symmetrical. In the asymmetrical fault where there is the aperiodic component, the highest peak is reached when the *α* equals 0. The initial value is always considered to be *i*=0 when *t*=0. [12,10.]

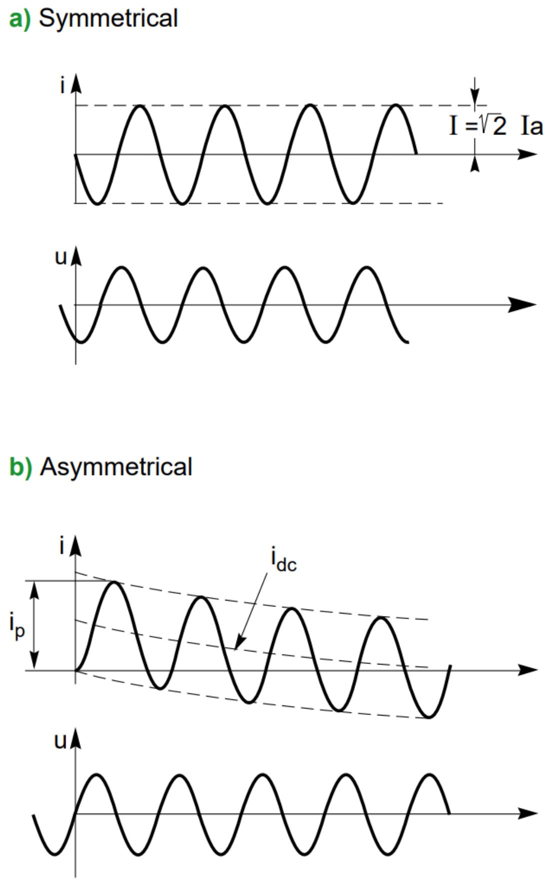


Figure 10. Symmetrical and asymmetrical fault [12,10].

The equipment list is only interested in the steady state of the short circuit and therefore the aperiodical component and transients can be ignored. Usually when calculating the short circuit currents calculating the peak current is essential for rating the components in the system to withstand the peak currents.

## 4.3 Short Circuit Calculations Using the Impedance Method

Two different short circuit currents were of interests for the test setup. Three-phase short circuit if all three voltage adjusters could be used and phase–neutral if only one could be used. A three-phase short circuit is a scenario that involves all phases and usually produces the highest current. Three-phase short circuit current $I_{sc3}$ is equal to [12,14]:

$$I_{sc_3} = \frac{U/\sqrt{3}}{Z_{sc}} \tag{8}$$

Phase to neutral short circuit current $I_{sc1}$ is equal to [12,15]:

$$I_{sc_1} = \frac{U/\sqrt{3}}{Z_{SC}+Z_{Ln}} \tag{9}$$

where,

$U$ = Phase-to-phase no-load voltage that is usually 3-5% higher than the on-load voltage

$Z_{SC}$ = Impedance of the phase

$Z_{Ln}$ = Impedance of the neutral conductor

Transformers and generators experience a voltage drop when connected to a load, and the voltage without the load is used in calculating short circuit currents. Measuring the open circuit voltage can be difficult in an electrical network and usually, the calculations are done before the network is built. Hence, the approximations of the expected no-load voltages are used [14]. In the case of the test room 227/228, the no-load voltage can be measured with a multimeter, which is why in chapters 7.1 and 7.2 where the short circuit current is calculated the 3-5% factor is not considered. Dividing the phase-to-phase voltage by the square root of three provides the voltage between L-N. Consequently, the L-N voltage is directly used in the calculations.

# 5 Finding the Impedance of the Test Setup

## 5.1 Used Impedance Measurement Methods

Three different methods were employed to measure the impedance of the voltage adjuster. The methods employed included LCR-meter measurement, measuring the voltage drop over an upstream impedance, and using an installation tester. The selection was made based on the availability of measurement equipment. In the voltage drop measurement and installation tester measurement, where the voltage needed adjustment, a 242 V L-N voltage (+5% of the 230 V nominal voltage) was employed. Voltage adjusters are labelled as voltage adjuster A, B and C.

