Tampere University

Kalle Rautiainen

DEVELOPMENT OF A LOSS ANGLE MEASUREMENT TECHNIQUE FOR ONLINE MONITORING OF INSTRUMENT TRANSFORMERS

Master’s Thesis
Faculty of Information Technology and Communication Sciences
Examiner: D.Sc. Kari Lahti
Examiner: D.Sc. Pertti Pakonen
June 2026

ABSTRACT

Kalle Rautiainen: Development of a loss angle measurement technique for online monitoring of instrument transformers
Master's thesis
Tampere University
Master's Programme in Electrical Engineering
June 2026

The energy transition, increasing electrification and the growing importance of security and reliability of electricity supply have created an increasing need for condition-based maintenance strategies in power systems. Loss angle measurement is a common method for assessing the insulation condition of high-voltage equipment. However, traditional loss angle measurements of instrument transformers require planned outages and extensive field work, which makes their implementation expensive and difficult to perform frequently. Therefore, an online loss angle measurement method could provide valuable information on long-term changes in insulation condition.

The objective of this thesis was to investigate whether an online loss angle measurement method tested at the substation could be developed into a reliable tool for continuous insulation condition monitoring of instrument transformers. The thesis is divided into two parts. The theoretical part presents instrument transformer technology, insulation aging mechanisms and loss angle measurement principles. The experimental part of the thesis includes laboratory measurements in which IoT-based measurement devices were tested with three different current sensing methods, including a split-core current transformer sensor, a solid-core current transformer sensor and a shunt resistor. The results were compared with reference measurements obtained using a traditional measuring bridge.

The results show that the proposed online measurement method can produce values comparable with reference measurements when a suitable current sensing method is used. The solid-core and split-core current transformer sensors introduced considerable phase errors, which led to physically unrealistic negative loss angle values. In contrast, the shunt resistor provided loss angle values that corresponded well with the reference measurements. The determination of accurate absolute loss angle values remains challenging, and the method appears to be best suited for monitoring long-term trends. Further development is required especially in understanding earth current formation in substation environments, validating the results under field conditions and improving the signal processing methods.

Keywords: loss angle measurement, instrument transformers, online monitoring, insulation condition monitoring

The originality of this thesis has been verified using the Turnitin Originality Check service.

TIIVISTELMÄ

Kalle Rautiainen: Mittamuuntajan jatkuva-aikaisen häviökulmamittausmenetelmän kehittäminen
Diplomityö
Tampereen yliopisto
Sähkötekniikan DI-ohjelma
Kesäkuu 2026

Energiamurros, lisääntyvä sähköistyminen ja sähkön toimitusvarmuuden kasvava merkitys ovat lisänneet tarvetta kuntoon perustuville kunnossapitostrategioille sähköjärjestelmissä. Häviökulmamittaus on yleinen menetelmä suurjännitelaitteiden eristysjärjestelmien kunnon arviointiin. Perinteiset mittamuuntajien häviökulmamittaukset edellyttävät kuitenkin suunniteltuja käyttökeskeytyksiä ja merkittävää työmäärää sähköasemalla, mikä tekee niiden toteuttamisesta kallista ja vaikeuttaa mittausten toistamista lyhyin aikavälein. Tämän vuoksi jatkuva-aikainen häviökulmamittausmenetelmä tuottaisi arvokasta tietoa eristyksen kunnon muutoksista.

Tämän diplomityön tavoitteena oli selvittää, voidaanko sähköasemalla testattua jatkuva-aikaista häviökulmamittausmenetelmää kehittää luotettavaksi työkaluksi mittamuuntajien eristyksen jatkuvaan kunnonvalvontaan. Työ jakautuu kahteen osaan. Teoriaosassa käsitellään mittamuuntajatekniikkaa, eristyksen vanhenemista ja häviökulmamittauksia. Työn kokeellinen osa sisältää laboratoriomittauksia, joissa IoT-pohjaisia mittauslaitteita testattiin kolmella eri virranmittausmenetelmällä: avattavalla virtamuuntaja-anturilla, kiinteällä virtamuuntaja-anturilla ja shunttivastuksella. Tuloksia verrattiin perinteisellä mittasillalla saatuihin referenssimittaustuloksiin.

Tulokset osoittavat, että ehdotettu jatkuva-aikainen mittausmenetelmä voi tuottaa referenssimittauksiin verrattavissa olevia arvoja, kun käytetään soveltuvaa virranmittausmenetelmää. Kiinteä ja avattava virtamuuntaja-anturi aiheuttivat merkittäviä vaihevirheitä, jotka johtivat fysikaalisesti epärealistisiin negatiivisiin häviökulma-arvoihin. Sen sijaan shunttivastus tuotti häviökulma-arvoja, jotka vastasivat hyvin referenssimittauksia. Tarkkojen absoluuttisten häviökulma-arvojen määrittäminen on haastavaa, ja menetelmä vaikuttaa soveltuvan parhaiten pitkäaikaisten trendien seurantaan. Jatkokehitystä tarvitaan erityisesti sähköasemaympäristössä muodostuvien maavirtojen ymmärtämisessä, tulosten validoimisessa kenttäolosuhteissa sekä signaalinkäsittelymenetelmien kehittämisessä.

Avainsanat: häviökulmamittaus, mittamuuntajat, jatkuva-aikainen mittaus, eristyksen kunnonvalvonta

Tämän julkaisun alkuperäisyys on tarkastettu Turnitin Originality Check -ohjelmalla.

USE OF AI IN THESIS

I have utilised AI tools in my thesis:

☐ No
☒ Yes

The AI tools utilised in my thesis and their purposes are described below:

Names and versions of AI tools: Microsoft Copilot (GPT-5), ChatGPT (GPT-5), Claude (Claude Opus 4.8)

Purpose of using AI tools: AI tools have been used for planning the structure of the thesis, finding sources, modifying Python code, assisting with text formatting and translating the abstract from English into Finnish.

Sections where AI tools were used: AI tools were used in Chapters 1–6.

I acknowledge that I am fully responsible for the entire content of my thesis, including the parts generated by AI, and accept accountability for any violations of ethical standards in publications.

PREFACE

I would like to thank Fingrid Oyj for giving me the opportunity to write my thesis on this interesting and meaningful topic. Many thanks to my advisor Mika Vartiainen, for the valuable support and guidance during the thesis process. I would also like to thank all my colleagues at Fingrid for their support and for sharing their ideas. Moreover, many thanks to my examiner Kari Lahti for the active guidance and supervision throughout this thesis writing process.

Lastly, I want to thank my family and friends for their support and encouragement during my studies.

Helsinki, 13 June 2026

Kalle Rautiainen

CONTENTS

1.INTRODUCTION ... 1
2. THEORETICAL BACKGROUND ... 4
2.1 Instrument transformer technology ... 4
2.1.1 Current transformers ... 4
2.1.2 Voltage transformers ... 6
2.1.3 Other instrument transformer types ... 8
2.2 Instrument transformer insulation technology ... 9
2.2.1 External insulation of instrument transformer ... 10
2.2.2 Oil-paper insulation ... 11
2.2.3 Other internal insulation technologies ... 15
2.3 Insulation aging, degradation and breakdown ... 16
2.3.1 Insulation aging and degradation ... 16
2.3.2 Insulation breakdown ... 20
2.3.3 Loss angle and how aging affects it ... 22
2.4 Insulation condition monitoring and loss angle measurements ... 24
2.4.1 Overview of insulation condition monitoring ... 24
2.4.2 Traditional loss angle measurements ... 26
2.4.3 Online condition monitoring ... 32
3. DEVELOPMENT OF NEW MEASUREMENT METHOD ... 34
3.1 Operating principle of the measurement method ... 34
3.2 Measurement method challenges identified during testing ... 37
4. LABORATORY MEASUREMENTS ... 40
4.1 High voltage laboratory ... 40
4.2 Implementation of the test measurements ... 40
4.3 New current transformer with good insulation ... 41
4.3.1 Results and analysis ... 44
4.4 Old current transformer with defective insulation ... 47
4.4.1 Results and analysis ... 48
4.5 Old voltage transformer with defective insulation ... 49
4.5.1 Results and analysis ... 50
4.6 Old voltage transformer from Tampere University ... 54
4.6.1 Results and analysis ... 55
4.7 Summary of the laboratory measurements ... 57
5. FUTURE IMPROVEMENT POSSIBILITIES ... 60
6. CONCLUSIONS ... 62
REFERENCES ... 64

LIST OF SYMBOLS AND ABBREVIATIONS

AC	alternating current
AIS	air insulated substation
BOPP	biaxially oriented isotactic polypropylene
CT	current transformer
DC	direct current
DFR	dielectric frequency response
DGA	dissolved gas analysis
DP	degree of polymerization
FFT	fast Fourier transform
GIS	gas insulated substation
GST	grounded specimen test
IEC	International Electrotechnical Commission
IoT	internet of things
IT	instrument transformer
PD	partial discharge
PMU	phasor measurement unit
RMS	root mean square
SF6	sulfur hexafluoride
UST	ungrounded specimen test
VT	voltage transformer

1. INTRODUCTION

The ongoing energy transition is changing how energy is produced, distributed and consumed. Energy production is shifting from fossil fuels towards renewable sources such as solar, wind, hydropower and geothermal. These renewable sources are often weather dependent unlike fossil fuels, which means controlling the power grid becomes more complex. At the same time electricity use is growing. These two factors together bring major improvement needs for energy infrastructure. As society becomes increasingly electrified, the reliability and security of electricity supply become even more important. Increased weather dependent production and integrated electricity markets can provide economic incentives to innovate various solutions of energy storage and grid balancing that are helping to improve the reliability of electricity supply.

Finnish transmission system operator (TSO) Fingrid responds to the energy transition with a large-scale investment program. In the “Main grid development plan 2026–2035” published in December 2025, Fingrid showcases a grid development plan for next 10 years. The plan includes various scenarios on how electricity production and consumption are expected to develop in Finland over the next 10 years. Fingrid has committed to building approximately 3800 km of new 400 kV transmission lines and in addition to that has several 110 kV transmission line and substation projects in the pipeline. Goals of the development plan are to strengthen the already clean and reliable power system as well as enable industrial scale investments utilizing clean energy. In the excellent competitiveness -scenario introduced in the development plan, total yearly electricity consumption in Finland could almost double from 85 TWh in 2025 to 160 TWh in 2035. Electricity production with wind and solar power during the same time period would increase significantly in this scenario. Wind power production would increase from 24 TWh to 95 TWh and solar power would increase from 1 TWh to 15 TWh. [1]

Digital substations represent a major step in substation technology by integrating digital communication and automation into traditional infrastructure. Digital substations can be embedded into substation automation systems and therefore leverage communication protocol standards such as International Electrotechnical Commission (IEC) 61850 as well as digitalization of signals and functions with high-speed data communication networks to replace conventional analog wiring. This enables real-time monitoring, advanced automation and optimized resource use which benefits grid owners, operators and maintenance teams. On the other hand, implementing this type of new technology can bring significant technical challenges in cybersecurity and interoperability. Consequently, when implementing digital substations, factors such as the security and reliability of the power system must be considered. [2] Condition monitoring is directly benefiting from real-time monitoring because data can be collected and made available continuously rather than only during periodic testing. This supports more proactive maintenance strategies, shifting maintenance from time-based toward condition-based decision-making. Digitalization can also be used to achieve broader engineering implications using system conceptualization, knowledge and optimization. Therefore, monitoring is not just an isolated measurement but more like part of a data-driven engineering process.

Online loss angle measurement technology for instrument transformers (ITs) would bring multiple benefits. Conducting traditional loss angle measurements is expensive because it requires planned outages and work from multiple stakeholder groups. In addition to that ordering a measurement on short notice can be challenging. Fingrid's grid development plan states that in addition to new grid investments, the aim is to make the most efficient use of the existing network to connect customer projects without compromising system security [1]. Development of online loss angle condition monitoring is directly supporting this goal. This monitoring method could be targeted specifically at the oldest devices and those most likely to fail, and their service life could possibly be extended with continuous measurement. The online measurement does not need to be as accurate as traditional measurement but the trends in the insulation characteristics must be noticeable.

The main objective of this thesis is to investigate whether an online loss angle measurement method tested at the substation can be developed into a reliable tool for continuous insulation condition monitoring of instrument transformers. Another objective is to identify suitable technologies and measurement arrangements that could support implementing the method. The work focuses on the influence of current sensing methods, practical implementation challenges and signal analysis, and evaluates the proposed method in a laboratory environment. It does not aim to provide full field validation or to develop a complete monitoring solution.

The structure of the thesis is as follows: the second chapter introduces comprehensive theory of instrument transformer technology and insulation technology used in those. After that, theory of insulation aging, degradation and breakdown as well as the term loss angle are presented. Theory chapter concludes with overview of insulation condition monitoring and traditional loss angle measurements. The third chapter presents the continuous loss angle measurement method and challenges identified with its implementation. The fourth chapter introduces the experimental part of the thesis, introducing laboratory measurements and the results obtained as well as the analysis.

The fifth chapter discusses improvement possibilities for the studied measurement method. The sixth chapter concludes the key points of the thesis.

2. THEORETICAL BACKGROUND

This chapter introduces the theoretical background for this thesis. It begins with an overview of conventional and non-conventional instrument transformer technologies. Then it discusses various insulation technologies used in these devices. Next, insulation aging and degradation mechanisms are explained in detail. The chapter concludes with presenting insulation condition monitoring methods, with particular emphasis on loss angle measurements.

2.1 Instrument transformer technology

Instrument transformers, more specifically current transformers (CTs) and voltage transformers (VTs) are essential parts of modern power systems. They are purpose-built transformers for measuring current or voltage. The main tasks of instrument transformers are to isolate the measuring circuit from the high-voltage circuit as well as enable the standardization of measurement and protection devices to specific design values. Other important tasks include protecting the instruments from overload and making it possible to install instruments and relays far away from the measuring point. [3, p. 198]

Characteristics of the instrument transformers can be examined with an equivalent circuit of standard transformer. However, it must be noted that CT's secondary winding is short circuited and VT's secondary winding is open circuited. Instrument transformers must show measured voltage or current at their normal load area as accurately as possible. However, idle current and leakage impedances of the windings will distort the measuring results. These distortions will show as current, voltage and angle errors of the instrument transformer. [3, p. 198] This chapter introduces current transformers, voltage transformers and other non-conventional instrument transformers. The focus is on oil-paper insulated instrument transformers as these are relevant for loss angle measurement.

2.1.1 Current transformers

Current transformers (CTs) are devices that are used to measure or monitor the current in power circuits. They are necessary in high power circuits where the current is larger than the current that measuring device can handle [4, p. 221]. Depending on the use case, another device can be paired to measure output current of the CT. Output current is used to calculate the primary circuit current for monitoring, equipment protection or billing purposes. This device can be, for example, a metering device, protective relay, data logger, or intelligent electronic device (IED) connected to the supervisory control and data acquisition (SCADA) system. [5]

CTs are basically similar in construction to standard transformers. They consist of magnetically coupled primary and secondary windings, wound on a common iron core. Primary winding is being connected in series with the network and therefore it must withstand the networks short-circuit current. Two main types of current transformers are wound primary type and bar primary type. The wound primary is used for the smaller currents and the bar primary type is used generally for currents larger than 100 A. [6, p. 54] Both types are shown in Figure 1.

