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Development of Synchronization Tester and IEC Safety Standard Compliance

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Degree Thesis for Bachelor of Engineering

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Abstract

This bachelor's thesis was written for the ABB Energy Industries department in Vaasa, Finland. The thesis work helps with crucial control system testing performed in the FAT area.

Synchronization of generators with the power grid is a fundamental part of properly maintaining the electrical network's functions. To ensure safe synchronization, meticulous testing of control systems is needed. This can be carried out with the help of a synchronization test bench.

This thesis project involved developing a nonfunctional synchronization test bench. Safety standard compliance regarding said test bench, power grid synchronization, and electrical safety in general is also considered.

This thesis aimed at initiating a novel synchronization test bench and ensuring its compliance with IEC safety standards. A fully functional and safe-to-use test bench is imperative to providing customers with high-quality products.

The first steps of this thesis were redesigning the synchronization test bench drawings and understanding the synchronization of generators with the power grids. The drawings are done on Zuken´s E³ electrical CAD software, which ABB Energy Industries uses as its main design and planning program. The practical part consisted of defining new measuring parameters for the various meters and filters, rewiring according to the corrected drawings, and adding various new components. Earthing wiring was done according to the IEC 60364 standard. All this was needed for proper and safe synchronization testing.

This thesis work resulted in a fully operational and safety-compliant synchronization test bench. Synchronization tests can now be performed safely and quickly with ease.

Language: English
Key Words: synchronization, IEC 60479, IEC 60364

EXAMENSARBETE

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Abstrakt

Detta examensarbete skrevs för ABB Energy Industries-avdelningen i Vasa, Finland. Examenarbetet underlättar viktig testning av kontrollsystem som utförs inom området för Factory Acceptance Testing (FAT).

Synkronisering av generatorer med elnätet utgör en grundläggande del av att korrekt upprätthålla nätverksfunktionerna. För att säkerställa en säker synkronisering krävs noggrann testning av kontrollsystemen. Detta kan utföras med hjälp av en synkroniseringstestbänk.

Detta examensarbetesprojekt involverade utveckling av en icke-fungerande synkroniseringstestbänk. Uppfyllandet av säkerhetsstandarder gällande testbänken, synkronisering med elnätet och el-säkerhet i allmänhet har också beaktats.

Syftet med examensarbetet var att ta i bruk en ny synkroniseringstestbänk och säkerställa dess överensstämmelse med IEC-säkerhetsstandarder. En fullt funktionell och säker testbänk är avgörande för att förse kunderna med produkter av hög kvalitet.

Modifiering av ritningarna för synkroniseringstestbänken och förståelsen av synkronisering av generatorer till elnätet var de första stegen i detta examensarbete. Ritningarna är gjorda i Zukens E^3 elektriska CAD-program, som ABB Energy Industries använder som sitt huvudsakliga design- och planeringsprogram. Den praktiska delen bestod av att definiera nya mätparametrar för olika mätare, nya filter och omkoppling enligt de korrigerade ritningarna, samt installation av nya komponenter. Jordningskablage utfördes enligt IEC 60364-standarden. Allt detta var nödvändigt för korrekt och säker synkroniseringstestning.

Resultatet av detta examensarbete var en fullt fungerande och säkerhetsmässigt överensstämmande synkroniseringstestbänk. Synkroniseringstester kan nu utföras säkert och snabbt utan svårigheter.

Språk: engelska
Nyckelord: synkronisering, IEC 60479, IEC 60364

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Tiivistelmä

Tämä opinnäytetyö on kirjoitettu ABB Energy Industries -osastolle Vaasassa, Suomessa. Opinnäytetyö auttaa ratkaisevassa ohjausjärjestelmien testauksessa, joka suoritetaan FAT-alueella.

Generaattoreiden synkronointi voimaverkkoon on olennainen osa sähköverkon toimintojen asianmukaista ylläpitoa. Turvallisen synkronoinnin varmistamiseksi tarvitaan huolellista ohjausjärjestelmien testausta, joka voidaan suorittaa synkronointitestipenkin avulla.

Tämä opinnäytetyöprojekti liittyi toimimattoman synkronointitestipenkin kehittämiseen. Turvastandardien noudattaminen koskien mainittua testipenkkiä, voimaverkon synkronointia ja yleisesti sähköturvallisuutta on myös otettu huomioon.

Tämän opinnäytetyön tavoitteena oli aloittaa uuden synkronointitestipenkin käyttöönotto ja varmistaa sen noudattavan IEC:n turvallisuusstandardeja. Täysin toimiva ja turvallinen testipenkki on välttämätön asiakkaille laadukkaiden tuotteiden tarjoamiseksi.

Synkronointitestipenkin piirustusten uudelleensuunnittelu ja ymmärtäminen generaattorien synkronoinnista voimaverkkoon olivat tämän opinnäytetyön ensimmäiset askeleet. Piirustukset on tehty Zukenin E³-sähköisessä CAD-ohjelmistossa, jota ABB Energy Industries käyttää pääasiallisena suunnitteluohjelmana. Käytännön osuus koostui uusien mittausparametrien, uusien suodattimien ja uudelleenjohdotuksen määrittelemisestä oikaistujen piirustusten mukaisesti, ja uusien komponenttien lisäämisestä. Maadoitusjohdotus tehtiin IEC 60364 -standardin mukaisesti. Kaikki tämä oli tarpeen asianmukaiseen ja turvalliseen synkronointitestaukseen.

Tämän opinnäytetyön tuloksena oli täysin toimiva ja turvallisuusvaatimukset täyttävä synkronointitestipenkki. Synkronointitestit voidaan nyt suorittaa turvallisesti, nopeasti ja vaivattomasti.

Kieli: englanti
Avainsanat: synkronisointi, IEC 60479, IEC 60364

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1 Introduction

This thesis work was commissioned by ABB, Energy Industries division in Vaasa, Finland. This thesis aims to develop and commission a synchronizing test bench, a prior thesis work that was yet to be operational, and to determine IEC safety regulation compliance. Synchronization testing is crucial for ensuring the reliability and safety of electrical systems, and making a functional test bench is a key priority for ABB's Energy Industries division. Synchronization is the process of aligning generators with the power grid.

1.1 The Commissioner

ABB is a global innovative technology leader in electrification and automation, employing more than 105,000 people worldwide in more than 100 countries, with a focus on innovation and sustainability, spearheading industrial transformation. ABB comprises four key business areas: Electrification, Motion, Process Automation, and Robotics & Discrete Automation. In 2023, ABB had an annual revenue of over 32,2 billion USD. [1]

ABB, together with its predecessor companies, has more than 130 years of experience in the fields of electrification and automation. Before the merger of two companies that became ABB, Elektriska Aktiebolaget, founded in 1883 by Ludvig Fredholm, manufactured electrical lightning and generators and merged with Wenström & Granström in 1890 to form Allmänna Svenska Elektriska Aktiebolget, later shortened to ASEA. Brown Boveri & Cie, established in 1891 by Charles E. L. Brown and Walter Boveri, was the first company to transmit high-voltage power. Asea and BBC merged on January 5th, 1988, to form the new enterprise ABB with their headquarters in Zurich, Switzerland, and had a revenue of 17 billion USD the same year. [2]

ABB Energy Industries, which commissioned this thesis work, employs about 3000 people worldwide, of which around 80 are in Finland and mainly in Vaasa, with their offices located in Stromberg Park, Vaasa. Energy Industries in Finland provides their customers with planning and delivery of electrical-, automation-, instrumentation, and surveillance systems for powerplants along with system analysis and maintenance services. The core of the Finnish unit’s expertise areas are gas engine, gas turbine, and hydropower projects for both export and domestic markets. Additionally, thermal- and nuclear power solutions are provided mainly for the domestic market. [3]

1.2 Background

The synchronization test bench is an integral part of ABB's FAT area. A synchronization tester is a vital tool to ensure that the synchronization circuits of the automation cabinets work properly with safety in mind. Synchronization of generators to power grids is a crucial part of the electricity network therefore synchronization must work properly.

1.3 Problem Statement

At the start of the thesis work the factory acceptance testing area or FAT area only had one working synchronization tester, commissioned in 2002 and was due for a replacement. In 2019 planning and development of a new synchronization test bench was underway as part of a bachelor's thesis. The new synchronization tester was planned to replace or be used in parallel with the old one, but it was not commissioned due to design flaws.