Before measuring the overall impedance, the resistance of all three voltage adjusters was determined using a mΩ-meter, results are in the Appendix 2 table 4. The reason for this was just quickly to see how the voltage adjusters compare to each other. The expectation was that the resistance should be approximately the same on all of them since there was a request made to the supplier for uniformity. Voltage adjusters were found to be internally connected in different ways, with differing wire lengths and transformer sizes, resulting in distinct impedance profiles. Only voltage adjuster B was studied with all the measurement methods. After measuring the impedance of voltage adjuster B, if there had been any doubt that the 10 kA could have been achieved with another voltage adjuster, it would have been studied.

### 5.1.1 LCR- and mΩ-Meter

For the LCR measurement, the Agilent 4263B LCR meter was used. LCR meter feeds AC-signal through the EUT and analyses the resistance, capacitance and inductance. Based on those parameters it then calculates the impedance. AC-signal frequency can be altered. Since the reactance is frequency dependent, the frequency will change the impedance. The voltage adjuster's input-output winding is assumed to be mostly inductive, and the expectation is that when the frequency increases by a multiple of ten, the impedance also increases by a multiple of ten. The optimal AC signal for the measurement would be 50 Hz since it is the same as the network frequency but since 100 Hz is the lowest frequency the LCR meter could feed it was used. [15,12-19.] Like he LCR meter the mΩ meter feed signal but it is DC through the EUT and calculates the resistance. For both instruments the test leads that are used must be zeroed so that they do not affect the result.

### 5.1.2 Voltage Drop Measurement

To measure the entire upstream impedance, one method involves calculating the voltage drop across it when connected to a load. Voltage after the voltage adjuster is set to be 242 V (230 V * 1.05) without the load. The voltage without the load is recorded for about 30 readings with 10-second intervals between each and the average of it is taken. Then the load is switched on and the same number of readings with the 10-second interval is taken from the same point. The voltage drop is calculated as the difference between the no-load and loaded measurements.

Two ways of calculating the upstream impedance when the voltage drop is known can be used. The first method requires measuring the impedance of the load to ascertain its value and the other method just measures the current. When the load's impedance is known the upstream impedance can be calculated using the voltage divider rule [11,43]. The voltage divider formula can be manipulated to a form where the $Z_1$ which is the impedance of the voltage adjuster, and the upstream network are found in the following way:

$$U_2 = \frac{Z_2}{Z_2+Z_1} * U \tag{10}$$

$$Z_1 = \frac{Z_2 * U}{U_2} - \frac{U_2 * U * Z_2}{U * U_2} \quad (11)$$

where,

$Z_1$ represents the impedance of the voltage adjuster and upstream network

$Z_2$ represents the load's impedance

$U$ is the voltage between L-N

$U_2$ is the voltage drop over the load

The second method is perhaps the simplest way to determine the impedance. Measuring the current and the voltage drop over Z1 enables to determine the impedances using Ohm's law (3). Because the current measurement is easier to execute, it is selected as the method of choice. Current measurement is done using a current clamp. The load is rated for 40 A in continuous use. Using as small as possible load resistance is desirable. Decreasing the load resistance results in an increase in both the current and the voltage drop across the upstream. Amplifying the measured current decreases the measurement uncertainty. The load circuit is adjusted so that approximately 40 A is running through it. The simplified test setup circuit diagram can be seen in figure 11.