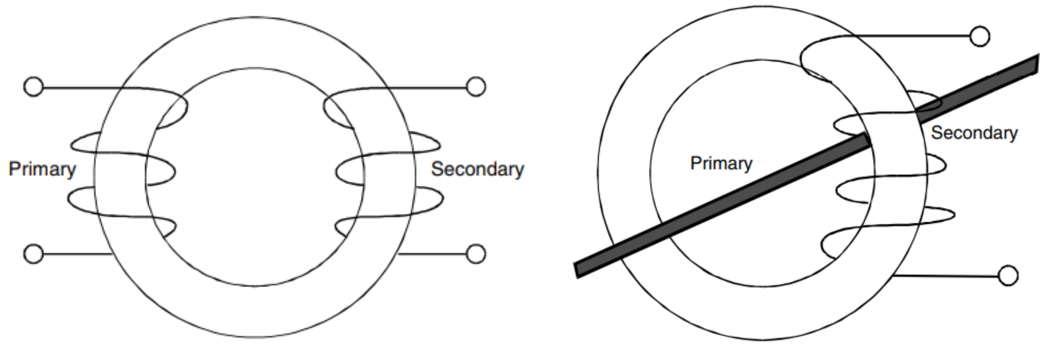


Figure 1. *Wound primary type (left) and bar primary type (right) current transformers. Modified from [6, p. 55].*

The CT secondary current is directly proportional to the primary current. This relation can be expressed with the following equation:

$$\frac{I_s}{I_p} = \frac{N_p}{N_s}, \tag{1}$$

where I_p is the primary current, I_s is the secondary current, N_p is the number of turns on the primary winding and N_s is the number of turns on the secondary winding. Turns ratio is the ratio between N_p and N_s. Current transformers typically have a turns ratio less than 1, meaning that the current I_s can be stepped down [5].

Characteristic quantities of CTs are presented in IEC standard 60044-1. Standard categorizes CTs into two classes according to their use case: CTs made for measuring purposes and CTs made for protection purposes. Two parameters defined for both classes are current error and phase displacement. Current error means deviation of the secondary current from the ideal situation where the idle current does not exist. Phase displacement is the angle difference between primary and secondary current phasors. Another important parameter for CT is burden which describes secondary circuit’s impedance and its power factor. Usually burden is presented as apparent power. When the burden is within the designed values, the CT will stay in its accuracy class meaning current error will not exceed the standard value. In the standards CTs are given accuracy classes which are defined with current error, phase displacement and composite error. CT's accuracy class must be selected according to the use case. [3, pp. 198–200, 203, 205]

The working function of the current transformer differs from a voltage transformer. CT operates with a set primary current which is not dependent on the secondary load current. Due to this, CT will operate into either a short circuit or a resistive load and should never operate into an open circuit [4, pp. 222–224]. If operated into an open circuit, the secondary impedance becomes infinite and the core saturates. This would induce a very high voltage to the secondary [6, p. 60]. High voltage in the secondary poses serious safety risks. For people in close proximity to the open circuit terminals, it can cause severe electric shocks. Moreover, the insulation materials used in CTs might not handle the excessively high voltages. This can result in arc flashes, insulation breakdown or failure [7].

Insulation materials used for outdoor CT installations are oil-paper and sulfur hexafluoride (SF6). The insulation material is hermetically sealed, so it is not exposed to outdoor humidity. CTs installed indoors are most often using cast resin as an insulation material. The advantage for these kinds of transformers is their electrical and mechanical strength. In addition to that they can be installed in any position. [3, pp. 211, 213]

2.1.2 Voltage transformers

Voltage transformers (also known as potential transformers) are used to measure or monitor the voltage in power circuits. Similarly as with the CTs, the VTs can also be paired with different kinds of measuring and protection devices [8]. VTs are also similar to conventional power transformers when it comes to construction. A VT has primary and secondary windings and the voltage produced at the load side is proportional to the number of turns in the secondary relative to the primary. This relation can be expressed with the following equation:

$$\frac{U_p}{U_s} = \frac{N_p}{N_s}, \tag{2}$$

where U_p is the primary voltage, U_s is the secondary voltage, N_p is the number of turns on the primary winding and N_s is the number of turns on the secondary winding. [8]

Characteristic quantities and requirements for voltage transformers are presented in IEC standard 60044-2 and technical specification 60044-5. In those documents VTs are divided into measurement and protection purpose voltage transformers similarly as CTs.

Voltage error and phase displacement have been defined for all VTs. Voltage error can be calculated with the following formula:

$$F_u = \frac{k_n U_s - U_p}{U_p} \times 100\%, \quad (3)$$

where k_n is the scale factor of VT, U_s is the root mean square (RMS) value of secondary voltage and U_p is the RMS value of primary voltage. Phase displacement is the angle difference between primary and secondary voltage phasors. In addition to these quantities, rated voltage factor k_R has been defined for VTs. It indicates the highest possible operating frequency primary voltage that the VT can thermally withstand for a certain time. [3, pp. 215–216]

As with CTs, standards have given VTs accuracy classes that have been defined according to the voltage error and phase displacement. Transformer must remain in its accuracy class when the voltage is 80 %, 100 % and 120 % of the rated value and burden is 25 % and 100 % of the nominal value. According to the IEC, VT's rated voltage must be chosen based on the nominal voltage of network. Burden of the VT is expressed as apparent power corresponding to the rated secondary voltage. [3, pp. 216–217]

Voltage transformers are usually built as single-phase and can be inductive or capacitive in terms of operating principle. Inductive VTs are used especially with operating voltages below 245 kV. With higher voltages, capacitive VT is usually a more economical choice. Capacitive VT basically consists of a capacitive voltage divider and an inductive voltage transformer. Inductive VTs structural principles are similar with CTs. [3, pp. 217–218] Diagrams of inductive and capacitive type VTs are shown in Figure 2.

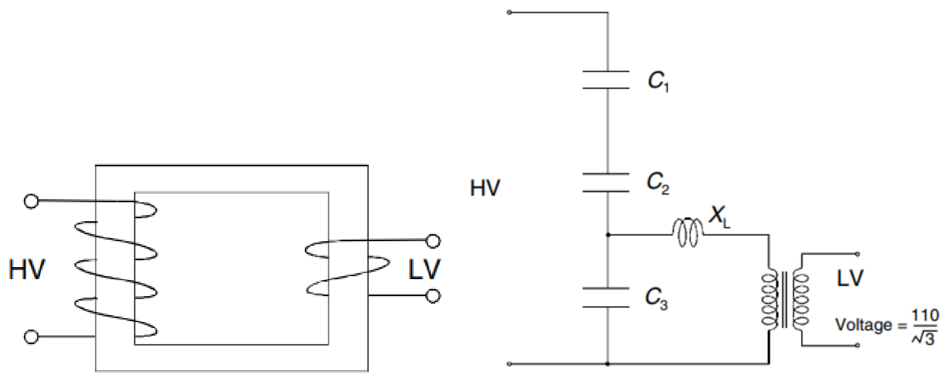


Figure 2. *Diagrams of inductive (left) and capacitive (right) voltage transformers. Modified from [6, pp. 46, 47]*

Insulation materials used with VTs are oil, SF6, and cast resin. Oil and SF6 insulated voltage transformers are produced for all voltage levels. Cast resin VTs are usually meant for medium voltage indoor installations. [3]

2.1.3 Other instrument transformer types

Apart from the conventional instrument transformers there are also other types of ITs available. Optical transducer is probably the most prominent out of these. Its main functions insulating and sensing remain the same. What separates it from conventional IT is that the link between the instrument transducer and the secondary output is not direct in case of an optical transducer. The link between the sensor and low voltage is based on optical converters and fibre channels. These optical converters are communicating with each other. One key difference to the conventional ITs is also more advanced electronic interface which is needed for its operation. As conventional ITs get diversity of functions and redundancies using multiple secondary coils, optical ITs achieve these functions and redundancies using multiple sensing units. Thanks to the lack of magnetic core and windings, optical instrument transducers can have noticeably smaller physical size and weight. Apart from these differences the conventional and optical ITs have quite similar structures. [9], [10]

Optical instrument transducers are using optical sensor technology. It is based on optical sensing media such as glass, crystals or plastics which is showing sensitivity to electric and magnetic fields and acting like a polarizer. When a light beam passes through this sensing media, its properties are altered. The light intensity at the detector fluctuates and this modulation of the light intensity caused by varying fields is then converted back into electrical signals. This interaction forms the basis of optical sensor concept. Optical current transducers use the magneto-optic effect sensor, meaning they respond to the magnetic field generated by current. Most current transducers use bulk-glass sensors due to its commercial availability. Optical voltage transducers commonly use electro-optic effect sensor, meaning they respond to an electric field. [11, pp. 38–39]

Optical transducers can be divided in two different types, hybrid and genuine transducers. Hybrid transducer is a conventional instrument transformer combined with an optical converter system. Furthermore, hybrid transducers can be separated in two types, depending on having active or passive sensors. Active hybrid transducer is changing the output of the conventional instrument transformer into optically isolated output. It is called active sensor because it often requires additional power source. Passive hybrid transducer structure consists of a passive optical sensor augmented into hardwire secondary of the conventional instrument transformer. [11, pp. 37, 39]

Genuine optical transducers as their name suggests are based on fundamental, optical sensing principles. These instrument transformers mostly have sensing technology that is fully passive. The sensing function works by the sensing material and communication is conducted by fibre optics. Genuine transducers versions are developed for current, voltage or combined current and voltage use cases. Even though the sensor of the genuine optical IT is passive, it still needs an electronic interface module in order to work. This module is powered in the control room. [11, pp. 37, 40–41]

Other non-conventional instrument transformer technologies include zero-flux current transformer, hybrid magnetic-optical sensor, Rogowski coils and integrated transducers. Zero-flux CT has a sensing element that is a semiconducting wafer placed in the gap of a magnetic core. It requires a power supply either from the line or from a separate supply. Benefit of the zero-flux CT is that it allows accurate current measurements in both direct current (DC) and alternating current (AC) applications. Hybrid magnetic-optical sensors are used in applications where a non-grounded current measurement is required. This can be for example in a case of series capacitive compensation of long transmission lines. Possible solution is then to use small toroidally wound magnetic core transformers which are connected to fibre optic isolating systems. Active current sensors requiring power supply are needed. [11, p. 43] Rogowski coil is a type of CT that has a nonmagnetic core and a high load impedance. It offers linear response and no possibility of saturation since the magnetizing components of error have been removed due to the air core. Contrary to conventional CT, Rogowski coil can be safely open-circuited since it has the high load impedance. [12, p. 135]

Integrated transducers are type of instrument transformers that can be integrated to the line or to the power station hardware. In this application non-conventional sensors are used in a suspended system. Optical fibres and special insulators are used with integrated transducers. Integrated transducers can be also used along with different power components like power transformers, circuit breakers, shunt reactors and switches. When sensors are mounted inside the apparatus, it leads to more compact equipment. Measuring equipment developed for gas insulated substations can be seen as integrated conventional ITs. [11, p. 44]

2.2 Instrument transformer insulation technology

The main insulation system for most instrument transformers consists of external and internal insulation. The external insulation system is usually an insulator with metal tanks at top and bottom. It needs to support the primary lead and the parts on top of the instrument transformer that are at line-potential. Material of the external insulation can be porcelain, composite or cast resin. The internal insulation system is usually integrated into the active part of an instrument transformer. In the case of a high voltage instrument transformer, the internal insulation material includes usually oil or SF_6. [11, pp. 17–18] This chapter discusses external and internal insulation systems and materials used in those. The main focus will be on the oil-impregnated paper internal insulations as those are used in the instrument transformers in Finnish transmission grid.

2.2.1 External insulation of instrument transformer

External insulator housing main functions are insulation as well as mechanical withstand and materials used for outdoor instrument transformers are porcelain and composite. In the Finnish transmission grid, older instrument transformers have porcelain external insulation, whereas newer ones are required to use composite insulation. [13] Resin can also serve as an external insulation material and in such cases, the same resin is typically used for both internal and external insulation. The specified conditions where the insulators are required to operate safely include mechanical stress, SF6-gas service pressure or oil volume and weight, lightning impulse withstand voltages, switching impulse withstand voltages and atmospheric pollution, contamination and rain. The mechanical properties of the insulator like size, shape and wall thickness are determined by the operating conditions. [11, p. 18], [14]

Porcelain insulators are commonly used with low pressure instrument transformers, but there are also high strength porcelain insulators available for ITs with higher working pressures. Internal plastic tubes are used to limit the pressure that is applied to the porcelain insulator. The tube is taking most of the pressure and the space between the porcelain and the tube is then filled with lower pressure. Material used in porcelain insulators is high strength and aluminous. If the insulator is longer than 1500 mm, it can be made of two or more parts connected together via joints. Extra care must be exercised during the jointing since the joints are prone to air bubbles which can moreover cause partial discharge. [11, p. 18]

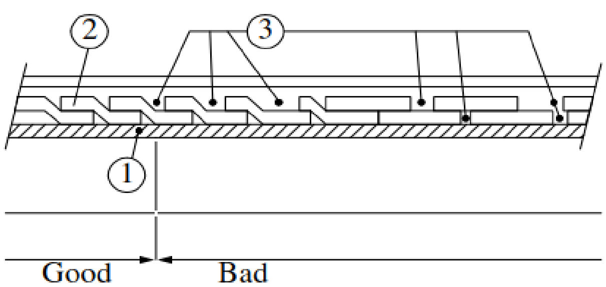
Composite insulators on the other hand can be used for all internal pressures. Three main components of the composite insulator are glass fibre resin tube for the mechanical strength, weather sheds made of polymer or silicone rubber for the pollution withstand capability and metal flanges. Regarding partial discharges or flashovers, the interface zone between tube and silicone is the most critical part. It must be taken care that the bonding is done right and there are no voids. [15] Composite insulator’s ability to repel pollution and contaminants is considered to be better than porcelain insulator’s because of the water repellent property of the silicone rubber material. However, it must be noted that there are not so much long term service documentation about composite insulators as there are about porcelain insulator. [11, p. 19]

2.2.2 Oil-paper insulation

The most common instrument transformer internal insulation system is the combination of oil impregnated paper and fluid, usually mineral transformer oil. It consists of layers of paper impregnated with transformer oil. [11, p. 19] Combining paper with transformer oil creates insulation with significantly better electric strength than either material alone [16, p. 123].