Since synchronization circuits of control system cabins are always tested before shipping them to the customer, a reliable test cabin is essential. This prompted ABB to assign the fixing of the non-working test bench and commissioning of it to the author.

Thanks to many safety standards, including The International Electrotechnical Commission or IEC for short, safety standards have improved over the years. To make sure the new synchronization tester meets the different safety standards set in place by agencies a part of this thesis work is to determine whether it is compliant and safe to use.

1.4 Purpose

The purpose of this thesis is to re-design and fix the issues of the synchronization tester, which was part of a thesis work in 2019. Commissioning and safety standard compliance testing of the test bench is a key component of the work going on in the FAT area. To ensure the safe testing of synchronization circuits in various projects, the test bench must meet the safety standards.

1.5 Confidentiality

Part of this thesis is deemed sensitive, and therefore, some chapters have been withheld from public access (methodology, test bench key components, and appendices).

2 Theory

To properly understand how a synchronization tester works, it is imperative to understand the general theories about the synchronization of generators to the electrical grid. An understanding of synchronization and how it works in practice enables further understanding of the importance of safety. Therefore, general safety standards will be explained and how they apply to power grid synchronization.

2.1 Synchronization

Synchronization of generators to the power grid is a delicate coordination of the isolated generator's frequency, voltage magnitude, and phase angle that must match the power grid. Both the generator and electrical grid can be affected by poor synchronization. If any of these criteria are not met, it can lead to the following:

- Damage to the generator prime mover due to rapid acceleration or deceleration when trying to match the frequency (speed) of the power grid.
- Damaging the step-up transformer windings because of high currents.
- Disturbances in the power system, such as power oscillations and abnormal voltage deviations
- Tripping the generator if picking up a load from the power grid

Synchronization control systems typically include voltage and frequency indicators along with a synchroscope. With the help of the indicators that engineers have available in a typical synchronization control panel, manual or automatic synchronization can be performed. In most modern power plants, automatic synchronization is used with manual control reserved as a backup. In power plant facilities utilizing more than one generator, synchronization becomes complicated, and therefore, multiple synchronization circuits must work in unison. Proper synchronization criteria, along with different synchronization methods, will be discussed in the next chapters. [4]

2.1.1 Synchronization Criteria

To properly synchronize a generator to a power grid, certain criteria must be met. To have both the generator and the power grid parallel, power systems can exchange power and load flows. Both sources must have virtually the same frequency, voltage amplitude, phase phase-angle, and phase sequence.

Frequency, voltage amplitude, and phase angle must, in practice, be the same when connecting a generator to the power grid. It is impossible to have all these three criteria met at the same time when closing a circuit breaker. Therefore, it must be within a pre-determined tolerance window. If the frequency, voltage amplitude, and phase angle are within the accepted window, little to no disturbance occurs when the power systems are parallel. [5]

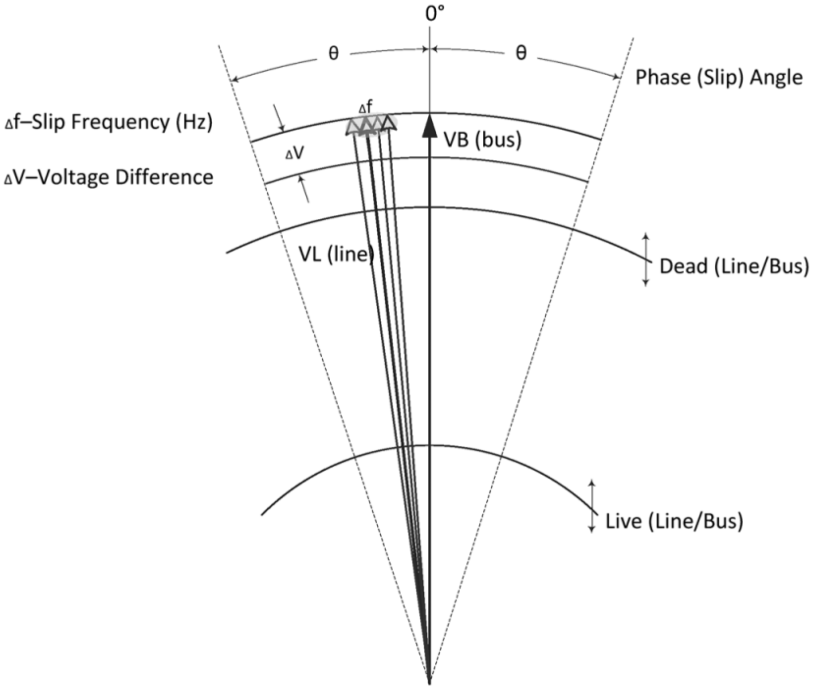

Figure 2.1 Synchronization window [5]

Figure 2.1 illustrates the synchronization window. The synchronization window shows the vertical target bus voltage (**VB**) and a phasor sweeping clockwise, indicating the oncoming generator (**VL**). A maximum allowed voltage difference between target and source **ΔV** is determined by settings along with the acceptable slip frequency **Δf** in hertz. The settings also determine the acceptable phase angle (slip-angle) in degrees (Θ). Dead (line/bus) and live (line/bus) voltage are given alongside these settings.

Slip frequency is the difference between target and source frequency at one instance measured in hertz. A typical maximum slip frequency is 0.05-0.5 Hz. Generators constructed according to IEEE standards C50.12 and C50.13 should have a voltage amplitude of 0 to +5 % higher than the bus and a closing angle of 0 to 10° when synchronizing. As the oncoming generator voltage increases the voltage amplitude reaches the window of allowance **ΔV**, measured in volts, pre-determined by the settings. When the difference in phase angles between **VB** and **VL** falls within the acceptable range, a circuit breaker closure command can be issued. The process of matching the phase sequences is referred to as "phasing". [4] [5] [6]

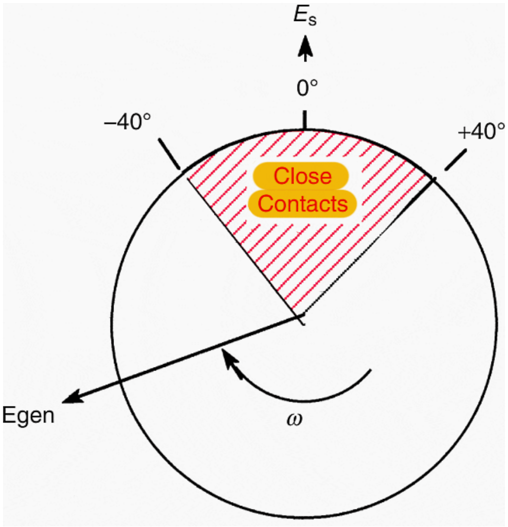

Figure 2.2 Closing angle [6]

The maximum closing range between **VB** and **VL** specified by the settings is shown clearly in **Figure 2.2** which is in this case ±40°. When the sweeping phasor is within this window it means that the difference between target (**VB**) and source (**VL**) phase angles is acceptable and that a circuit breaker closure can safely occur. A crucial criterion for safe synchronization, together with the aforementioned criteria, is that the source voltage has to exceed the target voltage to ensure reactive power flow out of the generator, avoiding damage to the source. [6]

2.1.2 Synchronization Methods

There are many methods of synchronizing a generator (source) to the bus (target). Synchronization can be done by manual switching, assisted manual switching, and automatic switching. Said methods each require synchronization circuitry, for example, meters, lamps, switches, and a protective relay. [5]

Synchronization typically begins with the excitation of the generator armature to bring it into synchronous operation, or constant rotational speed. To parallel the generator to the bus cannot happen safely unless the synchronization window criteria are met (see **Figure 2.1**). The voltage amplitude and phase angle of the generator must be matched to the bus. Before connecting the source to the target, operators adjust manual controls or a synchronous relay to closely match the voltage amplitude and the phase angle to the target so that they are in the synchronization window. [5]