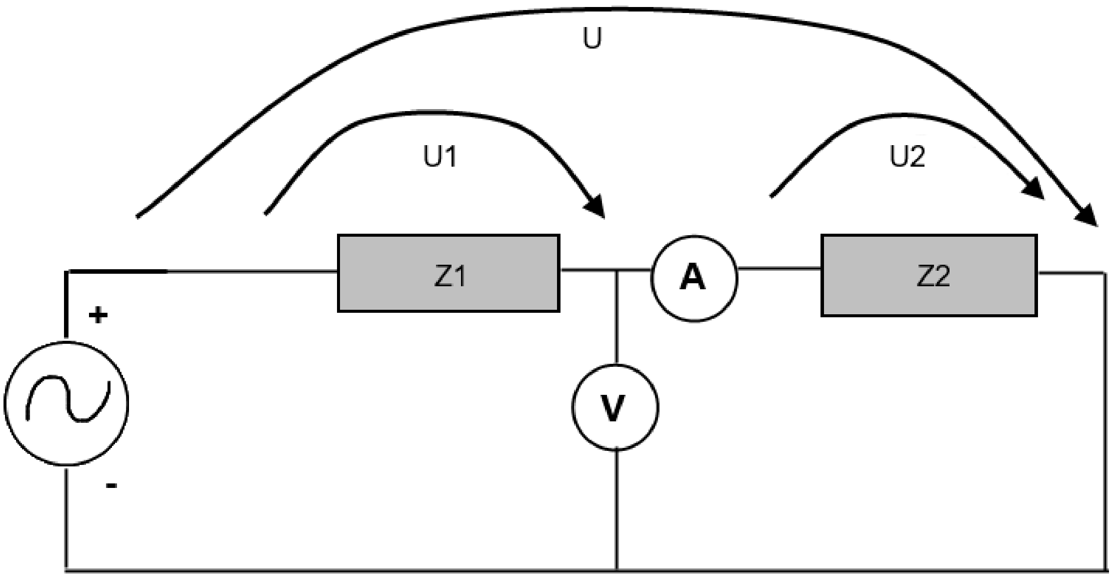


Figure 11. Simplified circuit diagram of the voltage drop measurement.

### 5.1.3 Installation Tester

A Fluke 1664 FC installation tester was used to measure the impedance of the system. An installation tester is a measurement device that can be used for many different measurements, e.g., Residual Current Device's (RCD) tripping time, voltage, frequency and earth resistance. It can also be used to measure loop and line impedances and based on those the tester calculates the continuous short circuit current. Loop impedance is the L-PE and line impedances L-N and L-L. A three-phase short circuit cannot be measured with the installation tester. There are two different impedance measurement options "ZI No trip" and "ZI Trip." No trip means that the tester will limit the test current from the line to the protective earth so that any RCDs will not trip. Measurements done with the "ZI No trip" mode might not be as accurate and if it is known that there are no RCDs in the system there is no reason to use it. When measuring the line impedances, the ZI Trip should always be used. [16.]

The Fluke 1664 FC offers a measuring resolution of up to 1 mΩ when high current loop option is selected for both loop and line impedance measurements [16]. This level of precision stands out when compared to other installation testers from Fluke or even competitors like Megger [17]. When using high current loop mode, the ZI Trip has to be selected first and then the measurement resolution can be changed from the default 10 mΩ to the 1 mΩ. The measurement time is considerably longer when the high current loop option is used. Consequently, it was only utilized to measure the impedance of the voltage adjuster when adjusting the output to 242 V. Additionally it was employed to see how the installation tester results compare against the PJC calculations. [16.]

## 5.2 Impedance of Conductors

In the test setup, there are the current carrying conductors before and after the voltage adjuster whose impedance must be considered as well. For the voltage adjuster measurements, there were different amounts of external resistance involved in all the measurements, which have been considered in the calculations. Four meters of cables is considered to be realistic for powering up the test setup. In the test room 227/228 the conductors' cross-section areas are 16 $mm^2$ and are made of copper. By knowing the conductors, total length $L$, cross-sectional area $A$, temperature, and the resistivity $\rho$ of the material, the resistance can be calculated as [18.]:

$$R = \rho \left(\frac{L}{A}\right) \tag{12}$$

The resistivity of copper at the temperature of +20 °C is $1.68 * 10^{-8}$ Ωm [19]. The resistivity of conductors increases with temperature, and this temperature-related rise in resistivity occurs when current flows through the conductor because it leads to heating. +20 °C matches well the ambient conditions in the laboratory, and therefore it is used. If approximately 4 m of cables is considered a realistic amount to use for the test setup, and the cross-section area of the conductors inside it is 16 mm$^2$, the conductors' resistance up to the supply of the test setup is:

$$R = 1.68 * 10^{-8} \Omega m \frac{4\ m}{16 * 10^{-6} m^2}$$

$$R = 4{,}2\ m\Omega$$

That is 1.05 mΩ per meter. The conductors' resistance is negligible compared to the impedance of the voltage adjusters. The reactance is ignored for conductors with a cross-sectional area of less than 150 mm2 since it is so negligible compared to the resistivity [12,16].

## 5.3 LCR-Meter Measurements

The LCR meter measurement did not produce results as linear as anticipated. The brush position changed the impedance and inductance. The signal did not solely traverse the input-output winding, as it formed a parallel circuit with the rest of the system, complicating the measurement interpretation. The results are shown in the table 1.