Mineral oil is the most used insulating fluid due to its wide availability and affordability. The most common mineral oil is transformer oil, whose required properties are defined by the IEC 60296 standard. Transformer oil is valued for its electrical properties and low viscosity. It is distilled out of crude oil and its boiling temperature is ranging between 250 – 300 °C. The fluid is nonviscous and thin, but it has notable drawbacks like susceptibility to oxidation and flammability. Flashpoint for transformer oil is over 130 °C. It needs to be noted that over time transformer oil can degrade due to oxidation, moisture and impurities. Mineral oils are composed of various hydrocarbon structures, primarily paraffins, naphthenes and aromatic oils. These different structures have all slightly different properties. [16, pp. 117–118]

Oil-impregnated paper is the most commonly used combination of liquid and solid insulation. It is used for instance in transformers, cables and capacitors. Thin paper sheets are easy to handle and mould into the desired shape. [16, p. 123] Construction structure of the paper layers plays an important role in the working function of the insulation. The withstand voltage is very high in the plane perpendicular to the paper layers. In contrast, in oil channels that run parallel to the paper layers, the flashover voltage is much lower. Thus, the paper layers must overlap properly to avoid long, continuous oil channels forming parallel to the layers. [11, p. 19] The electric field strength is high in thin oil layers and paper layers will also block the movement of impurities between oil layers [17]. This is visualized in Figure 3.



1. Metal tube
2. Paper strip
3. Oil channel

Figure 3. *Insulation layer overlapping principle [11, p. 20]*

Manufacturing oil-paper insulation is precisely defined process because in order to work correctly, homogeneity and density need to be the same in all parts of the insulation. Every type of IT has their own defined limit values and tests are performed to ensure that every manufactured device passes the limit. Drying the paper is an important stage in manufacturing the oil-paper insulation. Insulation paper contains between 7 and 10 % of water before drying process but it is reduced to between 0.1 and 0.2 %. Drying process uses temperature, vacuum as well as time and these parameters should be adapted to each unit depending on paper thickness and type. After drying, paper is impregnated with oil. It is important to select good quality oil since it is directly related oil-paper insulation properties and the service life of the IT. [11, pp. 59–60]

A study conducted by Federal University of Campina Grande was measuring breakdown voltage of mineral insulating oil with an electrode gap of 2.54mm. Six samples of breakdown voltage were taken and the mean value of the samples was calculated. Since the breakdown voltage can be affected by the presence of moisture, gases and solid impurities in the oil, a treatment was applied to the oil to make its characteristics better. Another six samples were taken after the treatment and the mean was again calculated. The results showed a mean breakdown voltage of 20.1 kV before treatment and 60.6 kV after treatment. [18] If these results are approximated into more common mode of presentation of kV/mm, then the results are 7.9 kV/mm before and 23.9 kV/mm after treatment.

A study conducted by Zhejiang University was measuring breakdown voltages of oil-paper insulation in different situations. First breakdown voltages of unaged, aged for 5 days, 10 days and 15 days were each measured respectively at different temperatures of 20 °C, 50 °C and 80 °C. Another experiment was performed using same aging times at 20 °C with 5 kHz, 10 kHz and 14 kHz frequencies measuring the breakdown voltage in high-frequency situation. There were 12 test samples taken for every situation of which the breakdown strength was calculated by measuring the thickness of the breakdown point and the statistical analysis of the two-parameter Weibull distribution was performed. The breakdown experiment results at different temperatures and at different high-frequencies are presented in the Table 1 and Table 2. [19]

Table 1. *AC breakdown field strengths at different temperatures and aging times.* [19]

Test temperature	Aging time	AC breakdown field strength (kV/mm)
20 °C	Unaged	76.02
20 °C	5 days	49.58
20 °C	10 days	42.21
20 °C	15 days	37.04
50 °C	Unaged	55.26
50 °C	5–15 days	28–29.19
80 °C	Unaged	36.79
80 °C	5–15 days	22.35–23.54

Table 2. *AC breakdown field strengths at different test frequencies and aging times.* [19]

Test frequency	Aging time	AC breakdown field strength (kV/mm)
5 kHz	Unaged	49.19
5 kHz	5 days	42.27
5 kHz	10 days	35.59
5 kHz	15 days	29.08
10 kHz	Unaged	43.38
10 kHz	5 days	37.81
10 kHz	10 days	31.93
10 kHz	15 days	26.88
14 kHz	Unaged	38.08
14 kHz	5 days	30.14
14 kHz	10 days	26.79
14 kHz	15 days	23.07

After comparing the two studies presented above [18], [19], it can be observed that oil-paper insulation has generally significantly greater breakdown strength compared to mineral oil alone. For example unaged oil-paper insulation at 20 °C had breakdown field strength of 76.02 kV/mm while breakdown field strength of mineral oil was approximated to 23.9 kV/mm. However 5–15 days aged oil-paper insulation at 80 °C had a breakdown field strength of only 22.35–23.54 kV/mm, which is lower than the treated mineral oil. Also, 15 days aged oil-paper insulation at 14 kHz had a breakdown field strength of 23.07 kV/mm. This shows that temperature, high frequency as well as aging time all have significant degrading effect on oil-paper insulation strength. It must be emphasized that these studies were conducted using different methods so direct comparison between the two studies must be approached with caution. The treated mineral oil being tested was not aged while it would have been also beneficial to compare aged oil with aged oil-paper.

Although liquid-immersed transformers have been mainly filled with mineral oil for more than one hundred years, at present there are also other options available. Since environmental issues are becoming more important, switching to biodegradable products seems tempting. Natural ester oils have emerged as alternatives for mineral oil. Natural oils are renewable since they can be extracted from vegetables like castor oil plant, soya, rapeseed and sunflower, to mention a few. In addition to this, they require less energy for their treatment and simple apparatus for their extraction. There are also two other major reasons for growing interest in natural ester oil based dielectric fluids. Firstly, their high values of both flash and fire points ensure excellent fire safety characteristics compared to mineral oils. Secondly, petroleum oils might get more scarce in the future which could cause rapid increase in their price. However, there remains challenge to substitute mineral oils with natural ester oils since they have differences in their characteristics. Challenging characteristics for natural ester implementation include pour point, oxidation stability, viscosity and ionization resistance [20]. Solving these issues is compulsory because they are affecting the operation, maintenance and monitoring of the transformer. [21]

Other more environmentally friendly insulation oil options are silicone oils and synthetic esters. The main raw ingredient for silicone oil is silica which is an abundant resource. Silicone oils are able to conserve their insulating properties for extended periods due to their low volatility, chemical stability and resistance to oxidation. Synthetic esters on the other hand are made of acid and alcohol. Characteristics of the synthetic esters can be modified by adjusting the materials used. Both silicone oils and synthetic esters have higher flash point than that of mineral oil. [22]

2.2.3 Other internal insulation technologies

Fingrid uses only oil-paper insulation for the internal insulation of instrument transformers. However, there are also other internal insulation structures available for transmission grid voltage level. Some of these are newer and could have better characteristics compared to the traditional oil-paper insulation. This chapter briefly introduces these other insulation technologies of which two are used in air insulated substations (AIS) and one is used in gas insulated substations (GIS).

Laminated pressboard and laminated wood are alternatives for oil-paper insulation. Producing the laminated pressboard is done by laminating individual sheets of high-density pressboard together with either a synthetic adhesive or casein glue. Laminated wood on the other hand is manufactured by joining pieces of wood veneers together. This happens under pressure and heat with a thermosetting synthetic adhesive. Laminated wood products have many different grades, which are defined by the density of the wood and the directionality of wood veneers. [23]

Another newer alternative for oil-paper insulation is biaxially oriented isotactic polypropylene (BOPP) film insulation. BOPP characteristics include high dielectric strength and low dielectric losses which make it a great dielectric material for high-voltage insulation. These superior dielectric properties are due to the biaxial stretching which transforms the spherulitic cast film morphology into highly oriented fibrillar morphology. It is produced by tenter frame process. BOPP applications are more widely used for capacitors but they can also be implemented for instrument transformers. [24]

Instrument transformers used at the gas insulated substations often use SF6 as their main insulation gas. SF6 is well working insulation gas for compact substations because of its excellent chemical, physical and dielectric properties. SF6 has a dielectric strength approximately three times higher than that of air at atmospheric pressure and thermal conductivity approximately twice that of air. These characteristics make SF6 insulated GIS much more reliable than conventional air insulated substations. Other benefits include smaller power consumption and much more compact structures. Disadvantages of SF6 insulated GIS include higher repair costs in case of a failure compared to AIS and SF6 nature as a powerful greenhouse gas. [25] Because of its high global warming potential, the use of SF6 is being phased out in the EU. The revised F-gas Regulation (EU) 2024/573 prohibits the putting into operation of new electrical switchgear using fluorinated greenhouse gases as the insulating or breaking medium, with phase-out dates introduced gradually by voltage level between 2026 and 2032. Existing installations may remain in operation, so SF6-insulated equipment will still be present in substations for a long time. [26]

2.3 Insulation aging, degradation and breakdown

The life expectancy of a transformer is largely determined by how its insulation system ages over time. Research shows that primary influences of aging are temperature, moisture and oxygen. [27, p. 26] This chapter explains the aging, degradation and breakdown of the oil-paper insulation. The term loss angle, which is relevant to this work, is introduced, and how aging affects its value is described.

2.3.1 Insulation aging and degradation

As transformer insulation ages its dielectric and mechanical properties gradually deteriorate over time. However, in most cases transformers operate at lower loads than they are specified for and that might extend their life expectancy. On the other hand, operating conditions for the insulation of transformer are usually not optimal. Factors like temperature, moisture, oxygen, acids and contaminants worsen the insulation condition and furthermore accelerate aging the most. [27, p. 26]

Transformer oil is being exposed to heat, oxygen and electrical discharges, which can lead to its degradation. This produces aging products which are reducing electrical properties and cooling efficiency meaning that primary functions of the oil are limited severely. Some aging products of oil are also detrimental for solid part of the insulation. Key factors of oil aging are usually temperature and moisture. Other catalysts for aging include copper, paint, varnish and oxygen. Important mechanism of oil aging is oxidation, which leads to formation of acids and other polar compounds. These products will have damaging effect on the aging process. [28]

Mechanisms of the oil aging are complicated. Oxygen is reacting with certain hydrocarbons according to the free radical process that generates hydroperoxides. These hydroperoxides are not stable and are decomposing to form ketones and water. Further, ketones can be oxidized to form carboxylic acids or cleaved to make aldehydes. The appearance of hydroxyl groups is resulting in the formation of alcohols and phenols. It can be stated that most oxidation products have a negative effect on the electrical properties of oil. As the oil is aging, the clearest change in its characteristics is the increase in acidity. Dissolved acids from oil can also damage other materials of the insulation like paper or pressboard. [28]

Aging of the insulation has significant effects on material properties. In case of oil impregnated paper insulations, the degree of polymerization (DP) of the paper is one of the most important of these properties. It is a measure of the average length of the cellulose macromolecules. With a new insulation the value of DP is at its highest, but it will decrease due to the continuous shortening of the cellulose molecules by chain scission as insulation ages. New instrument transformers are built with new unaged insulation which needs to be completely dry. However drying process requires long exposure times for high temperatures and that can cause early aging phenomenon. [29]

Insulation paper and pressboard are normally manufactured from unbleached softwood kraft pulp. Processed Kraft pulp consists of cellulose, hemicellulose and lignin of which notably the largest share is cellulose, around 80 %. DP value for new unbleached softwood kraft pulp is typically 1200-1400. In the real world many factors have an impact on the actual DP number of new presspaper and pressboard. These include tree type of the pulp, climate condition of the trees, chemical treatment of the wood and the manufacturing process. Due to these factors, actual DP of new insulation can typically vary on a range 1100-1350. [29] As the insulation ages and degrades the value of DP can decrease to as low as 150. At this point the insulation material has become highly deteriorated, brittle and friable. [27, p. 55]

Insulation aging also affects other properties of the material, though these are often related to DP value. Tensile strength refers to the mechanical strength of insulating paper and it is important for the functioning of electrical equipment. Choice of raw materials and the manufacturing process is affecting the tensile strength value and it has a direct correlation to the degree of polymerization. Burst strength is also measuring the mechanical strength of the insulation but while tensile strength measures uniaxial strength, burst strength tests the biaxial strength. It has a correlation with the DP as well, but the values are typically lower than for the tensile strength of the same insulation. Elongation and folding endurance are properties that refer to the brittleness of the material and both of these values are linked to the degree of polymerization. Smaller these values become the more brittle the insulation paper will be. [27, p. 22]

Insulation aging depends heavily on temperature. Montsinger's rule defines that depending on the material, insulation life expectancy is halved for every 6–10 degrees temperature increase [30]. Paper type of the insulation determines a designed maximum hotspot temperature inside the top of the transformer windings. It is 98 °C for normal kraft paper [31] and 110 °C for thermally upgraded paper [32]. Temperature has a strong decaying effect especially for the mechanical strength of the paper. Figure 4 illustrates how tensile strength, elongation and folding strength decrease in different temperatures.

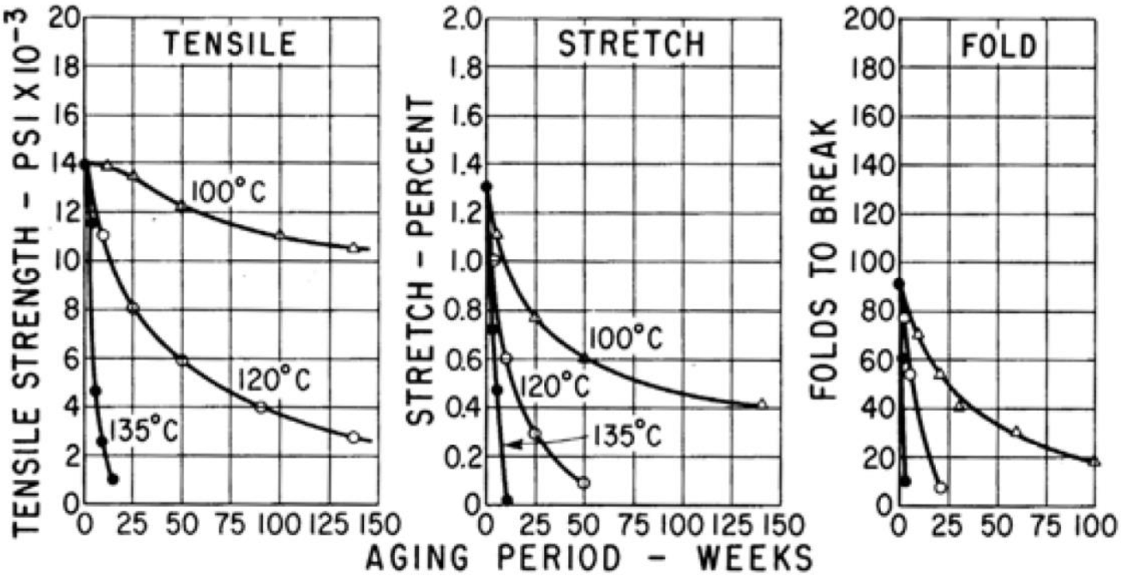


Figure 4. *The effect of temperature on three mechanical properties of vacuum dried and oil impregnated insulating paper. Modified from [27, p. 27]*