Manual synchronization is performed by a power plant operator manually controlling the excitation and speed of the generators via switches located on the control panel. When the phasor is within the synchronization window, the operator closes the circuit breaker to the bus. The synchronization control panel typically consists of a synchroscope, indicating lamps, separate generator and bus frequency meters, and AC voltmeters. The synchroscope displays multiple parameters. The slip rate or the difference between source and target frequencies is displayed, indicating whether the source frequency is higher or lower than the target. A dial pointer or LED lamps rotate around depending on the frequency mismatch. The instantaneous position of the indicator tells the phase angle difference between the source and target. The 12 o´clock position on the synchroscope indicates a 0° difference, and 6 o´clock indicates a 180° difference. A clockwise rotation means that the source frequency is higher than the target and vice versa. The goal is to close the circuit breaker when the dial is at the 12 o´clock position to minimize power-flow transients and damage to the generator. [4] [5]

Assisted manual synchronization is, in essence, the same as manual synchronization, with the difference being that a supervisory relay known as a sync-check relay is in series with the circuit breaker. This sync-check relay enforces a synchronization window for safe synchronization. The sync-check relay compares the voltage difference, slip frequency, and phase angle difference between the source and target. Modern relays can minimize the window to a slip frequency of 0.05 Hz and a phase slip angle of 10°. Circuit-breaker closing can only occur when the operator manually closes the switch and supervisory relay contacts are closed. [5]

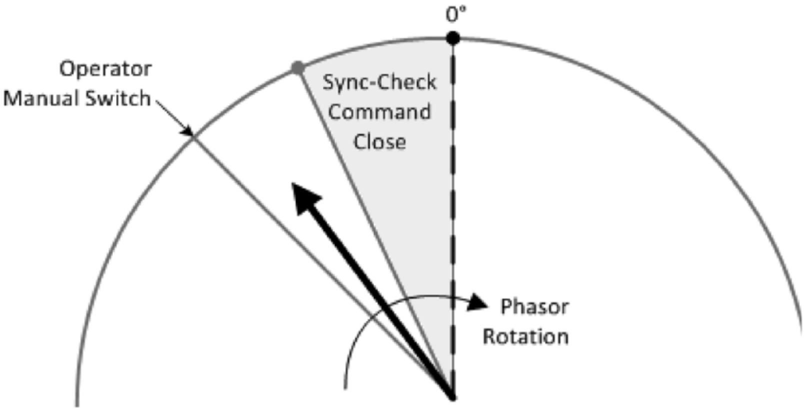

Figure 2.3 Assisted manual synchronization with sync-check [5]

Figure 2.3 shows the timing of the operator's manual circuit breaker command and the sync-check-relay command close as the phasor approaches 0°.

Automatic synchronization uses an automatic synchronizer device that monitors voltage, frequency, and phase angle. The synchronizer can then, based on these variables, output correction signals to a generator governor to match the voltage and frequency of the bus. When a synchronization window has been achieved, a circuit-breaker-close signal can be sent. [5] [6]

As the generator comes up to speed, the generator voltage is applied to the synchronizer. When the generator reaches a threshold voltage, the synchronizer begins to sense the generator (source) and bus (target) voltages, frequencies, and phase angles. In **Figure 2.4** below, a typical auto synchronizer block diagram is shown. [5]

As the generator voltage reaches the threshold, the synchronizer starts sensing the generator and bus voltages and frequencies (“Gen Sensing” and “Bus Sensing”). The difference is then calculated, and voltage correction signals are sent to the generator to match the bus. Frequency correction signals are subsequently sent to the prime-mover governor to match the speed of the bus. Lastly, when both voltage amplitude and frequency are at a desired level, phase angle slip is calculated to give an advance angle to close the breaker to achieve a breaker closure at 0°. Advance angle is important due to the physical time it takes for the breaker contact poles to touch and the output-relay contact-travel time. [5]

The advance angle can be calculated with the following formula:

$$\boldsymbol{A_A = 360(T_{CB} + T_R)F_S}$$

Where:

$\boldsymbol{A_A}$ = Advance angle, which is the generator phase angle with respect to the bus when the synchronizer initiates a close command

$\boldsymbol{T_{CB}}$ = Circuit breaker close time

$\boldsymbol{T_R}$ = Output relay close time

$\boldsymbol{F_S}$ = Slip frequency

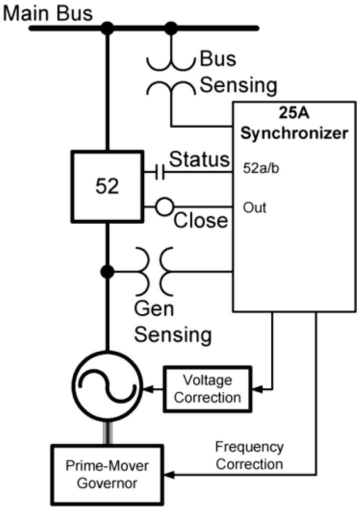

Figure 2.4 Typical auto synchronizer block diagram [5]

2.2 Typical Components in Synchronization Systems

There is a magnitude of different components used in synchronization systems. This chapter will focus on key components used to get a better understanding of how a synchronization test bench works.

2.2.1 Frequency Converter

Frequency converters, also known as variable frequency drives, are electric devices that convert alternating current from one frequency to another. Voltage amplitude usually stays the same before and after a conversion. Frequency converters are mainly used for motor speed regulation in various applications. They can be used in a synchronization test bench to simulate a generator and a busbar with different frequencies. [7]

There are many different types of frequency converters, however, the principal function of frequency converters remains the same. A fixed supply is converted into a variable output. Frequency converters are generally split into two different categories, which are **direct converters** and **converters with an intermediate circuit**. [8]

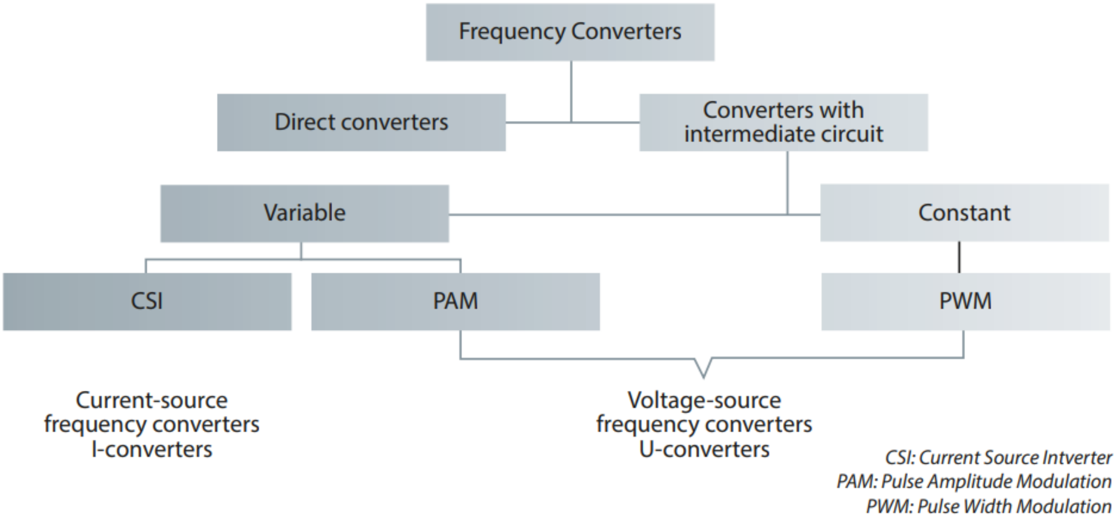

Figure 2.5 Overview of frequency converter types [8]

The main difference between **direct converters** and **converters with an intermediate circuit** is that a direct converter has no intermediate storage. The converter does not store electrical energy during the conversion process. [8]

Frequency converters with an intermediate circuit are divided into two subtypes which are **constant intermediate circuit** and **variable intermediate circuit** as shown in **Figure 2.5**. AC drives with an intermediate circuit consist of four main components, as shown in **Figure 2.6**. [8]