At nominal voltage, the measured impedance was 0.43 Ω at 100 Hz. Measurement results started to vary more when the brush was moved. At +15% the resistance was 2.53 Ω already at 100 Hz while at -15% the resistance was 0.31 Ω at 100 Hz. The LCR meter results were inconsistent, preventing any conclusions from being drawn from those. LCR meter measurement was carried out also for voltage adjuster A and it confirmed again that the impedance profiles of the voltage adjusters were different. In Appendix 2, the results of the 100 Hz measurement for both voltage adjusters A and B are presented, along with measurements conducted using a 1 kHz signal for both. Detailed results are provided in tables 5 and 6.

Table 1. Voltage adjuster B Inductance Measurement Input-Output 100 Hz:

| Brush position | Inductance [mH] | Resistance [mΩ] | Impedance [Ω] |
| --- | --- | --- | --- |
| -15% | 2.4 | 309.6 | 0.313 |
| 0% | 0.943 | 291.7 | 0.434 |
| +15% | 4.014 | 127.7 | 2.525 |

Later, this result was discussed with an expert in circuit analysis in the SGS Fimko, and it was shown that the circuit in figure 7 can have the resistance be frequency dependent as well. Even though the actual resistor value would not change, the interaction between the circuit's reactive elements leads to a change in the overall resistance. [20.]

## 5.4 Voltage Drop Measurement

Voltage drop measurement was carried out by using a data logger to measure the voltage. The current measurement was done by using a current clamp that was plugged into the data logger. The load was connected through cable that went through one of the robotic actuator tables. Approximately 30 readings with 10-second intervals were recorded each time the load was switched on or off. The voltage was set to be approximately 242 V. The voltage drop measurement results can be seen in Figure 12. When the load was on there were several noticeable glitches in the current readings that were filtered out from the result. The measured average current using the current clamp was 40.4 A, which indicates that the total load was 5.9 Ω.

Taking the average of the measurement with and without the load, the voltage drop over the voltage adjuster and other upstream impedances was 5.5 V. The whole upstream impedance is calculated by placing the 5.5 V and the measured current of 40.4 A in Ohm’s law (3):

$$5.5\,V * 40.4\,A = 136\,m\Omega$$

The impedance just over the voltage adjuster can be calculated when the mean of the PJC’s calculated upstream impedance of the phase and 4 meters of cable that were used up to the measurement point is negated from the result. The voltage adjuster‘s impedance is:

$$Z = 135.6\,m\Omega - 5\,m * 1.05\frac{m\Omega}{m} - 17\,\mathrm{m}\Omega$$

$$Z = 114\,\mathrm{m}\Omega$$

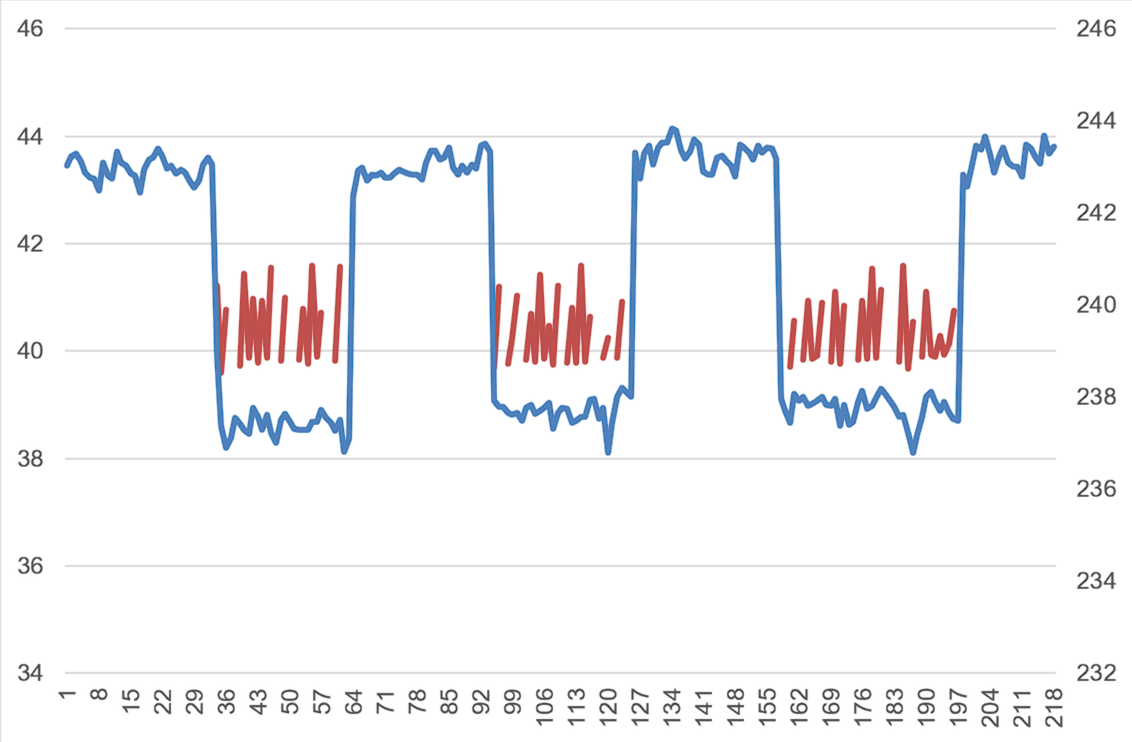


Figure 12. Voltage Drop Measurement - Voltage [V] (Blue Graph, right Y-axis) and Current [A] (Red Graph, left Y-axis)

## 5.5 Installation Tester Impedance

The installation tester was used to measure impedance over the voltage adjuster but also to see how the installation tester measurement compares against the PJC's calculation at the wall socket. Measuring over the voltage adjuster provided more accurate results with less deviation in the measurement results due to the higher impedance. More than one measurement was done to each interval to get more data and that way more reliable results.

The measuring result of the wall socket's impedance using the high current loop mode was 30 mΩ, which is lower than in the PJC's data. What was intriguing was that the installation tester calculated the short circuit current to be 7.7 kA which was lower than the one that PJC had calculated. Because of this contradiction in the PJC's data the 30 mΩ was used for the calculations where needed instead of the PJC's data for the L-N impedance. The cable in the wall socket test setup was only 0.5 m long and therefore the effect it has on the results is less than 1 mΩ.

High current loop mode was used to measure the impedance over the voltage adjuster when its output was set to the 242 V for increased accuracy. The mean value of the measurements was 195 mΩ. Measurement was also done when output was set to -15%, nominal value, and +15% of the input value but by using the ZI trip mode with 10 mΩ resolution as it was faster. When the voltage adjuster's impedance was being measured, changing its brush position affected the impedance of the system again. To contrast the measuring accuracy of the 10 mΩ resolution measurement with the 1 mΩ resolution high current loop mode measurement, the 242 V was measured also with the 10 mΩ resolution ZI trip mode. The mean of the 10 mΩ resolution measurement was 200 mΩ, which represents only a 2.5% difference from the 195 mΩ. See Appendix 2 table 7 for the 10 mΩ resolution measurements.

Table 2. Installation tester short circuit current measurement 1mΩ resolution

| Wall Socket 230 V | | Voltage Adjuster 242 V (230 V*1.05) | |
|---|---|---|---|
| Short circuit current [kA] | Impedance [mΩ] | Short circuit current [kA] | Impedance [mΩ] |
| 7.8 | 33 | 1.3 | 191 |
| 7.7 | 29 | 1.2 | 197 |
| 7.7 | 27 | 1.2 | 204 |
| 7.7 | 30 | 1.3 | 184 |
| 5.8 | 35 | 1.3 | 192 |
| 7.8 | 28 | 1.2 | 197 |
| - | - | 1.2 | 200 |
| - | - | 1.3 | 194 |

The test setup used four meters of cable, which resulted in eight meters of conductors factored into the measurements because in the L-N short circuit, the resistance of the neutral wire also influences the overall impedance as shown in the formula (9). If only the voltage adjuster's impedance is considered it can be calculated by subtracting all other known impedances which are the measured 30 mΩ upstream impedance and the 8 m of cable from the mean value of the 242 V measurement:

$$Z_{transformer} = 200\ m\Omega - 8\ \mathrm{m} * 1.05\ \frac{m\Omega}{\mathrm{m}} - 30\ m\Omega$$

$$Z_{transformer} = 157\ \ m\Omega$$

## 6 Voltage Adjuster Difference Observation

When the mΩ measurement was done, it was noticed that the voltage adjusters were not identical. The variations in impedances exceeded expectations, prompting the inspection of the voltage adjusters' maintenance panels. Upon examination, differences in wiring length and coil sizes among the voltage adjusters were noticed. All three voltage adjusters were ordered to be the same and the manufacturer stated even after asking them that the same circuit diagram applies to all of them. This raised questions, given the differences in the results obtained. In figures 13 and 14, the distinction between voltage adjusters B and C is clearly visible.