It can be stated that three main degradation processes for the insulation are hydrolysis, oxidation and pyrolysis. In reality, all these processes act simultaneously and moreover synergetic effects can take place between these processes. One process can activate the other. [27, p. 32] Pyrolysis refers to the process that takes place without access to water, oxygen or any other agent to initiate the decomposition. Pyrolysis is occurring in significant amounts only in temperatures above 140 °C so it is not considerable in normal operating temperatures. [27, p. 33]

Hydrolysis refers to cleavage of glycosidic linkages in the presence of water. It is catalyzed by acids and leads initially to cleavage of cellulose chains by consumption of water. [33] This will increase the rate of degradation. A new kraft insulation contains less than 0.5 % of water but during its lifetime the water content might increase up to 5 %. It has been shown that the rate of degradation of the paper at 4 % water content was 20 times greater than that at 0.5 % water content. Basically, this means that the aging rate of the insulation is increasing as it deteriorates. [27, p. 33] Hydrolysis of cellulose is a catalytic process influenced by dissociated acids and H^+-ions penetrating cellulose's amorphous zones. This implies that the aging factor depends both on the presence of organic acids and water, which facilitates acid dissociation. Low molecular weight watersoluble acids formed by paper aging and to some degree by oil aging, exhibit higher catalytic efficiency compared to larger hydrophobic acids. Acid catalyzed hydrolysis not only produces additional organic acids but also creates an auto-accelerating mechanism that worsens insulation degradation. [34]

Oxidation refers to reactions caused by molecular oxygen or other oxidizing agents that might be present. It can also refer to all non-hydrolytic processes that lead to cellulose fragmentation. [33] Oxygen will accelerate insulation degradation significantly. It is reported that if oxygen level in the oil stays below 2000 ppm, the rate of degradation of the full insulation system is five times lower than that of a free breathing transformer. However, the research is somewhat contradictory about the effect of oxidation on insulation aging and degradation. Other results suggest that by extracting the oxygen to below 300 ppm, the effect of oxygen can be reduced to a sixteenth of that of normal operating conditions. Other results state that aging of insulation paper having access to oxygen is only about 2–3 times higher than aging under vacuum. Oxidative depolymerization is catalyzed by hydroxy-radicals, which are produced by decomposition of hydrogen peroxide and organic hydroperoxides. Oxidation reactions are less significant in acidic environments so in such environments their importance would be reduced over time. [27, p. 33] [34]

Electrical discharges can damage solid insulation in such way that over time tree like erosion feature is forming through insulation. This phenomenon is called electrical tree and ultimate breakdown can eventually happen through it. Formation of the electric tree can start from the unevenness of the electrodes or from conductive impurities inside the insulation. Interfaces of the solid and liquid insulation materials are usually the weakest points of the insulation. Electrical discharges can also occur on the surface of solid insulation or at the electrode junction. [16, p. 131]

The aging and degradation of the insulation lead to formation of many different degradation products, of which some are stable and some might degrade further. The final degradation products of cellulose are water and carbon oxides. However, real transformer cannot be operated until the insulation components are fully degraded so in reality the main degradation product is modified cellulose. A degradation product is a concern if it threatens the safe operation of the transformer or if it is affecting the aging rate of insulation. Alternatively, degradation products can be useful when used as an indicator of aging or in some other diagnostic purposes. [27, p. 39]

The aging of cellulosic insulation in oil-impregnated systems produces various degradation products, including water, acids, furanic compounds and carbon oxides. Most of the water formed remains in solid insulation, while only less than 1 % dissolves in the oil. Hydrolysis and oxidation processes create acids, some of which accelerate further degradation. Furanic compounds can be used as diagnostic markers for insulation aging. Carbon oxides are ultimate degradation products and their levels help assess the condition of the insulation. Degradation products from oil are acids, peroxides and sludge. These can further impact the aging of both oil and paper. Other degradation products include hydrocarbons, hydrogen, cellulose fibres and different oil-soluble paper degradation products. [27, pp. 43–44]

2.3.2 Insulation breakdown

When voltage is applied across the insulation, a leakage current flows through it. Significantly growing leakage current indicates that the insulation is being damaged. In complete electrical discharge, insulation characteristics of the insulation are disappearing completely and the discharge connects the electrodes. In this case current through insulation is growing really high while voltage is dropping. Complete discharges are divided into two types, breakdowns and flashovers. In the breakdown, discharge channel is passing through the insulator. In the flashover, discharge channel is located at the interface of two different insulation materials. Electric discharge is incomplete when it is not connecting the electrodes. Partial discharges (PD) are one form of incomplete discharges. There are different kinds of partial discharges and they can develop into complete breakdown or flashover. [16, p. 63]

Basically breakdown happens as an electrical breakdown which is a multiphase chain of events. Many factors like ionization, excitation phenomenon, space charges, heating of the insulation and changes in the molecule and crystal structure will all affect the electrical breakdown process. It is supposed that the breakdown will start from non-homogeneous spot in the insulation or electrode surface where critical electric field is being exceeded locally and electric discharges are born. Insulation will be destroyed through chemical and physical processes due to these discharges and a charge carrier channel through is starting to form. Final breakdown happens when this channel connects the electrodes. [16, p. 130] Main focus in this thesis is on oil-paper insulators which contain liquid and solid insulating materials. Because of this we will focus here especially on breakdowns in liquid and solid materials.

There is a critical electric field strength that insulation material can withstand and it is dependent on many factors like temperature, voltage form, stress time and thickness of the material. When this critical electric field strength is exceeded, it will start failure process that will eventually lead to a breakdown. For the dielectric liquids, this process means formation of bubble- and tree-like discharges. These discharge types are often called streamers, and they happen before the complete electrical breakdown. As these discharges increase in length and numbers, they may eventually cross the gap between electrodes. Electric conductivity is greater in streamers in comparison with the surrounding medium so this would mean short-circuiting the electrodes and causing complete breakdown. The mechanisms of this streamer generation process depend on the composition of the insulation, the direction and magnitude of the electrical field, and the electrode geometry of the system. These phenomena have been studied widely, but many aspects are still unclear. Two theories are accepted to explain the breakdown process: the “bubble theory” and the “direct impact ionization theory”. The bubble theory supposes that the electrical breakdown starts in a bubble of gas near or at the electrode. This bubble can be created due to heat generated by the strong electrical field. On the contrary, direct impact ionization theory assumes that breakdown process occurs in liquid and structures that develop are liquid of different density compared to the surrounding medium. Literature often favors the bubble theory since it explains the experimental observations better. [35]

Streamers are usually formed in parts of the insulation where electric field is strong, for example at protrusions or at sharp edges. The streamer propagation processes are different at negative cathode and positive anode electrodes. When a high electric field is concentrated at a negative electrode, electrons are injected into the dielectric liquid. These electrons interact with liquid molecules releasing energy through joule heating, which can evaporate some portions of the liquid and form gas bubbles. If a gas bubble is sufficiently long lived, electrons traveling through it can gain enough energy to ionize more molecules. If this reaction continues, the streamer continues to propagate. When the electrode generating a strong field is charged positively, no electrons will be injected into the liquid. Instead, in order to start the streamer, an electron must be liberated from a molecule through an ionization process. This process is random by nature. Liberated electron must be made available close to the electrode in order to induce a cascade reaction as electrons are accelerated towards the positive electrode. Similarly as with negative electrode, the heat generation of this process leads to evaporation of the liquid and formation of a gas bubble. Electrons accelerating towards positive electrode will induce further ionization and the streamer will continue to propagate. [35]

Despite the notable research work, knowledge about breakdown mechanisms in solid insulation is still insufficient. For a breakdown to happen, amount of charge carriers must increase to a level that the insulation loses its special characteristics. This happens via process that activates thermally or electrically. In practice there are many other factors affecting the breakdown process as well. These include heating caused by pre-discharge current and dielectric losses, electrostatic forces on interfaces and electrochemical reactions in the insulation itself. Regardless of the mechanism, breakdown in solid insulation leads to thermal destruction of the insulator at the breakdown location and it always loses permanently its insulation capability. [16, p. 128]

The International Council On Large Electric Systems (CIGRE) has been conducting broad surveys of IT failures. It has defined that a major failure is a sudden explosive event that has caused an immediate emergency system outage or trip. Minor failures and defects are classified into other categories. In the worst case scenario, instrument transformer insulation breakdown can lead to explosion of the IT. This has many serious consequences, most obvious of which are direct cost of replacing the damaged IT and direct cost of replacing neighboring equipment damaged in the explosion. It also poses serious risks of injury for personnel working at the substation. On top of that, there might be costs through undelivered electricity during the repair and replacement of damaged equipment. [36]

2.3.3 Loss angle and how aging affects it

In an insulation system exposed to an alternating voltage field, power losses happen due to the dielectric after-effect, molecular friction and the inherent conductivity of the material. These power losses are referred as dielectric losses. In the case of direct voltage, power losses are primarily caused by conductivity alone. Both insulation conductivity as well as power losses typically grow as temperature rises. Loss angle of the insulation is describing how much insulation differs from the ideal insulation. Ideally the phase difference between current and voltage would be 90° but in a real world it is slightly less. [16, p. 54] Value of the loss angle can be calculated with capacitive and resistive currents in the following way:

$$tan\,\delta = \frac{I_R}{I_C}, \tag{4}$$

where δ is the loss angle, tan δ is the dissipation factor, I_R is the resistive current and I_C is the capacitive current. The bigger the resistive component is the bigger the loss angle will be. Loss angle and equivalent circuit of the insulation are presented in Figure 5.

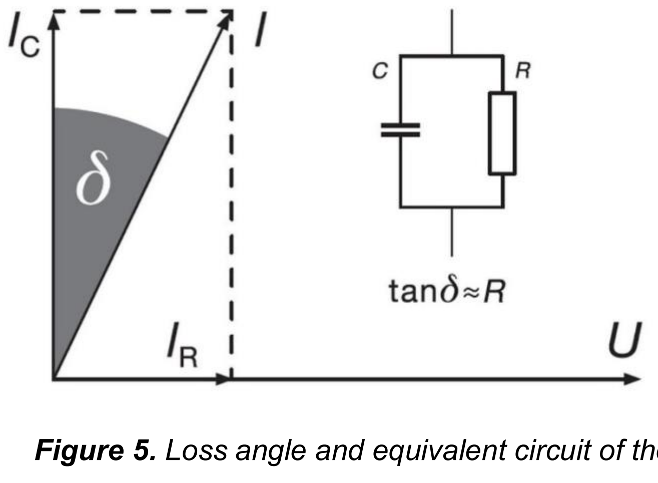


Figure 5. *Loss angle and equivalent circuit of the insulation. [37]*

The tan δ value of insulation is increasing as material is aging or e.g. when partial discharges incept in the insulation system. Especially moisture is increasing $\tan\delta$ significantly. A study was conducted to examine how moisture and aging influence the dielectric properties of individual transformer insulation materials. The experimental results were then correlated with the $\tan\delta$ values typically measured in a transformer. The results were as follows: [38]

As moisture contents of mineral oil is increasing, $\tan\delta$ is slowly increasing as well. When moisture contents reaches a certain threshold, the increase of loss angle becomes significant. Aging of sealed and unsealed mineral oil was compared at 115 °C. Value of $\tan\delta$ is increasing in both unsealed and sealed cases, though for sealed mineral oil it is more radical. Loss angle of the sealed sample is believed to be higher because of the by-products and catalysts produced during aging. These catalysts like moisture and acids are reported to accelerate the aging process. In an unsealed sample these catalysts are believed to possibly evaporate out from the sample. Colors of the samples on the other hand show a contradictory result. Unsealed oil sample color looks more severely aged but that might be due to oxidation. Similarly as with mineral oil, insulation paper $\tan\delta$ is increasing when its moisture contents increases. Moisture is located at capillaries of cellulose insulation and conductivity of paper is changing due to its increase. This will lead to increase in $\tan\delta$ value. Moisture on pressboard has similar effect on $\tan\delta$. [38]

In the final part of the study $\tan\delta$ values were calculated in two conditions. The other considered condition was good when the insulation is fairly dry and the other was wet condition. Data from the earlier results was extracted directly or obtained by extrapolation. The difference in $\tan\delta$ value was really significant between dry and wet cases so it can be stated that “wetness” of insulation is a factor influencing heavily on the increase of loss angle. [38]

Amount of moisture contents in the insulation system largely determines how the value of $\tan\delta$ behaves in different frequencies. In the oil-paper insulation, dissipation factor is basically always rising while moving to smaller frequencies. However, when moisture content is high, there happens increase in $\tan\delta$ value also at higher frequency. It is beneficial to be aware of this when planning measurement arrangements. This event is illustrated in Figure 6.

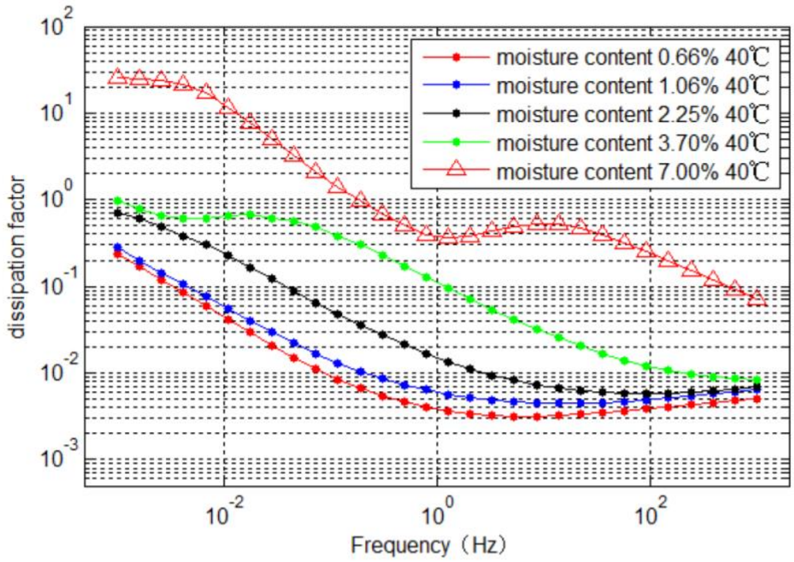


Figure 6. *Dissipation factor of oil-paper insulation samples of different moisture content at 40 °C. [39]*

A further characteristic of instrument transformer insulation is its small capacitance, which has two important implications for loss angle measurement. First, the small capacitive current means that tan δ values are generally higher than in many other insulation structures as typical solid insulations achieve values of 0.001–0.0001. Second, the small capacitance results in very small measurement signals, which increases the sensitivity of the measurement to external interference and makes accurate phase angle determination more challenging.

2.4 Insulation condition monitoring and loss angle measurements

This chapter presents an overview of the insulation condition monitoring as well as the traditional loss angle measurements. The last subchapter discusses online condition monitoring and why it is needed. Consequently, this chapter lays the foundation for the actual development work conducted later in this thesis.