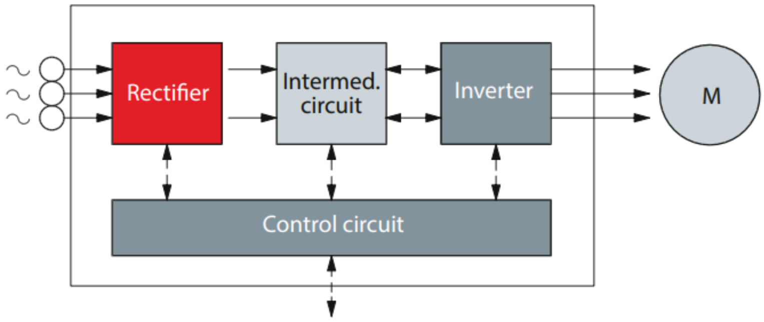

Figure 2.6 Block diagram of AC drives with an intermediate circuit [8]

The **rectifier** is connected to either a single-phase or three-phase AC voltage supply and generates a pulsating DC voltage. The rectifier consists of diodes and/or thyristors or bipolar transistors, allowing current flow in one direction from the supply to the intermediate circuit. [8]

The functions of the **intermediate circuit** depend on the rectifier and inverter that it is connected to, but the main functions include:

- Acting as an energy buffer so that the motor can draw and return energy to the grid via the inverter.
- Disconnecting the rectifier from the inverter
- Reducing mains interference

The **inverter** is the last step before generating an output voltage and frequency to the motor. From the intermediate circuit, the inverter gets a variable direct current, variable DC voltage, or constant DC voltage. The frequency of the motor voltage is generated in the inverter. The controlling method of the inverter depends on what type of input it receives from the intermediate circuit. If the input is a variable current or voltage, it only needs to generate the equivalent frequency. In the case of a constant voltage, the voltage amplitude is also generated. [8]

Lastly, the **control circuit**, or the control board, transmits and receives signals to and from the other components in the frequency converter. The main four tasks of the control circuit are:

- Controlling the AC drive semiconductors.
- Exchanging data between the AC drive and other devices (PLCs).
- Measuring and displaying faults, conditions, and warnings.
- Performing protective functions for the AC drive and motor.

In general, the basic functions of frequency converters can be summarized as rotating and positioning the rotor by opening or closing the speed and torque control of the frequency converter. It also monitors and displays the operating states. [8]

2.2.2 Output Filter

Output filters are effective in mitigating damage to the motor and increasing operational safety and installation lifetime. Different passive output filters can be used in different systems. The filter components in this chapter are the most common and solve the major application requirements. This chapter will mainly focus on the sinusoidal output filter or sine wave filter. [9]

The different filter components:

- dv/dt reactors (increase inductivity and smoothen signals).
- dv/dt filters (low inductance and insignificant reduction in the control dynamic).
- Sinusoidal output filters (high inductance and capacitance for optimizing the output signal)

Sine wave filters are low-pass frequency filters consisting of inductors and capacitors, therefore sometimes called LC filters. These kinds of filters are mainly used in combination with variable frequency drives. Sine wave filters convert rectangular PWM signals into smooth sine waves with low residual ripples. These sinusoidal phase-to-phase voltages and current waveforms reduce the motor's acoustic noises, as well as insulation stress and bearing currents in the motor, thus prolonging the motor's lifetime. [10] [9]

Some advantages of sine wave filters:

- Protects motor against voltage peaks.
- Reduction of motor losses.
- Eliminates acoustic noises from the motor.
- Decreasing electromagnetic emissions from motor cables by eliminating high frequencies.
- Reduction of bearing currents.

In essence, there are two different types of sine wave filters which are differential mode (symmetric) filters and common mode (asymmetric) filters. Most sine wave filters used are differential mode filters, also called symmetric sine wave filters. These filters are useful in applications where smooth sine wave voltages are required. The residual ripple of the signal can be adjusted based on the values of the inductors and capacitors (L and C). The result of using a sine wave filter with a PWM signal input is shown in **Figure 2.7**. [10] [9]

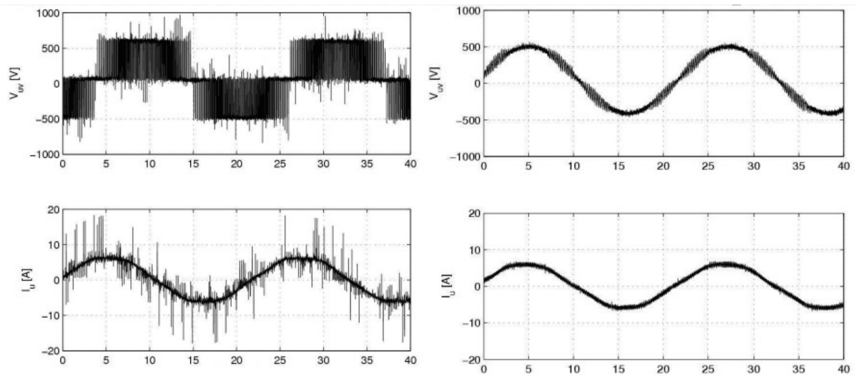

Figure 2.7 Voltage and current without and with sine wave filter [10]

2.2.3 Transformers

Transformers are typically used in applications where a change in voltage is required. Having higher voltages in distribution power lines enables having lower currents for the same power, thus reducing power losses in the distribution lines. These higher transmission voltages can then be transformed to lower, more usable voltage levels that can then be used to supply electrical equipment. Transformers can be used in a synchronizing test bench to simulate a busbar at different voltage amplitudes or to simulate a generator with varying voltage amplitudes. [11]

A transformer works on the principle of Faraday´s law of induction, which is a phenomenon where a current is induced when the magnetic flux through a conducting coil is changed. With the help of this principle, two or more electrical circuits can be linked together in a transformer in the form of mutual induction. Mutual induction is the magnetic induction of voltage in a coil by another coil nearby. Transformers can either increase or decrease (step-up or step-down transformers) the voltage and current levels of their supply without modifying the frequency or power level when transferred from one winding to another. [11] [12]

A basic single-phase transformer, shown in **Figure 2.8**, consists of two separate coils wrapped around a common closed magnetic soft iron core. This core is not solid but is made up of multiple individual laminations connected to reduce magnetic losses. The two coils are called primary windings and secondary windings, primary windings are usually defined as the supply side and secondary windings are on the load side. [11]

An electromagnetic field is induced in the secondary coil by the magnetic flux generated by currents flowing in the primary coil. A desired voltage level on the secondary side can be achieved based on the relation between the number of turns on the primary and secondary sides. The AC supply on the primary side must be sinusoidal. [11]

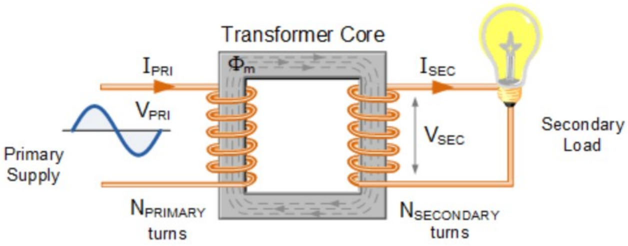

Figure 2.8 Single-phase voltage transformer [11]

A three-phase transformer works in the same way as a single-phase transformer, instead of having one winding for the primary and secondary sides there is one winding for each phase. The windings are connected to each other on the primary side and secondary side. Primary and secondary windings can be connected in several ways with the most common configurations being the star (Y) and delta (D). The low-voltage side is commonly connected in the star configuration and the delta is mainly used to reduce the third harmonic voltage (a multiple of three of the fundamental frequency). In the star configuration, the three windings are connected at their ends, hence the symbol “Y”, with the connection point being neutral. In the delta configuration, both ends of the windings are connected, as shown in **Figure 2.9**. In a three-phase transformer based on the primary and secondary side configuration, the voltages can be in phase or displaced. [11] [13] [14] [15]

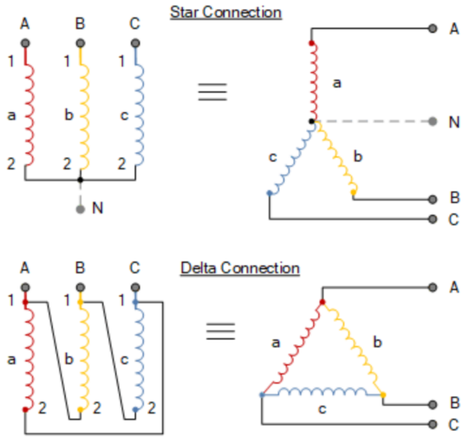

Figure 2.9 Star and delta winding connection scheme [13]