Figure 13. Voltage adjuster B maintenance panel open. Brush winding on top.

Figure 14. Voltage adjuster C maintenance panel open. Size difference of the coil with the brush is clearly noticeable between voltage adjusters B and C.

Further investigation revealed some design flaws as well in the voltage adjusters. Voltage adjuster B had the output neutral circuit breaker bridged. The bridged neutral connection could lead to hazards in setups using custom adapters or devices with schuko plugs, where incorrect line and neutral placements might occur. This misalignment could create a deceptive situation where it appears that the power is off, but a risk of electric shock still exists. In voltage adjuster C neutral on the output side and the output was marked the wrong way around.

This reveal eliminates the possibility of using all three voltage adjusters in the test setup. This restriction confines the test setup to accommodate only a single-pole switch.

The variation in impedances might make the phase angles deviate from the 120 degrees between each other. If this is the case, calculating the short circuit current using the impedance method would be inaccurate as it assumes the phase angles to be symmetrical. Consequently, it was decided not to consider using all three voltage adjusters in the test setup, confining it to accommodate only a single-pole switch. The chance of reaching the 10 kA also dropped significantly since the L-N fault current is lower.

# 7 Results

## 7.1 Short Circuit Current After the Voltage Adjuster

All the impedances now measured the L-N short circuit at the potential test table after the voltage adjuster can be calculated. Considering the smallest impedances measured, including the voltage adjuster’s 114 mΩ impedance, the installation tester's average upstream impedance of 30 mΩ, and 4 m of cabling resulting in L-N short circuit as 8 m of conductors. When the voltage is set to 242 V (230 V * 1.05), the L-N short circuit current is calculated using the formula (9):

$$I_{SC1} = \frac{242\,V}{Z_{phase} + Z_{neutral}}$$

$$I_{SC1} = \frac{242\,V}{114\,m\Omega + 2 * 4\text{ m} * 1.05\frac{m\Omega}{\text{m}} + 30\,m\Omega}$$

$$I_{SC1} = 1.59\,kA$$

If all the voltage adjusters had been identical the three-phase short circuit current could have been utilized. This was not the case but if it had been, and the same voltage adjuster’s impedance would have been used as well as the 4 m of cable. Only the phase’s impedance is considered therefore the mean of the PJC’s evaluated phase impedance is used which is 17 mΩ. The three-phase short circuit current is calculated using the formula (8):

$$I_{SC3} = \frac{242\ V}{Z_{phase}}$$

$$I_{SC3} = \frac{242\ V}{114\ m\Omega + 4\ m * 1.05 \frac{m\Omega}{m} + 17\ m\Omega}$$

$$I_{SC3} = 1.79\ kA$$

The three-phase short circuit and the phase to neutral short circuit current do not differ more than approximately 200 A. This is due to the voltage adjuster's impedance that forms most of the total impedance and therefore the result does not get affected as much by the impedance of the neutral that gets added in the L-N short circuit. The 10 kA requirement is not reached with either of the fault currents.

### 7.2 Short Circuit Current at the Test Room Wall Socket

The results showed inconsistency within the short circuit calculations of the PJC. The impedance between L-N that the PJC had estimated at the wall socket was approximately 36 mΩ while the calculated L-N short circuit current mean was 10.45 kA. The installation tester measured the impedance of L-N to be 30 mΩ and the short circuit current to be 7.7 kA. Clearly, the formula for measuring the short circuit current was different or PJC made fault in the Excel file where they provided the results. It is evident that the installation tester utilizes a formula similar to formula (9), because when the 30 mΩ and the measured no-load voltage of 234 V are inserted into the formula (9), the short circuit current of the wall socket is:

$$I_{sc1} = \frac{234\ V}{Z_{phase} + Z_{neutral}}$$

$$I_{sc1} = \frac{234\ V}{30\ m\Omega}$$

$$I_{sc1} = 7.8\ \mathrm{kA}$$

The result of it turns out to be approximately the same as the installation tester's 7.7 kA. Because of these divergent results, it might be required to contact the PJC later and ask if their calculations are correct and how the software they used determines it.