2.4.1 Overview of insulation condition monitoring

Importance of diagnostics and condition monitoring is growing ever more important in the electricity production, transmission, distribution and use of high voltage devices. As electricity quality requirements become stricter, the number of unplanned outages should be kept to a minimum. Economic questions are also at stake as electricity is sold on the open market. Cost reasons are defining the need to focus the condition monitoring and inspections only on devices where it gives the most benefit. Condition monitoring can be divided into on-line and off-line monitoring. On-line condition monitoring can be either continuous or periodical. Cost-effectiveness of condition monitoring can be estimated by comparing the operating expenses of device with condition monitoring and without it. It is also needed to take into consideration the possible detriments of the failures and expenses of those. Costs of the condition monitoring consist of installation, maintenance, as well as expenses due to failure of the condition monitoring system. Returns of condition monitoring can be seen as reduction of failure frequency and decreasing maintenance and examination needs. The condition of the device and the need for replacement can be assessed using diagnostic measurements. This has a big impact on planning future investments. In addition to reducing the severe failures and interruptions, condition monitoring and failure diagnostics can guide for performing better life-extending maintenance measures. [16, pp. 179–181]

Loss angle measurement is an important method for condition monitoring of high voltage device insulation. It is discussed more in the next chapter. Dielectric frequency response (DFR) measurements are defined to be the preferred methods for measuring moisture content of the cellulose insulation. Introduced in 1995, DFR can be used for transformers, bushings and cables. The results are usually presented as capacitance and/or dissipation factor/power factor versus frequency. [40] Thus, it can be stated that DFR is basically same as loss angle measurement, but it is just implemented in a wider frequency band and often with a smaller voltage [13].

Insulation resistance test is another test which measures the condition of the insulation. It measures material’s ability to withstand a rated service voltage without allowing leakage current to pass through it. Test device often called as Megger is portable test instrument which can be used to measure various electrical components and equipment. It is applying a DC voltage over the insulation and measures the leakage current. Then, using Ohm’s law the insulation resistance can be calculated, and the value is compared to industry standards, historical data or minimum acceptable resistance values. [41]

As transformer is being exposed to electrical and thermal stresses, it can result in incipient transformer faults and lead to breakdown and release of several different gases from transformer oil. Dissolved gas analysis (DGA) is measuring the generation of these gases and therefore tells important information about the overall condition of the insulation. Advantages of DGA include: advanced warning of developing faults, status checks on new and repaired units, convenient scheduling of repairs and monitoring of units under potential overload conditions. [42]

Type of the fault defines the composition of the generated gasses whereas formation rate of the gasses is defined by magnitude of the fault as well as amount of oil and age of the transformer. Transformer insulation will generate gasses even in normal aging reaction but in such situations formation rate is small. During thermal or electrical faults, the amounts of gasses are growing fast and their composition changes. DGA determines the concentrations of gases like hydrogen, methane, acetylene, ethylene and ethane. Interpretation of DGA results is not unambiguous and usually electronic measurements are needed alongside it. When examining the DGA samples taken from instrument transformers, it needs to be taken into consideration that the interpretation instructions for power transformers do not apply as such to ITs. [16, pp. 206–207]

Condition of the insulation paper can be determined with paper samples that are measuring its degree of polymerization. Breaks in the cellulose chains are directly causing a loss of mechanical strength of the paper insulation. It must be taken into account that the DP is a localized value and it can vary considerably depending on the location of where sample is taken from. There might be also variation in the DP for different layers of paper. Thus, sampling should be done to areas that are subject to the most potential damage. The most degraded area is supposedly the part with the highest local temperature, most often located at the top of the winding. It is advised to use a reference paper sample from the area that is subjected to least amount of stress. This will allow more realistic comparison than a new paper that has never been subjected to any aging. [27, p. 57]

In particular, the maintenance, condition monitoring and care program of instrument transformers has to be decided with cost effectiveness in mind, since ITs have a low capital cost and their failure rates are generally low compared to power transformers. As a result of this, diagnostics and maintenance of ITs are usually made based on economic considerations. Practices vary between utilities, some have basically no condition monitoring for ITs while some other utilities practice active condition monitoring and maintenance programs. Data plays important role in condition monitoring and making maintenance decisions. Both old data from the device in question and data from other similar devices are useful when making decisions. [11, p. 101]

2.4.2 Traditional loss angle measurements

Traditional loss angle measurements which are also known as tan delta (tan δ) measurements are commonly used method for condition monitoring of high voltage device insulation. The measurement is well suited for condition monitoring of devices like bushings, instrument transformers, cables and capacitors. Tan δ measurement is measuring two values, loss angle and capacitance of the measured device. Traditionally these measurements are conducted with Schering bridge or current comparator bridge but other bridge connections are also used. The values of the device measured with bridge are compared to the known standard reference. Usually a compressed gas capacitor is used as the standard for capacitance and the standard for dissipation factor is a combination of a standard capacitor in series with a resistor. [16, p. 193]

Schering bridge is simple in its basic structure. It can be used for measuring tan δ as well as insulation structure resistance and capacitance. [16, p. 194] Schering bridge structure with its connection arrangements is shown in Figure 7.

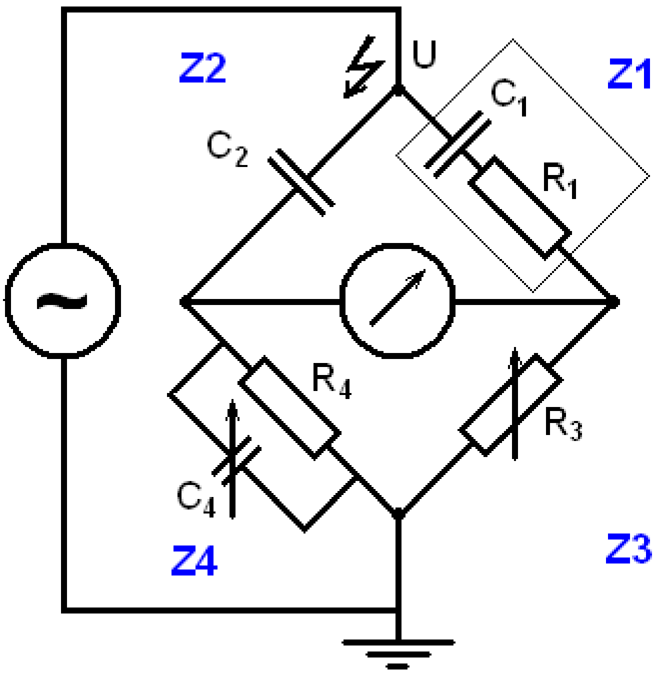


Figure 7. *Schering bridge. [43]*

In Figure 7 the object to be measured is described by its corresponding equivalent circuit, a series connection of resistor R_1 and capacitor C_1. C_2 is a reference capacitor which dielectric losses are extremely small compared to the measured object. The high voltage connected to point U is mainly applied to the capacitor C_2 and the measured object. Other components can be dimensioned for a smaller voltage and placed outside the high voltage area. R_3 is an adjustable resistor and C_4 is an adjustable capacitor. R_4 is a fixed resistor. Necessary balancing of the bridge can be done by changing the values of R_3 and C_4. Modern Schering bridges are generally used nowadays, performing the balancing of the bridge and storage of measurement values automatically. [16, p. 194]

Equilibrium condition of Schering bridge is as follows,

$$\frac{Z_2}{Z_4} = \frac{Z_1}{Z_3}, \tag{5}$$

where,

$$Z_1 = R_1 - j\left(\frac{1}{\omega C_1}\right), \tag{6}$$

$$Z_2 = -j\left(\frac{1}{\omega C_2}\right), \tag{7}$$

$$Z_3 = R_3, \tag{8}$$

$$Z_4 = \frac{R_4\left(-j\left(\frac{1}{\omega C_4}\right)\right)}{\left(R_4 - j\left(\frac{1}{\omega C_4}\right)\right)}, \tag{9}$$

When the real parts of the left and right sides of the equation are equal to each other and the imaginary parts are equal to each other, the equilibrium condition implies that,

$$C_1 = \frac{C_2 R_4}{R_3}, \tag{10}$$

$$R_1 = \frac{C_4 R_3}{C_2}, \tag{11}$$

This still follows,

$$C_1 R_1 = C_4 R_4, \tag{12}$$

The loss factor tan δ is then given by,

$$tan\,\delta = \omega C_1 R_1 = \omega C_4 R_4, \tag{13}$$

A similar equilibrium analysis could also be performed using an equivalent circuit, in which the test piece would be described by a parallel-connected capacitance and resistance. [16, pp. 194–195]

The Schering bridge has been widely used due to its frequency-independent balanced equations, inexpensive setup compared to other bridges and ability to measure small capacitances at low voltages. It has also few other advantages compared to other AC bridges. These include capability of operating at high voltages and low power losses as well as high accuracy across a wide range of conditions and precise tan δ evaluation. [44]

Current comparator bridge is another widely used measurement bridge. It is more suitable for measurement of high capacitance test samples than Schering bridge. Principle of the current comparator bridge is to change the number of turns of the coils N_x and N_s so that the magnetic fluxes they induce are equal. [16, p. 195]

In the equilibrium state of the current comparator bridge, the following holds,

$$(I_x + I_{rx})N_x = (I_s + I_{rs})N_s, \tag{14}$$

$$(U\omega C_x + I_{rx})N_x = (U\omega C_s + I_{rs})N_s, \tag{15}$$

The unknown capacitance is,

$$C_x = \frac{N_s}{N_x}C_s, \tag{16}$$

Current comparator bridge structure can be seen in Figure 8.

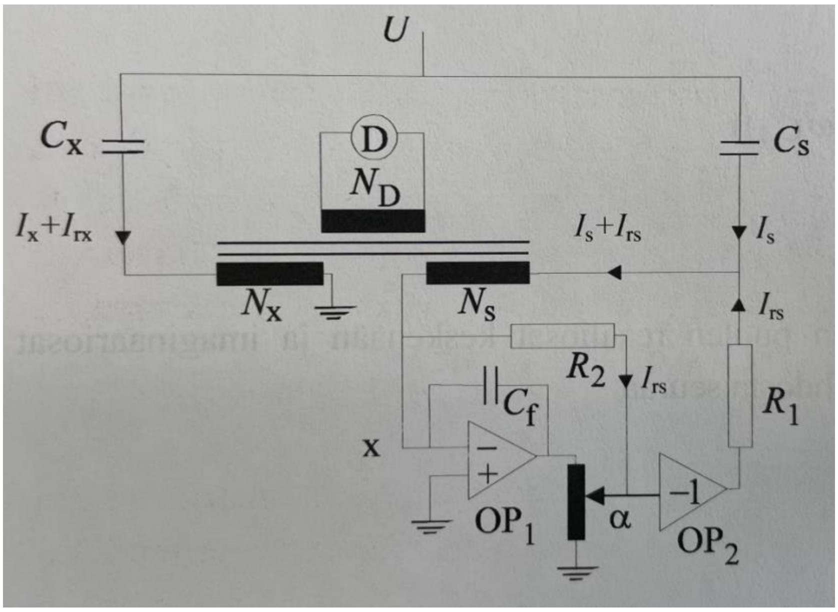


Figure 8. *Current comparator bridge. [16, p. 196]*

Figure 8 presents a method for compensating losses of capacitance C_x. When examining the connection, it must be noted that both point x as well as other terminals of capacitors C_x and C_s are at zero potential.

Tan δ measurements are conducted with well known and reliable technology. However traditional measurement method has its disadvantages. It requires many work hours performed by a few different parties. There might be for example need for involvement of transmission system operator (TSO), distribution system operator (DSO), maintenance company and measuring company. Even though the actual measurement is quite simple, the complexity of involving many different parties makes the implementation expensive and difficult to organize at short notice.

Preparation work takes up most of the time in loss angle measurement at a substation. Tan delta measurements are conducted with de-energized equipment so at first grid needs to be rerouted from the bay that is going to be measured. This requires communication between grid operators and the maintenance company. In many cases there might be need for switching done with remote control by both TSOs and DSOs control rooms. All the necessary circuit breakers and disconnect switches need to be opened as well as main grounding with the earth switches must be done before the actual measuring work at the substation can start. After this the maintenance company electrician can install the grounding cords for the field and start removing the jumpers from the current and voltage transformers to be measured. The measurement arrangement can be seen in Figure 9.

Figure 9. *Measurement arrangements of the loss angle measurement. Current transformer being measured in the front left and voltage transformer on the right. Jumpers have been removed from primary terminals and orange grounding cords have been installed. Measurement voltage cable is hooked to the primary terminal of the CT.*

Conducting the actual tan delta measurements is fairly straightforward. Voltage and grounding cables need to be connected to the instrument transformer that is being measured. Information of the measured instrument transformer is entered into the measuring software. Information to be entered includes the type of instrument transformer and its more specific values as well as prevailing weather conditions. The metering device can then convert values into the reference conditions. Common measurement voltages are 10 kV and 2 kV but the measuring is also possible with other voltages. Measurement software saves results automatically and shows them in a table. Measurement setup at the substation with Doble M4100 measuring device is shown in Figure 10.

Figure 10. *Doble M4100 measurement setup.*

When it comes to different modes of loss angle measurements, two common modes of implementation are ungrounded specimen test (UST) and grounded specimen test (GST). In the UST mode, capacitance is measured between ungrounded high voltage and low voltage windings. It is therefore well suited for checking insulation without interference from ground connections. Whereas, the GST mode includes all possible leakage paths in its measurement, also through the capacitance between the high voltage winding and the transformer frame. [45]

The measured tan δ values are converted to a reference level where humidity is low and the temperature is constant at 20 °C. In such conditions, the tan δ value for a new insulation should be in the range of 0.2–0.3 %. In the case of old insulation, the values are generally higher. It is important to compare measurement results with previously done measurements as well as measurement results between different phases. For example, if three phases are measured and one of them deviates from the rest, it is a clear sign of degraded insulation or moisture. Loss angle value under 0.5 % is considered as good, 0.5–1 % is acceptable but as the value gets closer to 1 % measurement is often repeated to confirm the results. Values above 1 % generally mean that the device needs to be renewed. Values of the capacitance are also followed in loss angle measurements and compared to previous measurements or factory tests. [13]

2.4.3 Online condition monitoring

Online measurements of electrical equipment refer to measuring certain parameters or conditions while the equipment is energized and in use. It is helping to make the right decisions for operation and maintenance of transformers and other important grid components. Increase of online measurements is driven by the need to facilitate the transition from time-based and/or operational-based maintenance to condition-based maintenance. This will help to improve the asset life management and to enhance failure-cause analysis. [46, p. 194]

There are plenty of benefits in conducting online measurements for electrical equipment. However, it needs to be recognized that some components need it more than others. Defining factors can be things like components criticality, age and fault history. Based on these issues, a decision can be made whether online condition monitoring is needed or not. Benefits of online measurements can be divided into direct and strategic benefits. Direct benefits are cost savings that can emerge from reducing unnecessary equipment inspections. Strategic benefits on the other hand are based on the ability to perform maintenance in time before catastrophic events occur. These can be preventing injuries to workers or public, protection of the equipment or avoiding other large harmful events. [46, pp. 194–195]

To get the most out of online measurements the whole digital condition monitoring system is needed. For example, Fingrid launched a digital condition monitoring system for detecting partial discharges in 2022. There was long-term research and development work before the system was introduced to substations. Aim of the initiative is to automate maintenance processes. The project introduces new technologies, such as monitoring systems utilizing sensor technology and data analytics, which can reduce downtime for customers due to maintenance and failures. This method is based on monitoring partial discharges, i.e. measuring electromagnetic radiation at radio frequencies. Development of the PD monitoring technology consists of development of the actual measuring devices as well as developing a working data platform and user interface. Data side of it is important since the whole digital condition monitoring is based on data driven decision making. [47]

Online loss angle measurements can be conducted with digital instruments without measuring bridge. The principle is to calculate the capacitance and $\tan\delta$ directly from the measured current and voltage. Measured voltage and current signals will be digitalized with analog-to-digital converter. In this method balancing tasks are not needed like with the Schering bridge. The phase shift of the current and voltage can be directly computed from the digital signals with discrete Fourier transform. [48]

Online condition monitoring of instrument transformers is not limited to insulation condition monitoring, and other methods are also used. For example, it can be also conducted based on continuous phasor measurement unit (PMU) values which can help to detect faulty instrument transformer circuits weeks before the failure. Upcoming software for Fingrid offers this feature and because the software is used in control room, very fast response is possible if necessary.