The connection of all the windings in a three-phase transformer is indicated by something called a vector group symbol. A vector group symbol uses letters and numbers to indicate the transformer configuration, as shown in **Table 2.1**. The letters tell what types of connections are used on both the primary and secondary sides, while the numbers represent a phase displacement and use a clock face notation to represent it in electrical degrees. The primary side windings or high voltage side is used as a reference (12 o´clock position), and depending on the relation between primary and secondary windings, the displacement can be from 0° to -330° with 30° increments (one hour on a clock face) with the high voltage as reference. Phase rotation is always anti-clockwise. [14] [15]

Table 2.1 Vector group symbol descriptions

First symbol for the primary side: always capital letters	D = Delta, Y = Star, N = Neutral
Second symbol for the secondary side: always small letters	d = Delta, y = Star, n = Neutral
Third symbol: phase displacement expressed as the clock hour number	0, 1, 6, and 11 (these are the most common)

One of the most common transformer configurations is a Dyn11. The Dyn11 has a delta (D) connection on its primary side and a star (y) connection on its secondary side with a neutral (n) line. The phase displacement of such configuration is 30° or as represented by a clock face at 11 o´clock (see **Figure 2.9**). [14] [15]

A normal transformer can only transform the supply voltage to a set level on its secondary side. Variable autotransformers are transformers that can regulate a fixed AC input into a variable output voltage. This variable autotransformer, unlike a traditional transformer with two separate windings, only has one common winding. The single common winding is wrapped around a laminated magnetic core in a similar way to the traditional transformer, and a rotating carbon brush is used to “tap” the secondary voltage at various locations along the common winding. This common winding is tapped at various points along its length, thereby providing a percentage of the primary voltage supply to the secondary load side, as shown in **Figure 2.10**. The primary current I_P is flowing through downwards the common winding while the current I' is flowing in the opposite direction. The secondary current I_S is the sum of I_P and I'. The secondary voltage V_S is determined by the position of the secondary tapping point. The mathematical relation between primary and secondary currents and voltages is $\frac{V_P}{V_S} = \frac{I_S}{I_P}$. [13] [16]

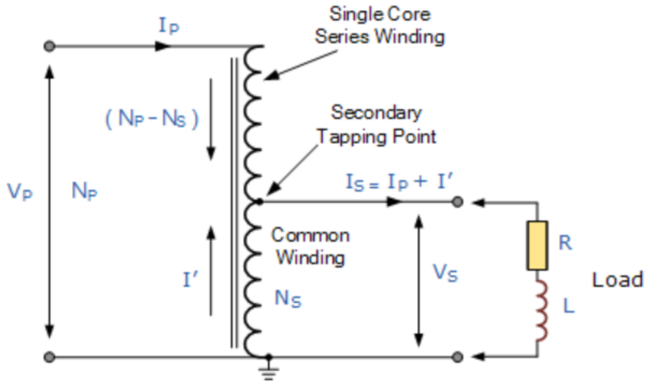

Figure 2.10 Variable autotransformer design [13]

2.2.4 Synchroscope

A synchroscope is an essential tool used in the synchronization of power networks. Synchroscopes work of the synchronization window discussed in chapter **2.1.1 Synchronization Criteria**, where voltage amplitude along with frequency and phase angle must be matched to be able to safely synchronize two power systems.

A typical synchroscope measures and displays the frequency difference between two power sources and the phase angle difference. In addition to matching frequency and phase angle, separate indicators are often used to display whether the voltage of the source is too high or too low in relation to the target. [17]

There are both analog and digital synchroscopes available to be used in synchronization procedures. Analog synchroscopes rely on electromagnetic fields to rotate a phasor like a clock pointer through 360°, indicating the frequency of the source in relation to the target. If the phasor is rotating clockwise, the source frequency is higher than the target and vice versa. The rotation speed is proportional to the frequency mismatch between the source and reference (bus). An off-center static pointer means that the source frequency matches the bus frequency, but there is a mismatch between phase angles. When the phasor is stable on the center arrow, usually at the 12 o´clock position, both the frequency and phase angle are matched. Analog synchroscopes have a limited operating frequency range, only a few percent above and below the nominal frequency of the system. [17]

Digital synchroscopes replace the rotating phasor of an analog synchroscope with rotating indication LEDs placed in a circle. The LEDs work in the same way as the phasor in an analog meter. There is usually a separate LED color for indicating when the two systems being synchronized are in phase with each other and two LEDs for indicating whether the generator or source voltage is out of proportion with the target voltage. Digital synchroscopes are equipped with several user settings that can be modified according to specific parameters of the installation, such as synchronization window parameters and advance angles, as discussed in Chapter **2.1.2 Synchronization Methods**. [17] [18]

2.3 Safety Considerations in Synchronization Testing

Personal safety should always be the number one priority whenever working with electricity. Accidents can happen to anyone, even if you consider yourself seasoned. This chapter will discuss the dangers of electricity in a working environment and how it can be avoided.

Electric shock is a pathophysiological effect of current flowing through a body. Current flowing through a body affects mainly the muscular, circulatory, and respiratory functions and can cause serious burns. Depending on the type of current (AC/DC), the magnitude of the current, the path it takes, and the duration of time a person is in contact with a conductive live electrical part, the degree of danger can widely differ. [19]

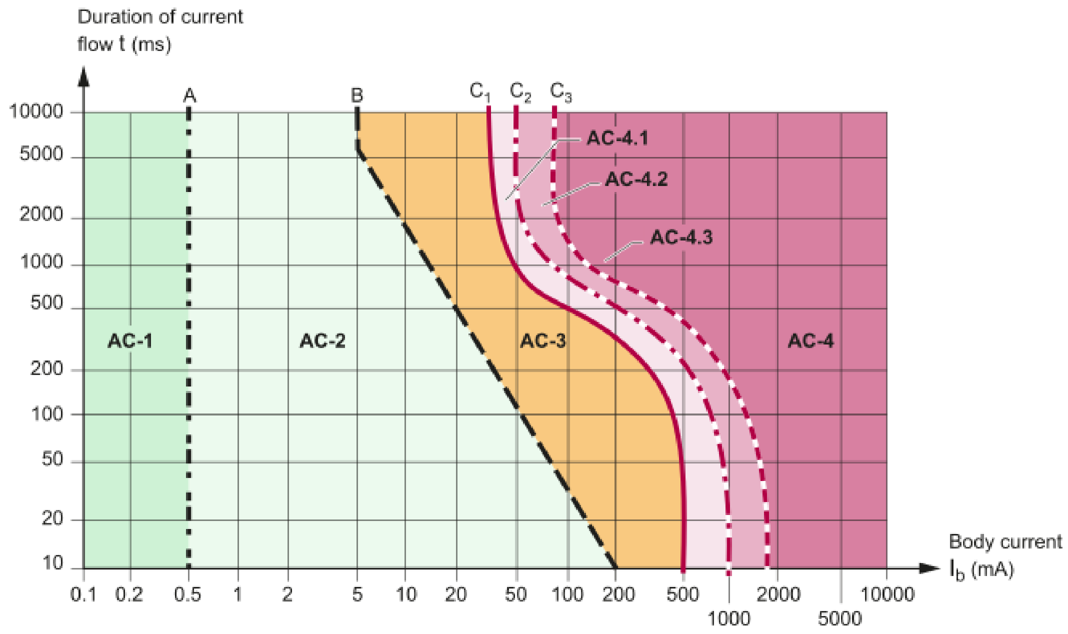

Figure 2.11 Effects of AC on the human body [19]

Effects of sinusoidal alternating current in the range of 15Hz to 150Hz can go from an absence of feeling the current or, in severe cases, even death. A value of 0.5mA independent of time is considered the threshold for perceiving current flow. With sinusoidal alternating currents with a frequency of 50-60Hz, there is a considerable decrease in the threshold of ventricular fibrillation if the duration of current flow is longer than one cardiac cycle. For shock durations under 0.1s, fibrillation may occur if the current exceeds 500mA. [19] [20]

Figure 2.11 describes four different zones with different levels of harm to the human body published by **IEC 60479-1**. The current flowing through the human body, measured in mA, and the duration of current flow, measured in milliseconds when passing from left hand to feet, is shown in the figure. Relevant IEC standards, such as **IEC 60479,** will be discussed more in-depth in the next chapter. [19]

The zones and curves described:

AC-1 zone: Imperceptible.
AC-2 zone: Perceptible.
AC-3 zone: Reverse effects: muscular contractions.
AC-4 zone: Possibility of irreversible effects.
AC-4-1 zone: Up to 5% probability of heart fibrillation.
AC-4-2 zone: Up to 50 % probability of heart fibrillation.
AC-4-3 zone: More than 50% probability of heart fibrillation.
A curve: Threshold of perception of current.
B curve: Threshold of muscular reactions.
C_1**curve**: Ventricular fibrillation unlikely to happen.
C_2**curve**: Threshold of 5% probability of ventricular fibrillation.
C_3**curve**: Threshold of 50% probability of ventricular fibrillation.