## 8 Future of the Test Setup

The 10 kA prospective short circuit current was not achieved with the current equipment. In the end, it was questioned was the 10 kA short circuit current possible even to begin with from the test room 227/228 wall socket. One potential solution to achieve a +5% voltage increase would be to research if it is possible to add a large autotransformer with a +5% tap next to the building's main transformer which could maintain the 10 kA requirement. Constructing the test setup might also be considered later without raising the voltage. Training personnel to conduct the test holds value, even if it would not be as authentic as the actual test scenario. Moreover, optimizing the transmission line to the test table by shortening its length and using thicker conductors could potentially support the 10 kA capacity without increasing voltage, if there were inaccuracies in PJC's calculations.

# 9 Conclusion

Three different methods of measuring the impedance over the voltage adjusters were introduced. LCR-meter analysis proved not to be particularly useful in this kind of scenario since the results were difficult to understand and utilize since the circuit did not behave like it was assumed. The frequency dependency of the resistance made it hard to evaluate the impedance at 50 Hz. The voltage drop measurement principle was simple and easy to utilize. However, the current measurement had some unwanted interference. Finally, the installation tester was an easy and fast way of measuring the impedance. To increase the measurement accuracy, multiple measurements were taken and the mean of the results was calculated.

For using the data gathered from the measurements, theory about short circuit calculation had to be studied as well. Only the continuous short circuit current was of interest and therefore the math behind the calculations in the end were quite simple. Attention still had to be paid to all the external factors in the test setups, like cable lengths and uncertainties in the measurements that could have affected the results. Because of the background studies that had to be made, the thesis project taught me a lot about electrical networks and calculating the fault currents there. The topics were previously unfamiliar to me, as they were outside the scope of experience in the electronics field.

Because the initial assumptions that were given were proven wrong, it raised doubts about the necessity of the entire research process. The focus shifted from just ensuring a 10 kA short circuit current to delving deeper into understanding the voltage adjuster's impedance. Impedance also turned to be higher than initially assumed but either way, this data of the transformers still is valuable for other testing purposes. It was good to notice the design differences and flaws of the voltage adjusters, which eventually can be fixed to improve testing safety.

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## Appendix 1: PJC's short circuit calculations

Table 3 PJC calculations. SGS short circuit currents from 400V Building's main transformer and 400V, 125 A output wall socket in test room 227/228.

| | | Building Main Transformer | Test Room 227/228 Wall Sockets | Referred in Chapters |
|---|---|---|---|---|
| Ik1minph_n | [A] | 15 910 | 9 210 | 7.2 |
| φ1ph_n | [°] | -79,5 | -44,1 | |
| Ik1minph_pe | [A] | 15 910 | 8 780 | |
| φ1ph_pe | [°] | -79,5 | -41,2 | |
| Ik2min | [A] | 14 040 | 10 960 | |
| φ2 | [°] | -82,6 | -58,8 | |
| Ik3min | [A] | 16 210 | 12 650 | |
| φ3 | [°] | -82,6 | -58,8 | |
| Ikmax | [A] | 18 790 | 15 300 | |
| Ik1maxph_n | [A] | 18 490 | 11 680 | 7.2 |
| φ1ph_n | [°] | -80,7 | -49,7 | |
| Ik1maxph_pe | [A] | 18 490 | 11 260 | |
| φ1ph_pe | [°] | -80,7 | -46,9 | |
| Ik3max | [A] | 18 790 | 15 300 | |
| φ3 | [°] | -83,2 | -63,3 | |
| Ipk | [A] | 45 330 | 26 750 | |
| R0min ph-n | [mΩ] | 3,46 | 27,3 | |
| X0min ph-n | [mΩ] | 13,8 | 20,1 | |
| Z0min ph-n | [mΩ] | 14,3 | 33,9 | 7.2 |
| R0max ph-n | [mΩ] | 4,05 | 33,4 | |
| X0max ph-n | [mΩ] | 13,8 | 20,1 | |
| Z0max ph-n | [mΩ] | 14,4 | 39,0 | 7.2 |
| R0min ph-pe(n) | [mΩ] | 3,5 | 31,3 | |
| X0min ph-pe(n) | [mΩ] | 13,8 | 19,7 | |
| Z0min ph-pe(n) | [mΩ] | 14,3 | 37,0 | |