Impending failure in the VT circuit can generate relatively small, random and intermittent excursions of the measurements from a steady state. These excursions show as small voltage drops and erratic phase-angle changes in PMU measurements. These failures can happen to one or multiple phases at the same time. This monitoring algorithm was applied to two real-world VT fuse failure cases and results were discussed in detail in the research paper. Results show that automatic detection of PMU values could bring a significant benefit to condition monitoring practices of the utilities. Applying this method could be beneficial, especially detecting failures days or weeks before it happens. [49]

A current trend in condition monitoring is now going towards implementing digital condition monitoring systems for increasing the efficiency of the grid management. Focus should not be only on making the best technology but also thinking about how these new and traditional technologies can be used together. In practice, the most robust solutions are achieved when different condition monitoring systems are complementing each other in the best possible way.

3. DEVELOPMENT OF NEW MEASUREMENT METHOD

A couple of years ago, Fingrid started developing an online loss angle measurement method for instrument transformers. The technology used in the method has proven to work but a few unsolved problems remain in the implementation of the installation and analysis of the results. In this chapter operating principle of the measurement method as well as challenges encountered are explained.

3.1 Operating principle of the measurement method

The operation principle of the measurement method is based on measuring the phase difference of current and voltage. If the measured instrument transformer is a current transformer, the measured parameters are CTs earth current and a voltage reference. If voltage transformer is being measured, then both earth current and voltage can be directly taken from the VT. It is also measured how the phase difference is changing over time. [50] In an ideal case the phase difference between current and voltage would be 90° but basically it is smaller as real insulation system is never ideal, because it always has some conductivity and dielectric losses. These factors are causing an increase in the resistive component of the current. As the resistive component of the current increases, the phase angle between current and voltage decreases. This is resulting in a higher $\tan\delta$ value in the insulation. [13]

Every phase of the instrument transformer has its own internet of things (IoT) measuring device named IoT5 and in the case of CT measurement it gets 4 earth current inputs from the CT and a voltage reference. Inputs from the CT are coming from secondary terminals S1, S2, S3 and S4 and there is also one spare input at the measuring device. Voltage reference can be taken from capacitive voltage output of the CT or secondary of the voltage transformer. These voltage transformers might be located in the bay or at the end of the busbar. Circuit diagram of the measuring arrangement of CT is presented in the Figure 11.

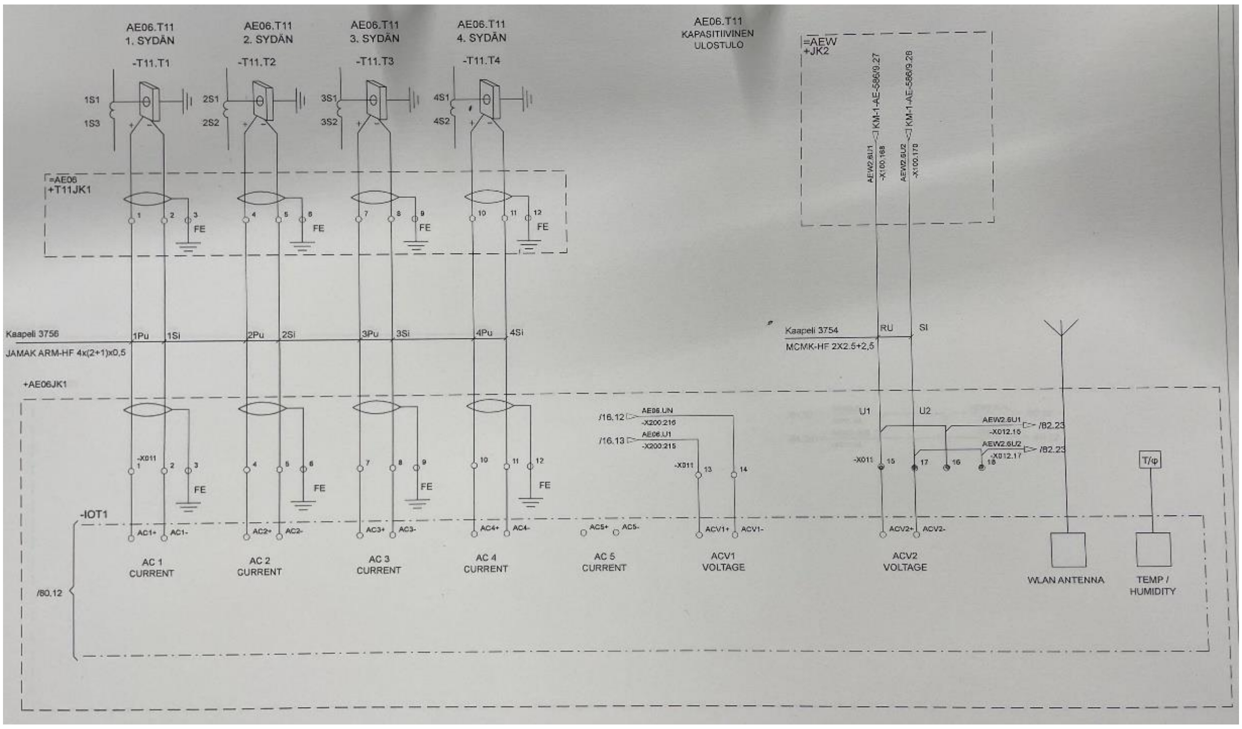


Figure 11. *Circuit diagram of the IoT measurement arrangement.*

There are two possible ways to do the measuring implementation with these devices. Both types have been tested for current transformers at one of Fingrid's substation. In the other solution IoT5 devices are installed on the legs of a CT. In the second solution IoT5 devices are installed inside the bay's distribution cabinet. Both options have their advantages as well as disadvantages. Onwards from the measurement device, data is transmitted through a wireless base station. Figure 12 shows pictures of both installation methods. Figure 13 and 14 present system diagrams of both methods.

Figure 12. *IoT5 device installed on the CT leg (left) and IoT5 devices installed inside the distribution cabinet for every three phases (right).*

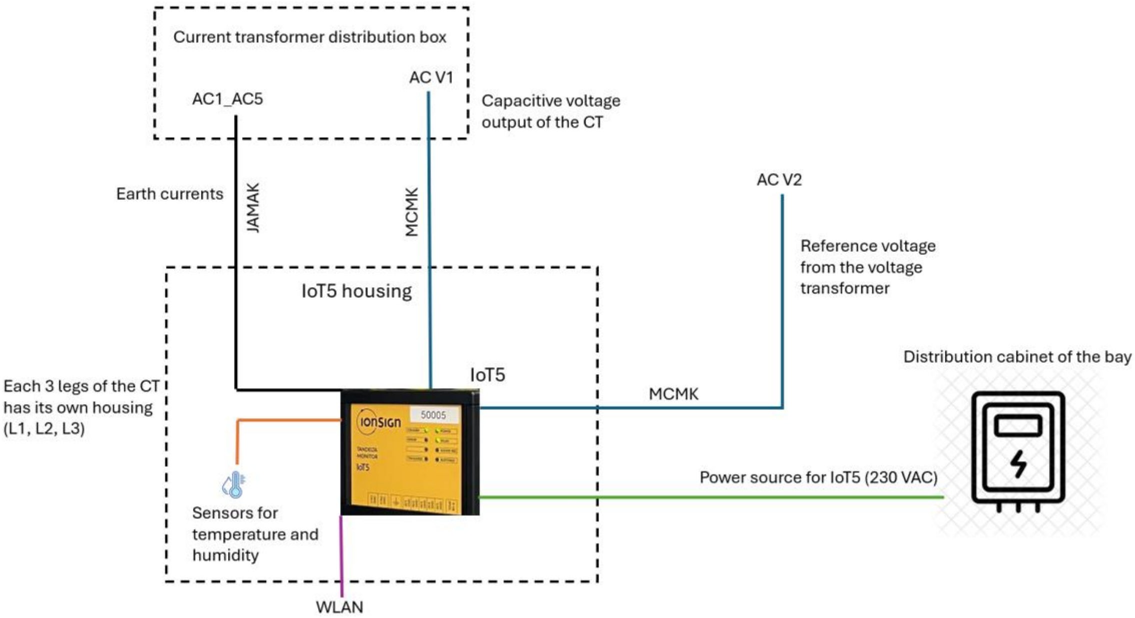


Figure 13. *System diagram of the pole installation method, where IoT5 devices are mounted on the legs of a CT.*

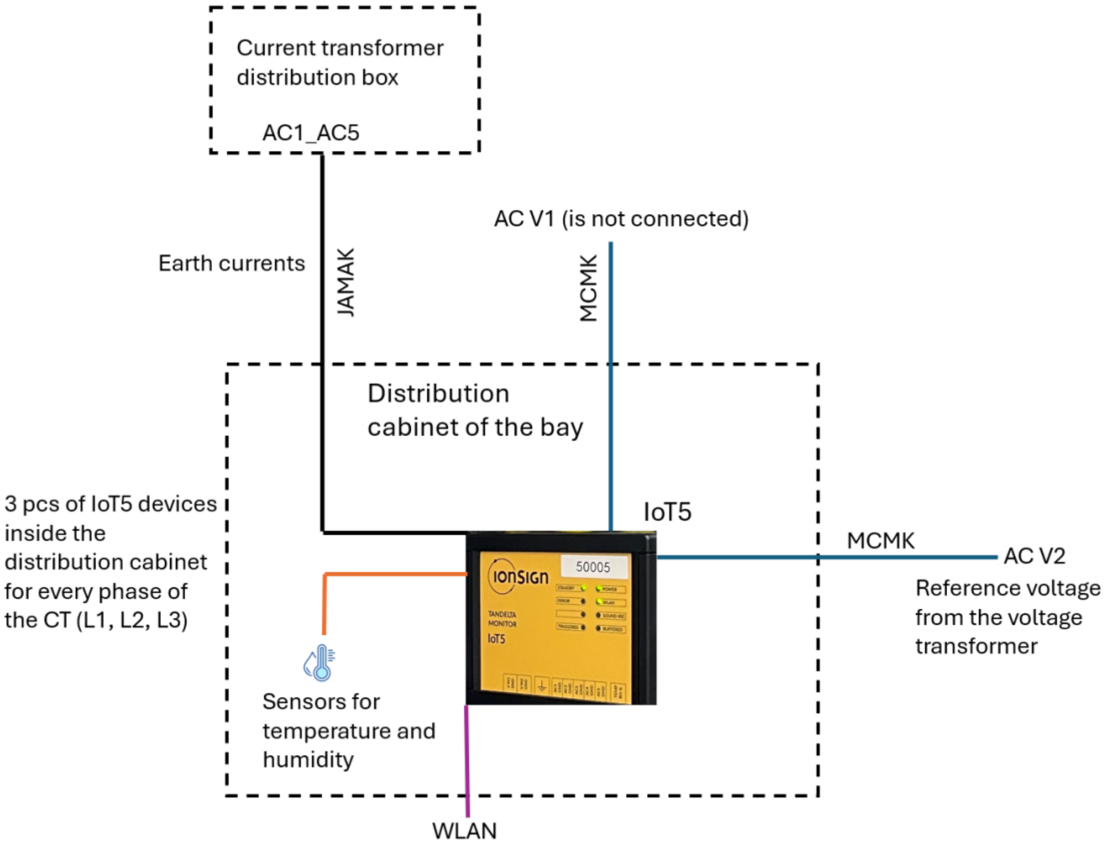


Figure 14. *System diagram of the distribution cabinet installation method, where IoT5 devices are mounted inside the bay's distribution cabinet.*

Analysis of the results is an important part of the successful measurement method. One thing to note when analyzing the results is that there is only one analog-to-digital converter in the measuring device, even though there are many outputs. Therefore, only one sample can be taken at a time, which causes the sample's phase to change slightly. [50] In practice analysis is done by comparing the phase differences of different signals in time series. Since the assumed ±90° phase difference cannot be systematically seen with this measurement method, focus is concentrated more to the changes of the phase differences as a function of time rather than absolute phase difference values. [51]

3.2 Measurement method challenges identified during testing

As stated before, recognized challenges of online loss angle measurement are in technical implementation and analysis of the results. There might be also other challenging aspects that are still unknown. One challenge is related to the current magnitude. Measured currents are so small that interference signals at the substation can interfere with the measured current while the signal is flowing from CT to the distribution cabinet. Placing the measuring devices in the CT legs helps in reducing this problem, but it does make the installation more difficult. It might be also unwanted to bring the 230 V voltage to the CT leg. [50]

Another challenge in the implementation appeared from the fact that most of the IoT devices at the test substation were installed incorrectly. The connections were made incorrectly in such a way that they measure secondary current instead of earth current. However, one of the measuring devices is installed correctly and reliable measurement data can be received from it. Other devices in the same bay are missing the capacitive voltage measurement. However, data from those devices can still be used since phase difference between capacitive and transformer voltages is systematic. [51]

Challenges also arose related to the components used. Split-core current transformer sensor was selected for current sensing due to the easy installation. Installation is much easier with split-core compared to other alternatives since the sensor can just be clipped to the conductor without removing the conductor from instrument transformer core. Downsides of split-core current transformer sensors include an unsuitable transformer ratio for this use case and lower accuracy than other options. Transformer ratios for split core sensors are often 1:3000 which converts transformed current to a very small value because even initial earth currents are small, about tens of milliamperes. Measurement accuracy with split core is usually worse than with solid-core current transformer sensors or shunt resistors. However, in loss angle measurement only phases of current and voltage as well as curve shapes need to be measured accurately and it does not matter if absolute magnitude values are not really accurate. Later in this thesis laboratory tests are conducted with IoT device using different types of sensors and comparison can be made how split-core sensor performs against other options. [50]

Both split-core and solid-core current transformer sensors that will be used in the laboratory have an amplitude error of $\pm$10 % when tested at 60 Hz [52], [53]. Current transformer sensors also experience phase angle errors, which are primarily caused by the magnetizing current. This magnetizing current causes the primary current referred to the secondary to differ in phase from the burden current. Consequently, the phase shift can change as the secondary burden changes, meaning the phase error is burden- and operating-point dependent. [54]

Split-core current transformer sensors installed inside CT secondary terminal box at the test substation can be seen in Figure 15.