Fires can be caused by electricity, called electrical fires. Electrical fires can ignite due to overloads, short circuits, earth leakage, and electric arcs. In Finland, every year, over 2000 electrical fires are registered. [19] [21]

An electrical accident is referred to when a person has come to harm due to an arc flash directly or indirectly, such as falling because of an arc flash. For both electrical professionals and laypersons, almost all electrical accidents reported to Tukes occur in installations or devices operating at less than 1kV. Most of the electricity-related incidents reported to Tukes are predominantly caused by alternating current (AC), and only about one accident per year is related to direct current (DC). Tukes is the Finnish safety and chemicals agency within the Ministry of Employment and the Economy of Finland. [21]

In Finland, there are laws and regulations to ensure electrical work is done safely. These regulations set important standards, including:

- What kind of qualifications are needed to do electrical work.
- What kind of inspections are required.
- What are the technical requirements for the installation.
- How safety is maintained during electrical works.

All electrical work related to the construction and repair of electrical installations must be authorized with the following conditions:

- A sufficiently qualified person is appointed as a supervisor of electrical works. This person must be employed by the entrepreneur performing electrical work.
- Persons who, under the control of the supervisor of electrical works, independently carry out or supervise electrical work must have sufficient professional skills.
- The necessary tools, measuring instruments, and premises are available, as well as safety regulations and standards.
- A formal notification is sent to Tukes (the Safety Technology Authority in Finland) before electrical work activities can begin. With the notification the entrepreneur (a company or a person) proves through the included attachments that the stated requirements are fulfilled.

Authorization rules do not apply when it is considered layman´s work. Work is considered layman’s work, for instance, when working on installations having a nominal voltage below 50VAC or 120VDC. [22]

In Finland, there are three different qualification requirements with an issued certificate for the three categories:

- Category 1 (S1) covers all kinds of electrical work.
- Category 2 (S2) covers all installation and repair work not exceeding 1000 V.
- Category 3 (S3) covers repair work of appliances and machines not exceeding 1000 V.

When working with electricity, it is always important to follow instructions and know how to stay safe. The following chapters will discuss relevant safety standards when working with a low-voltage synchronization test bench.

2.4 IEC Safety Standards Relevant to Synchronization Testing and Safety

IEC stands for International Electrotechnical Commission and is one of the bodies entrusted by WTO or the World Trade Organization to monitor national and regional organizations that use IEC International Standards.

Consensus in the IEC regarding international standards means:

- All views have been taken into account.
- All major issues have been addressed.
- All major opposition has been overcome.
- A two-thirds majority of all participating experts agreed with the solution in the standard.
- A two-thirds majority of participating IEC members (National Committees) have approved of the standard, and less than 25% of all IEC members have voted negatively.

To further ensure that consensus is a democratic decision, a public inquiry is a vital feature of the IEC. Any IEC member country can submit an international standard for a public inquiry. This also allows experts outside the IEC to comment on any IEC standard. [23]

Multiple IEC standards are relevant to synchronization testing and some of them will be discussed more in-depth in this chapter. Regarding electrical safety, relevant IEC standards include **IEC 60479**, **IEC 60364**, **IEC 61140**, **IEC 61008**, and **IEC 61009** series. [19]

IEC 60479 and **IEC 60364** are safety standards regarding the effects of current on human beings and livestock and low-voltage electrical installations respectively. These standards will be discussed more in-depth in chapters **2.4.1** and **2.4.2** since they are deemed most relevant for a low-voltage synchronization test bench installation.

IEC 61140 describes common aspects of installations and equipment for protection against electric shock. This international standard applies to protecting persons and livestock against electric shocks not exceeding 1000Hz. Fundamental principles and requirements that are common to electrical installations, systems, and equipment with no limitations to the magnitude of the voltage or current or the type of current up to 1000Hz are within the scope of this standard. [24]

Fundamental rules of protection against electric shock, in general, imply that hazardous-live-parts should not be accessible nor accessible-conductive-parts under normal operating conditions or single-fault conditions. [24]

To meet the fundamental rule for protection against electric shock under normal operating conditions, basic protection, as specified by **IEC 61140**, is necessary. To provide sufficient protection for different installations with different voltage levels, the following bands are specified:

- High voltage (HV): protection is ensured by special measures, in particular earthing arrangements.
- Low voltage (LV): protection is ensured via basic and fault protection.
- Extra-low voltage (ELV): fault protection may not be needed, and under certain conditions, basic protection is provided by limitation of voltage.

Table 2.2 specifies the different voltage limits for the bands mentioned above for both AC and DC systems.

Table 2.2 Limits for voltage bands

Voltage band		AC	DC
HV		> 1000 V	> 1500 V
LV		≤ 1000 V	≤ 1500 V
	ELV	≤ 50 V	≤ 120 V

The upper limit of 120VDC in extra-low voltage bands is not necessarily true due to different environmental and contact situations described by **IEC TS 60479-1**, refer to **Table 2.2**. The waveform of the current and the path taken through the body widely affect the level of danger. Therefore, it is essential to consider whether an ELV value of less than 120VDC is necessary to meet the standard. [24]

If an accessible, non-hazardous-live part becomes a hazardous-live-part or if an accessible conductive part under normal operating conditions that is not live becomes a hazardous-live-part, it is considered a single-fault condition. Even in the event of mechanical failure where a protected hazardous live part becomes accessible, it is considered a single fault. To meet the fundamental rule under single-fault conditions, additional protection might be necessary. Each protective measure should be independent of each other, meaning that a failure in one protective measure should not affect other protective measures. Simultaneous failure in multiple protective measures is unlikely, and therefore, it is not normally taken into consideration. Additional protection may be required if the intended use of an installation implies an increased risk of harm to a person. Additional protection may be provided in the system or the equipment. [24]

In general, basic protection consists of one or more protection measures that, under normal circumstances, prevent contact with hazardous-live-parts. These protective measures can consist of basic solid insulation that prevents contact with live parts or insulation provided by air. Barriers or enclosures can provide further protection. Protective barriers should be mechanically stable, durable, and secured in place. Often, placing hazardous-live-parts out of arm’s reach where other protection measures are not viable may be necessary. In the case of low-voltage installations, placing objects out of arm’s reach means that simultaneous contact with conductive parts between which a hazardous voltage can exist is not possible. Hazardous live parts separated by more than 2.5 meters are normally deemed out of arm’s reach. [24]

Additional protection may be provided by a residual current protective device (RCD). In the case of low voltage protection, an RCD with a 30mA limit is used. Using a residual current protective device is recognized as additional protection in the event of failure of basic protection and/or fault protection. [24] [25] [26]

IEC 61008 and IEC 61009 both define the use of residual current operated circuit-breakers without (RCCB) and with integral overcurrent protection (RCBO), respectively. Both RCCBs and RCBOs are, in essence, circuit breakers that cut off the electricity supply when detecting leakages that can result in an electric shock. RCCBs must be used in series with a main circuit breaker (MCB) or fuse to protect them from damage. RCBOs are used in applications where there is the need to combine protection against overcurrent and protection against earth leakage currents. [25] [26] [27] [28]

IEC 61140 defines measures to be taken to protect against electrical shock. In chapter **2.4.1**, the effects of current on human beings are discussed as defined by **IEC 60479**, and different earthing methods in accordance with **IEC 60364** will be discussed in the following chapter **2.4.2**.