| | | | | |
|---|---|---|---|---|
| R0max ph-pe(n) | [mΩ] | 4,0 | 38,4 | |
| X0max ph-pe(n) | [mΩ] | 13,8 | 19,7 | |
| Z0max ph-pe(n) | [mΩ] | 14,406 | 43,182 | |
| R1min | [mΩ] | 1,6 | 7,463 | |
| X1min | [mΩ] | 13,422 | 14,836 | |
| Z1min | [mΩ] | 13,517 | 16,607 | 5.4, 7.1 |
| R1max | [mΩ] | 1,749 | 8,971 | |
| X1max | [mΩ] | 13,422 | 14,836 | |
| Z1max | [mΩ] | 13,535 | 17,337 | 5.4, 7.1 |

## Appendix 2: Additional Measurement Results

Table 4 mΩ meter measurement. Input-Output across all the voltage adjusters.

| Variac position (percentage of the input voltge) | Voltage Adjuster A Resistance [mΩ] | Voltage Adjuster B Resistance [mΩ] | Voltage Adjuster C Resistance [mΩ] |
|---|---|---|---|
| 85% | 200,9 | 31,52 | 14,6 |
| 93% | 201,5 | 31,51 | 14,62 |
| 100% | 201,8 | 31,51 | 14,62 |
| 105% | 201,5 | 31,51 | 14,62 |
| 110% | 200,3 | 31,51 | 14,62 |
| 115% | 200,1 | 31,51 | 14,62 |

Table 5 Voltage adjuster B Inductance Measurement Input-Output:

| Brush position | Test frequency [Hz] | Inductance [mH] | Resistance [mΩ] | Impedance [Ω] |
|---|---|---|---|---|
| -15% | 100 | 2,4 | 309,6 | 0,313 |
| | 1000 | 0,128 | 401,5 | 0,403 |
| 0% | 100 | 0,943 | 291,7 | 0,434 |
| | 1000 | 0,559 | 1227,8 | 3,254 |
| +15% | 100 | 4,014 | 127,7 | 2,525 |
| | 1000 | 4,136 | 5260 | 25,42 |

Table 6 Transformer A Inductance Measurement Input-Output:

| Brush position | Test frequency [Hz] | Inductance [mH] | Resistance [mΩ] | Impedance [Ω] |
|---|---|---|---|---|
| -15% | 100 | 4,517 | 285,6 | 2,823 |
| | 1000 | 4,847 | 9312 | 28,82 |
| 0% | 100 | 1,0975 | 215,6 | 0,227 |
| | 1000 | 0,1275 | 361,2 | 0,676 |
| +15% | 100 | 6,198 | 266,5 | 3,885 |
| | 1000 | 6,531 | 11577 | 39,22 |

Table 7 Installation tester short circuit current measurement 10mΩ resolution (L-N 230 V)

| Test | Wall socket | | min 178V | | max 268 V | | 230 V | | 242 V | |
|---|---|---|---|---|---|---|---|---|---|---|
| | kA | mΩ | kA | mΩ | kA | mΩ | kA | mΩ | kA | mΩ |
| 1 | 7,7 | 30 | 0,47 | 380 | 0,69 | 420 | 1,2 | 200 | 1,2 | 200 |
| 2 | 11,6 | 20 | 0,54 | 330 | 0,63 | 450 | 1,2 | 190 | 1,1 | 210 |
| 3 | 23,1 | 10 | 0,47 | 380 | 0,62 | 450 | 1,2 | 190 | 1,3 | 180 |
| 4 | 7,7 | 30 | 0,41 | 400 | 0,58 | 490 | 1,3 | 180 | 1,1 | 220 |
| 5 | 7,7 | 30 | 0,48 | 370 | 0,65 | 440 | 1,3 | 180 | 1,2 | 200 |
| 6 | 7,7 | 30 | - | - | - | - | - | - | 1,3 | 190 |
| 7 | 5,8 | 40 | - | - | - | - | - | - | 1,2 | 200 |
| 8 | 4,6 | 50 | - | - | - | - | - | - | 1,2 | 200 |