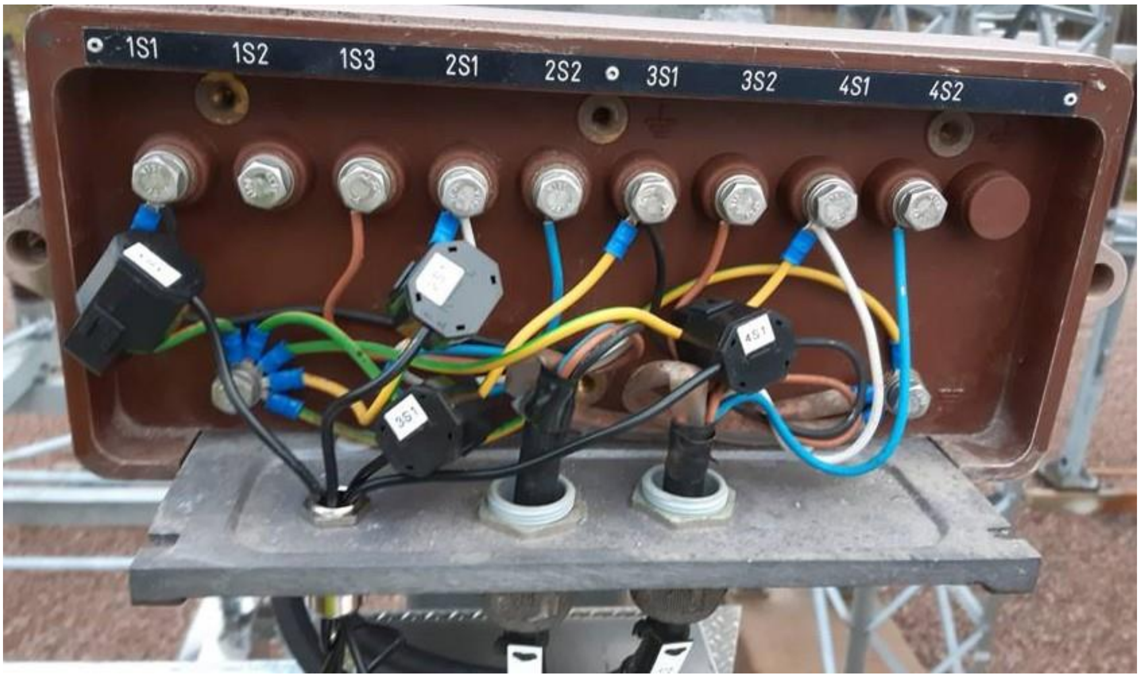


Figure 15. *Split-core current transformer sensors (black colored) installed inside CT secondary terminal box.*

External factors are also bringing challenges, especially for analyzing the measurement results. There are many of these factors that need to be first recognized and then dealt with in the analysis. The most significant circumstances that effect the results are outside temperature, humidity and load situation of the instrument transformer among other things. [50], [51] Another factor that must be considered in the analysis arises from the measuring device itself. Since the IoT5 device has only one analog-to-digital converter, the different channels are not sampled simultaneously but sequentially. As a result, the sampled signals are shifted slightly in time relative to each other, which appears as a phase difference between the current signals. This can be resolved by taking the exact sampling time intervals of the different channels into account in the analysis. [51] In addition to that, phase angle error can also vary between individual current transformer sensors. These possible qualitative differences between sensors could be resolved by performing a check measurement for each sensor before installation, so that the sensor-specific phase error can be taken into account in the analysis. [50]

4. LABORATORY MEASUREMENTS

This chapter first introduces the High Voltage Laboratory and the test measurement implementation. Different instrument transformers measured are presented as well as different measurement arrangements are illustrated with pictures. Laboratory measurement results and analyses are discussed.

4.1 High voltage laboratory

Test measurements are performed at the High Voltage Laboratory of Tampere University, located in Hervanta Campus. It is the only notable independent high voltage laboratory in Finland offering services for both academia and industry. The laboratory offers wide range of high quality testing and diagnostics facilities for both electrical and environmental tests as well as comprehensive dielectric characterization and visualization capabilities. [55]

4.2 Implementation of the test measurements

Aim of the high voltage laboratory measurements is to test the operation of the IoT5 loss angle measurement device. Measurements are carried out by testing the IoT5 device with different sensors. These sensors are split-core current transformer sensor, solid-core current transformer sensor and a shunt resistor. Temperature in the laboratory during measurements was 18 °C and relative humidity was 30 %.

The split-core sensor used is a CR3110-3000 current transformer from CR magnetics. It has 75 A maximum input current to be linearly sensed, 15 V maximum secondary voltage, effective turns ratio of 3100 including losses and 440 Ω DC resistance of the secondary. The solid-core sensor on the other hand is a CR8401-1000-G current transformer also from CR magnetics. It has 4 A maximum input current to be linearly sensed, 0.6 V maximum secondary voltage, effective turns ratio of 1005 including losses and 49 Ω DC resistance of the secondary. Both split-core and solid-core current transformer sensors can be used in a frequency range of 20 Hz to 1 kHz and have an amplitude error of ±10 % when tested at 60 Hz. [52], [53]

The results obtained are compared with reference results measured with an automatically balanced Tettex 2877 measuring bridge. Instrument transformers to be measured are a new CT (Arteche CA-123) with unaged insulation system in good condition, old CT (Arteche CTG-123E) and VT (Arteche UTE-123E) with defective insulations as well as an old VT (Messwandler-Bau NUE0110a) from Tampere University.

There are four different measurement methods and four ITs to be measured so in total there will be 16 measurements to conduct. However, objective is to measure the same IT with all four methods at the same time which makes results between different measurement methods more comparable and also saves time. The goal is to measure every transformer at approximately the same voltage levels, which are close to the 110 kV grid operating voltages. In practice the exact RMS voltages varied between the measured transformers and measurement methods, falling mainly in the range of approximately 65–73 kV, as shown in the result tables. Before increasing the voltage up to these operating levels, measurements were also made at a lower voltage such as 10 or 30 kV RMS. The measured instrument transformers and the measurement arrangements will be introduced in more detail in the next subchapters.

After the laboratory measurements, the measurement results are analyzed with cross-correlation and fast Fourier transform (FFT) methods. Cross-correlation is a method used to estimate the phase delay between two sinusoidal signals. The phase delay is determined by locating the peak of the cross-correlation function between the two signals. Cross-correlation based methods have been widely applied in many fields such as radar, underwater acoustics and biomedicine for phase delay estimation. [56] The FFT is an algorithm that implements the discrete Fourier transform in a computationally efficient manner. In short, FFT takes a signal in the time domain and converts it into the frequency domain, making the frequency components of the signal visible. While the time-domain shows how a signal varies over time, the frequency domain reveals the individual frequency components that together form the overall signal. This is particularly useful in situations where time-domain analysis alone is insufficient. [57]

4.3 New current transformer with good insulation

The first IT to be measured is a new 123 kV current transformer from Arteche (CA-123) manufactured in 2021. It is an unused spare device from Fingrid storage so the expected $\tan \delta$ values are small. The entire measurement arrangement is shown in Figure 16.

Figure 16. *Measurement arrangement for the new CT. In the foreground, the current transformer to be measured, the yellow IoT devices connected to it, and the white measuring bridge signal connection box. The current transformer is connected with a busbar to a blue compressed gas capacitor, which in turn is connected to a black voltage transformer. The voltage transformer is connected to the test transformer, which creates the voltage. The reference voltage for the IoT devices is brought from the voltage transformer with the black cable.*

At first, earth currents were measured in a way that secondary of each coil was grounded separately and each coil was also measured separately. The CT frame was connected directly to the laboratory ground. This resulted in earth currents and capacitances which were minuscule, in the order of picofarads and microamperes. With the used measurement sensors, it is not possible to conduct reliable measurements when the quantities to be measured are so small.

Thus, the measurement arrangement was fixed in a way shown in Figure 17.

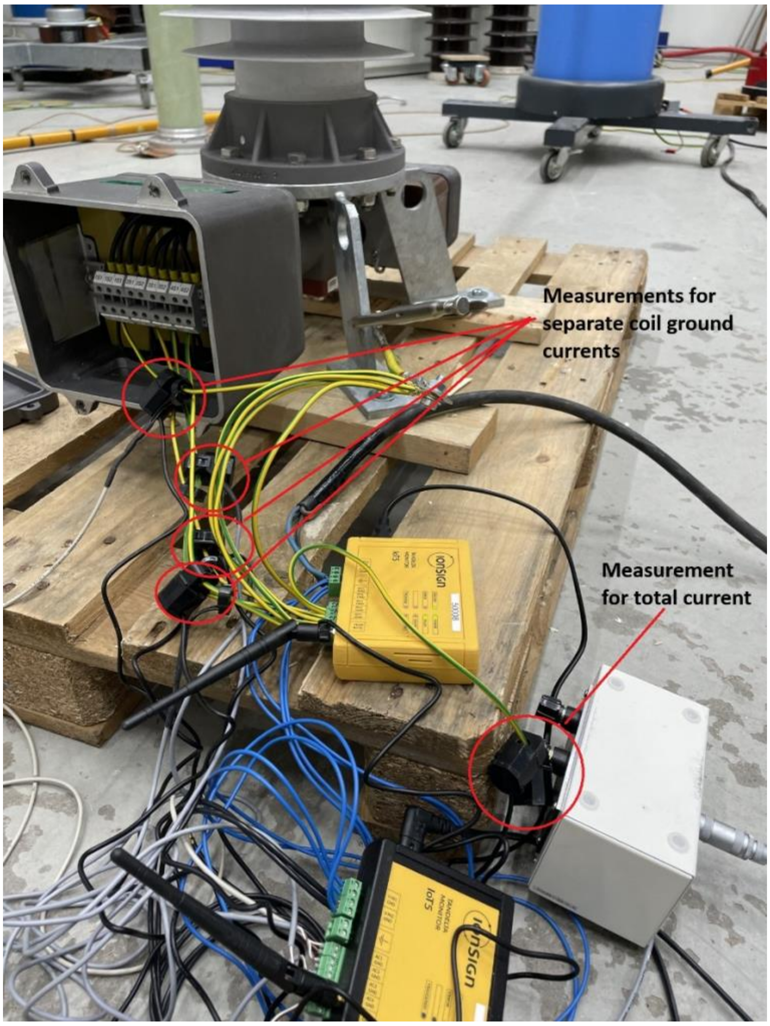


Figure 17. *Measurement connections for IoT measurement of the new CT. Measurement sensors for total current and separate coil ground currents are highlighted in the picture.*

In the fixed measurement arrangement earth current is still measured directly from every separate coil terminal but in addition to that the total earth current is also measured. The total current is formed as the sum of the earth currents flowing through the secondary terminals and the device frame groundings. With this measurement arrangement, the total earth current is in the milliampere range which is much higher than the earth currents measured from individual coil terminals. This total earth current magnitude starts to be big enough to be measured and analyzed reliably. However, because the device frame and all secondary terminals are connected through the same total current sensor, the sensor also measures the earth current flowing through the device frame grounding. This is not desirable since the goal is to measure only the condition of the oil-paper insulation between high-voltage and low-voltage windings.

4.3.1 Results and analysis

Measurement results measured with Tettex 2877 measurement bridge can be seen in Table 3.

Table 3. *Measurement results of the new CT with unaged insulation measured with Tettex 2877 measurement bridge.*

U_{rms}	I_{cx}	Tan δ	C_x
30.86 kV	9.64 mA	0.00204	966.1 pF
66.75 kV	20.4 mA	0.00210	966.5 pF
68.34 kV	21.8 mA	0.00210	966.6 pF
73.11 kV	22.6 mA	0.00210	966.6 pF

Tan δ value is around 0.2 % which means that the insulation is in good condition. Tan δ value is also increasing very slowly when voltage is raised. Overall, these results seem to be in line with each other. The measured CT is an unused device and the results are also in line with it.

Figure 18 shows the current graphs for the new CT measured using IoT device with solid-core current transformer sensors. In the graph all current signals and the reference voltage signal are shown. It can be seen that current signals Winding 1, Winding 2, Winding 3 and Winding 4 are really small and they are also far from a sine wave in shape. These sensors are the ones that are directly measuring the secondary terminals separately. This means that analyzing the phase difference of current and voltage is basically infeasible from these current signals.

Only the Total current signal is resembling a sine wave. This signal is the total earth current formed as the sum of all the terminals and the device frame. And yet the shape of the signal is quite far from proper sine wave and there is some interference in the signal. This could be due to non-linear current component that is involved in the signal. E.g. it could be a resistive current which is disproportionately large in this CT due to its very small capacitance.

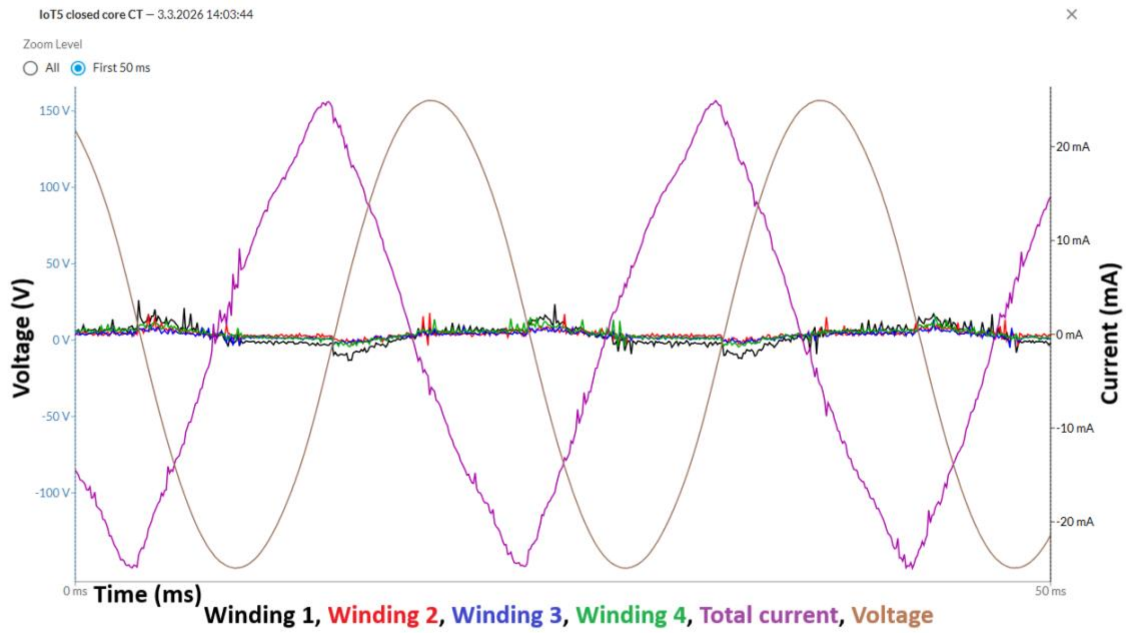


Figure 18. *The new current transformer measured with solid-core current transformer sensors at approximately 70 kV RMS voltage.*

Measurements with split-core current transformer sensors as graphs can be seen in Figure 19. Graphs look fairly similar compared to the measurements done with solid-core sensors. The biggest difference is that the Total current signal is slightly more one-sided than in the case of solid-core sensor measurements. It looks like there is a spike in the signal or that part of the signal is being cut off.