2.4.1 Effects of current on human beings (IEC 60479)

The effect of current depends mainly on the path of the current through the body as well as the magnitude and duration of the current flow. The time/current zones, as depicted in **Figure 2.11**, are not in practice applicable for protection measures against electrical shocks. The touch voltage, which is the product of the current flowing through the body (touch current), and the body impedance (resistance of the human body) as a function of time, is what determines the effects on the human body. Touch voltage is not linear due to variance in the body impedance. [19] [20]

Body impedance can vary greatly depending on the current path through different body parts, such as skin, flesh, and muscles. Also, touch voltage, duration of current flow, frequency, moisture, surface area of contact, and temperature affect the body impedance. [20]

In **IEC 60479**, the effects are primarily based on findings related to alternating current at 50-60Hz. However, these findings are applicable over the frequency range 15-100Hz. The main risk of current exposure is ventricular fibrillation (irregular heart rhythm) caused by alternating current (AC). Accidents related to direct current (DC) are much less frequent. [20]

The internal impedance of the human body can be mostly considered resistive. The value depends on the current path and, to a lesser extent, the surface area. The impedance of the skin can be considered as a network of resistances and capacitances due to the structure of the skin. The skin comprises a semi-insulating layer and small conductive parts (pores). Skin impedance falls when the current is increased and depends on voltage, frequency, duration of the current flow, surface area of contact, pressure of contact, moisture, and temperature. For lower voltages, skin impedance varies greatly, and for higher voltages, it decreases considerably, making it negligible when the skin breaks down. The initial resistance of the skin limits current peaks of short impulses, like shocks from electric fences. [20]

The sinusoidal alternating current effects on the human body in the frequency range of 15-150Hz are described in **IEC 60479**. The threshold of perception depends on several factors, such as the area of the body in contact with an electrode and the conditions of contact (dry, wet, pressure, and temperature). The threshold of reaction is assumed by **IEC 60479** to be 0.5mA independent of time. Immobilization is when the effect of the current is so strong that an individual cannot move voluntarily. The threshold of let-go is the level where an individual cannot let go of the electrode or source due to muscle contractions, which is assumed to be 10mA in adult males but differs from person to person. In **Figure 2.12**, currents at 60Hz were tested on a group of men and women to see what percentage of people at different current levels experience muscle contractions to the degree that they cannot let go. [20]

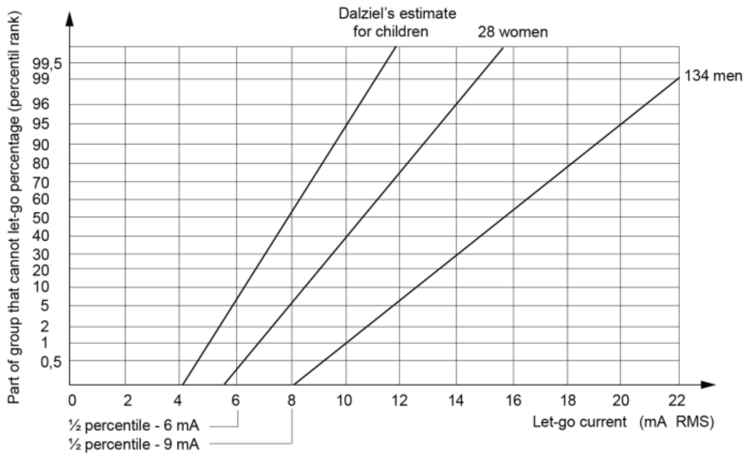

Figure 2.12 Let-go currents for 60Hz sinusoidal current [20]

The ventricular fibrillation threshold depends on physiological parameters, such as the body's anatomy and the state of cardiac function. Electrical parameters, such as duration and path of current flow, also affect it. With sinusoidal currents at 50-60Hz, the threshold is considerably lower if the current flow is longer than one cardiac cycle. Fibrillation may occur for current magnitudes above 500mA and a duration of below 0.1 seconds and is likely to occur at currents over several amperes (see **Figure 2.11**). [20]

Other electrical effects on the human body, such as muscular contractions, rise in blood pressure, and disturbances of formation and conduction of cardiac impulses, may occur but are generally non-lethal. Currents over several amperes lasting more than seconds cause serious burns and, in some cases, internal injuries. High voltage accidents generally do not cause ventricular fibrillation, but instead, it is likely to experience different forms of cardiac arrest. [20]

2.4.2 IEC Earthing Standard (IEC 60364)

Low voltage electrical installations are described in the **IEC 60364** standard in which proper earthing systems are provided. Three different earthing arrangements are specified in **IEC 60364** up to 1500 VDC or 1000 VAC, primarily frequencies 50 and 60 Hz. The three families of earthing arrangements that will be discussed in this chapter are TN, IT, and TT earthing arrangements. [29] [30]

The different codes of earthing arrangements in **IEC 60364** have the following meanings:

Table 2.3 Earthing arrangement code names

First letter	Second letter	Subsequent letter(s) (if any)
T = direct connection of one point to earth	T = direct electrical connection of exposed conductive parts to earth independently	S = protective function provided by a conductor separate from the neutral conductor
I = live parts isolated from earth or connected via high-impedance	N = direct electrical connection of the exposed conductive parts to the earthed point (PE)	C = neutral and protective functions combined in a single conductor (PEN)

As mentioned above, multiple ways of earthing a system according to specific needs exist. To furthermore clarify **Table 2.3**, the letter T stands for “Earth”, which derives from the French word “Terre”, the letter N means “Neutral”, S means “Separate”, C means “Combined” and lastly, I means “Isolated”. There can be many variances of, for example, a TN earthing arrangement as seen in **Figure 2.13**. [29] [31]

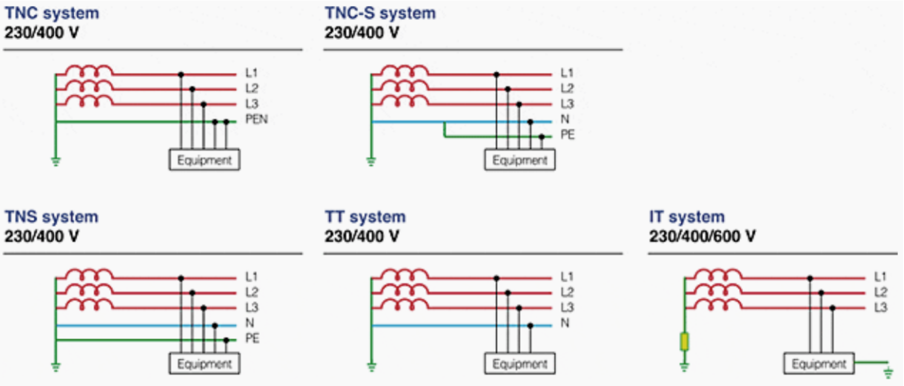

Figure 2.13 Earthing arrangements [29]

The source of a TN power system is directly connected to the earth at the source, while the exposed conductive parts are connected to said earth via protective conductors (PE). As shown in **Figure 2.13**, there are three types of TN earthing arrangements. The protective conductor can be combined with the neutral point (TN-C), or a separate protective conductor can be used throughout the system (TN-S). The last method of a TN arrangement is where a PEN is separated elsewhere in the installation (TNC-S). [30]

An inappropriate system design utilizing a TN earthing arrangement with multiple sources might cause some operating current to flow through unwanted parts of the system. These currents can cause a fire or lead to corrosion or electromagnetic interference. [30]

TT systems only have one point directly earthed, and the exposed conductive parts are connected to earth electrodes electrically independent of the supply earth electrodes. The neutral and earthed components are linked through an electrode system that returns to the source earth (and neutral). In IT systems, all live parts are isolated from earth or have one connection to earth through an impedance. The exposed conductive parts are earthed independently or collectively to the system earthing. [29] [30]

3 Methodology (Confidential)

4 Test Bench Key Components (Confidential)

5 Results

To ensure that testing at ABB's FAT area is uninterrupted and can be carried out smoothly, it was necessary to commission the non-functional synchronization test bench. The process of developing the test bench was done in multiple phases.

The first phase was re-evaluating existing components and deciding which components had to be replaced or added. Some essential components, such as measuring devices and filters, had to be replaced, and some were added to guarantee the safety of the test bench. The new measuring devices are accurate and reliable, and the filters used produce smooth sinewaves. As for increased safety, the added components result in a safe-to-use test bench that won’t cause shorts or electrical shocks. The components selected were most suitable for the test bench and complied with all the criteria.

After settling on what components to use, the second phase commenced. The second phase was to fix and re-design the existing drawings with the new components. The schematic is now more cohesive and easily comprehensible. Furthermore, the circuit diagram now has the correct components, and everything is connected accordingly. The drawings have been finalized and approved.

The third and final phase was to send offer requests of needed components to respective companies to get quoted. After receiving the quotations, an investment from ABB was made, and the components were ordered. When the components arrived, it was time to install them. All wiring was checked with a multimeter to ensure that none of the components had been improperly connected nor had any internal faults, such as shorts. Also, an analysis of the filters was made.

In **Figure 5.1** below, the unfiltered and filtered sinusoidal current signal is shown. The signals were measured with an oscilloscope, the unfiltered signal was measured before the filter and the filtered signal was measured across the resistance of the filter. The output current from the filter is too weak to measure using the probes available due to there not being any load. With the probe being 100 mV/A, an RMS current of approximately 0.2 A can be seen on the filtered signal.

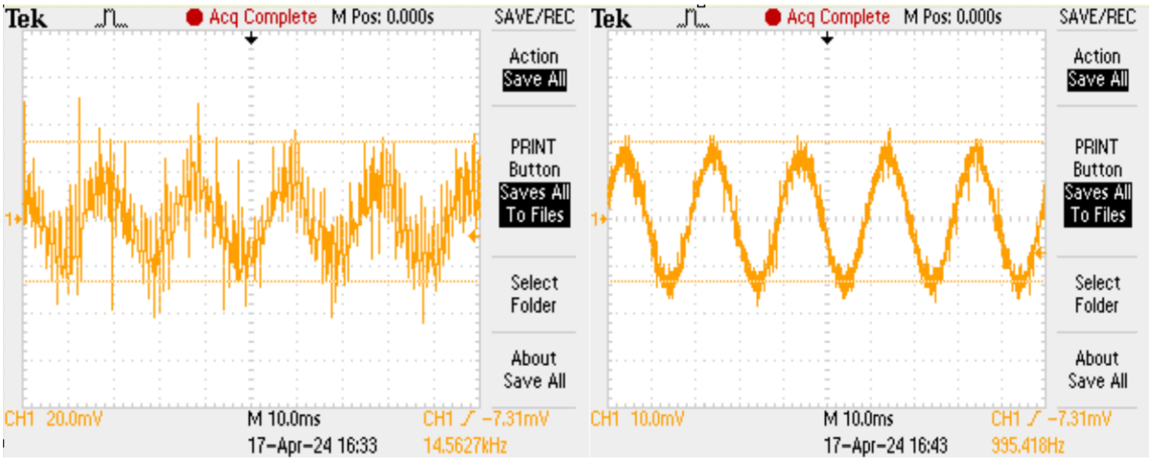

Figure 5.1 Unfiltered and filtered sinusoidal currents

Measurements of both the generator and the busbar side outputs were also conducted with the oscilloscope to ensure that the actual signals were within the scope of the criteria. The measurements were done by setting the generator and busbar voltages to 100, 110, and 120VAC and measuring all line voltages. In **Figure 5.2** below the oscilloscope readings of both the generator and busbars are shown, the voltage was set to 100VAC and measured L1-L2 for both sides.

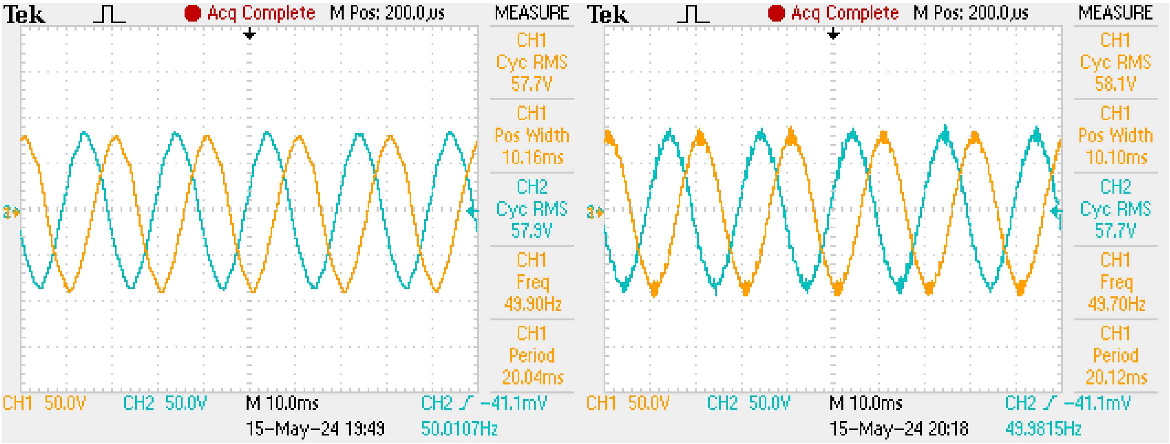

Figure 5.2 Generator and busbar output voltages L1-L2

The maximum errors between all phases for each voltage level selected are shown below in **Table 5.1**. All the inaccuracies are below the accepted level, which is 5%. These inaccuracies result from the signals containing noise due to imperfectly calibrated components and thermal drift.

Table 5.1 Calculated line voltage errors

Generator	100V	110V	120V
L1-L2	1,4V	2,1V	1,6V
L2-L3	1,9V	2,3V	1,0V
L3-L1	1,8V	3,3V	3,0V
Max error:	1,90%	3,00%	2,50%

Busbar	100V	110V	120V
L1-L2	0,6V	0,8V	0,8V
L2-L3	1,1V	0,5V	1,4V
L3-L1	0,9V	0,5V	1,4V
Max error:	1,10%	0,73%	1,17%

The functions of the test bench are listed below:

- Adjustable voltage (90-130VAC) and frequency (45-65Hz) on the generator side.
- Adjustable voltage (100VAC, 110VAC, and 120VAC) and frequency (45-65Hz) on the busbar side.
- Indication of voltages and frequencies on both sides.
- Indication of breaker position with a mimic.
- Local and remote control of voltages and frequencies:
  - Local control using switches located on the control panel.
  - Remote control using external signals from cabins being tested.
- Visualization of the system's relation by a synchroscope.

The result of this thesis was a fully operational, safe-to-use test bench that complied with all the initial criteria. The test bench has been used in projects, demonstrating its full functionality and reliability.

6 Conclusion

This bachelor's thesis project involved lots of research to understand how the synchronization of powerplants to the grid works. This included researching typical components used in synchronization circuits. With the help of the research, the synchronization test bench could be properly planned and constructed. A solid basis for the theory was provided in **Chapter 2**.

Having an additional functional synchronization test bench speeds up the testing process. It also ensures that if the old one, which was commissioned back in 2002, fails there is now a backup. The old test cabin was great for helping with the planning, especially when it came to the filtering of the outputs.

Due to time constraints and delivery times of components, the project quickly became stressful. However, this taught me how to handle stress when it comes to projects by being organized and planning. Time management was crucial so that the project could be finished on time. I had a strict schedule, for example, installing new components and rewiring the test bench at the FAT area as soon as components arrived and then documenting it afterward.

There is always room for improvement. In the case of the test bench, a rack of some sort could have been implemented to carry all test cables. The small size of the test bench has the benefits of being nimble and doesn’t take up much space. However, there are downsides, for example, the wiring inside the cabin does not have much space, and if something needs to be fixed or replaced in the future it can be difficult to do. Furthermore, the filter design could be improved to minimize thermal drift and stabilize the output signals even more, along with more exact calibration of some essential components.

I am pleased with the outcome of this project, as it fulfills all the requirements set in place. Most importantly, it is safe to use and meets the different standards that ABB requires. All in all, the project was joyful and gave me much insight into how synchronization works in practice. The project offered me a lot of challenges and difficulties during the research and development that had to be overcome, along with new methods for problem-solving. A key takeaway from this whole project is that a good initial plan is essential. However, obstacles will arise, thus sometimes needing to deviate from the original plan on the fly.

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