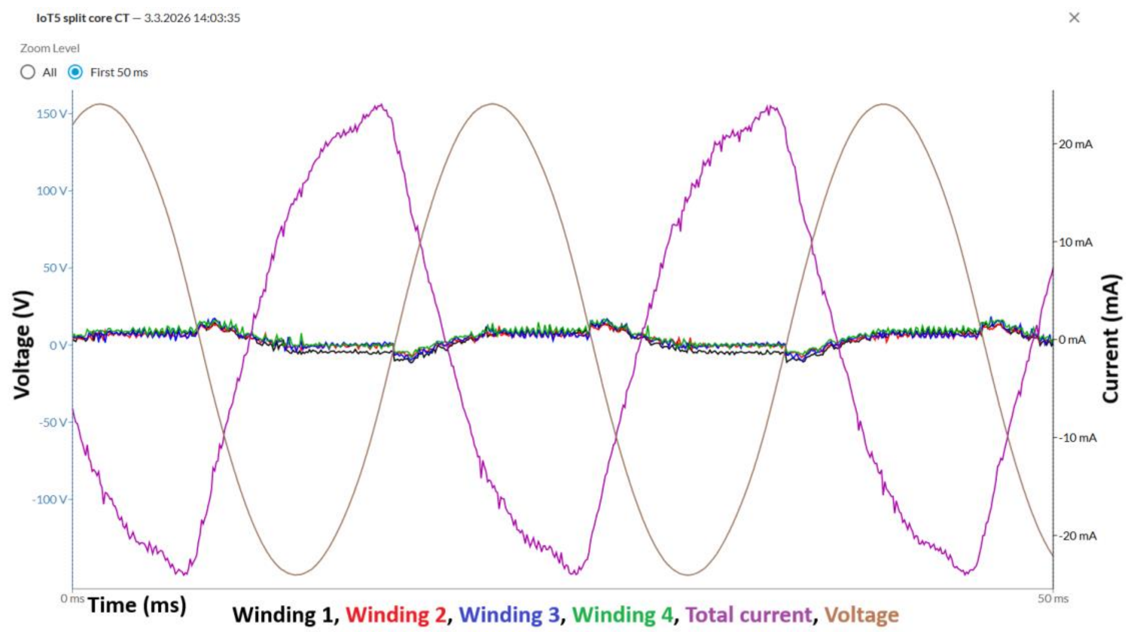


Figure 19. *The new current transformer measured with split-core current transformer sensors at approximately 70 kV RMS voltage.*

Measurements with shunt resistor sensor as graphs can be seen in Figure 20. In addition to the total current measured with shunt resistor, the figure also presents the total current measured with split-core sensor in the same graph as a reference. So, the same signal is measured with two different measurement techniques. It can be clearly observed from the graph that these measurement techniques differ in terms of the magnitude and disturbance of the graph they provide. It must be also noted that in the shunt resistor measurement the phase is shifted by 180 degrees and appears to be behind the voltage in the diagram. The sampling time is different than in the previous measurements because changes had to be made to the connections of the measurement devices.

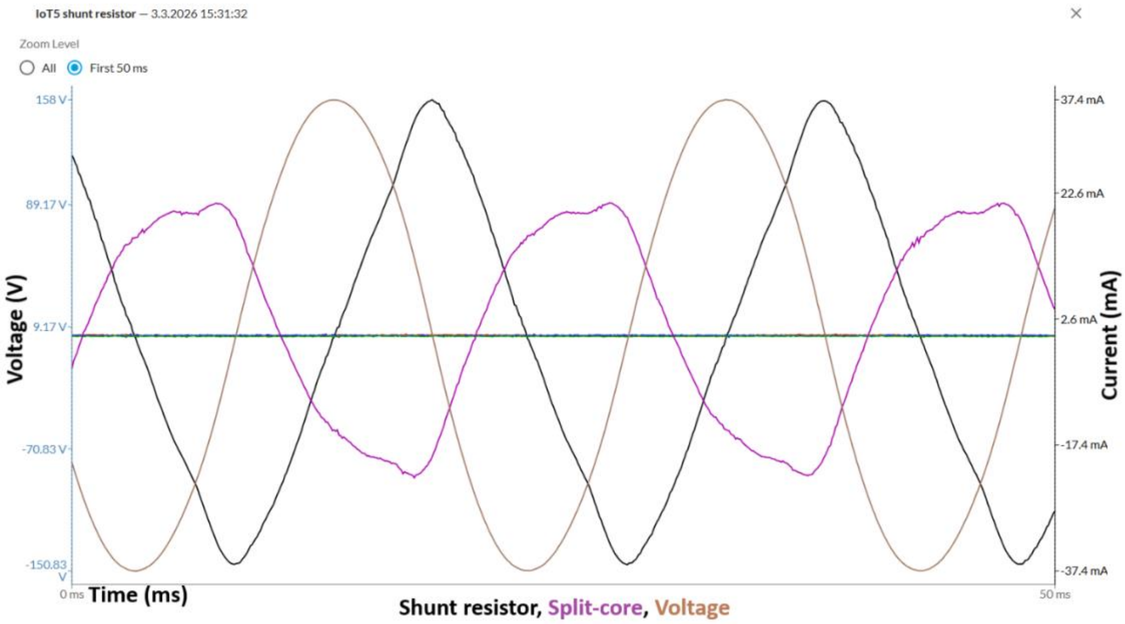


Figure 20. *The new current transformer measured with shunt resistor sensors at approximately 70 kV RMS voltage.*

IoT device measurements were analyzed with Python, using cross-correlation and FFT methods. Both methods first read two wav-files, current- and voltage-signals and then validate that sample rates of the signals match. After that, Phase difference of the signals is computed. Advantage of the FFT-method is a more precise angle resolution which is beneficial when analyzing the loss angle. However cross-correlation method might be more robust for example with noisy data. Lastly, the code calculates the loss angle based on computed phase difference.

The analysis was selected to be conducted for all three IoT measurements using different sensors at approximately 70 kV RMS voltage. Table 4 presents the analysis results of new CT IoT measurements and compares them with tan δ values obtained with the Tettex 2877 device.

Table 4. *Results of the Python analysis of new CT IoT measurements at 70 kV RMS voltage.*

Measurement	Phase-dif. xcorr	Phase-dif. FFT	Tan δ xcorr	Tan δ FFT	Tan δ Tettex
solid-core CT	106.5	105.67	-0.2962	-0.2806	0.0021
split-core CT	132	130.95	-0.9004	-0.8677	0.0021
shunt resistor	90	89.94	0	0.0010	0.0021

It can be observed from the analysis results that both solid-core CT and split-core CT have a phase difference clearly over 90 degrees, and therefore negative tan δ values which should not be possible. This means that solid-core and split-core CT sensors are causing a significant phase offset. Shunt resistor on the other hand seems to be working better and its values analyzed with FFT-method start to be quite close to Tettex measurement results. However, in the cross correlation method phase difference is calculated in 1.5 degree steps which means that in this case when phase difference is close to 90 degrees, tan δ value will appear as 0. The 1.5 degree resolution arises because the cross correlation method shifts the signal one sample at a time, meaning the phase resolution is determined by the number of samples per signal period. This clearly demonstrates why using FFT-based method works better, especially in the case when tan δ value is small.

4.4 Old current transformer with defective insulation

The next IT to be measured is an old 110 kV current transformer manufactured in 1985, also from Arteche (CTG-123E). It was removed from substation operation due to the weak values in online partial discharge- and traditional loss angle-measurements. Comparing the measurement results of two different CTs can give interesting information about capabilities of the tested measurement methods. Measurement arrangements used can be seen in Figure 21.

Figure 21. *Measurement arrangement for the old CT.*

It was noticed during measurements that the old CT with defective insulation is in bad condition. When the measurement voltage is raised up from the 20 kV RMS, breakdown happens after which measurements are no longer continued with this test piece.

4.4.1 Results and analysis

Measurements of the old CT with defective insulation do not give too much valuable results for comparison since breakdown happened when voltage was raised from 20 kV RMS and measurements could not be continued. This means that the insulation was likely in very bad condition. However, the CT could be measured at 20 kV level before the failure and it is interesting to find that with this defective CT measured at low voltage, the secondary terminal currents are in the mA range, spiking around 3 to 4 mA. This can be seen in Figure 22.

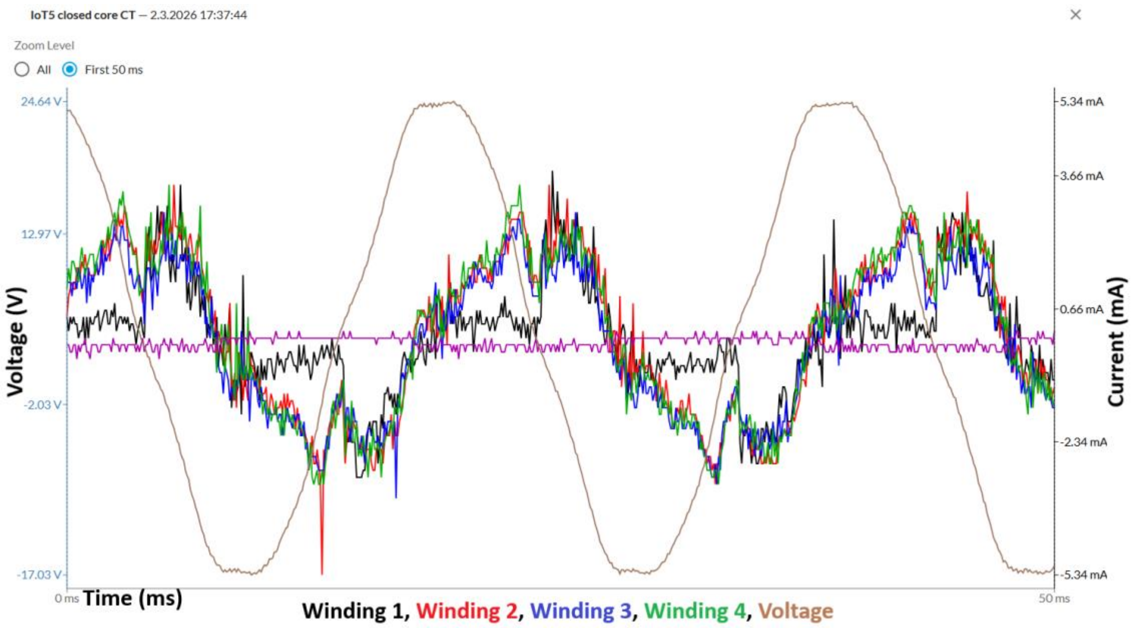


Figure 22. *The old current transformer measured with solid-core current transformer sensors at low voltage.*

These secondary terminal earth currents are greater than the ones measured with operating voltages from the new CT. This is another sign indicating that the insulation is seriously defective. However, interference present in the secondary terminal current signals is substantial, making sine curve fitting and loss angle calculation infeasible. In addition to the interference, a large spike can be observed especially in the Winding 1 signal near the voltage zero point, which suggests partial discharge activity. Furthermore, the voltage waveform appears distorted, which indicates a non-linear load.

4.5 Old voltage transformer with defective insulation

Third measurement object is an old 110 kV Arteche (UTE-123E) VT from 1985. This voltage transformer has two separate secondary windings. Similarly as with the older CT, it was also removed from operation due to the weak values in online partial discharge- and traditional loss angle-measurements. Measurement arrangements used can be seen in Figure 23.

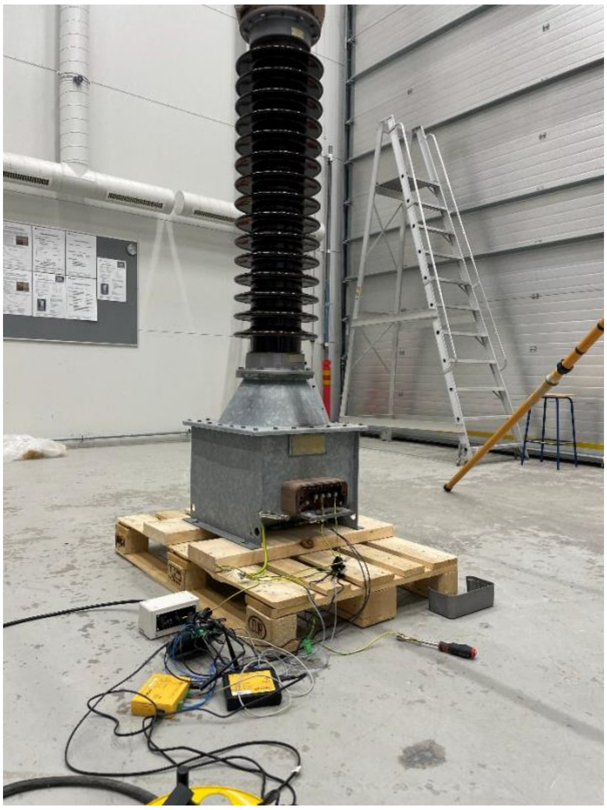


Figure 23. *Measurement arrangement for the old VT.*

Measurements of the old VT with defective insulation were successful and brought measurement results also at operational voltages. Analyzing this VT is interesting because we can compare the results to the traditional loss angle measurements done at the substation few months before laboratory measurements. After the substation measurements, this VT was removed from the operation.

4.5.1 Results and analysis

Measurement results measured with Tettex 2877 measurement bridge can be seen in Table 5.

Table 5. *Measurement results of the old VT with defective insulation measured with Tettex 2877 measurement bridge.*

U_{rms}	I_{cx}	Tan δ	C_x
10.49 kV	1.59 mA	0.0962	469.0 pF
29.56 kV	4.70 mA	0.0826	486.9 pF
65.16 kV	9.88 mA	0.0794	469.6 pF
71.52 kV	10.4 mA	0.0844	450.5 pF
73.04 kV	10.4 mA	0.0869	439.9 pF

Tan δ values are around 8–10 % which shows that the condition of the insulation is deficient. Table 6 shows the measurement results of the same VT, which were measured a few months earlier at the substation.

Table 6. *Measurement results measured at the substation with Doble M4100 measuring device.*

Test Mode	ENG	GND	GAR	UST	Test kV	mA	Watts	%PF corr	Corr Fctr	Cap (pF)	IR_{auto}	IR_{man}
GND	H1,H2	X1,Y1			10.007	4.642	1.601	4.93	1.43	1476.6	Q	
GND	H1,H2	X1,Y1	@2kV		2.000	4.508	0.4410	1.40	1.43	1435.0	Q	

IWC:	mA: 4.642/4.642 , 1/1	Watts: 1.601/1.601 , 1/1	Cap(pF): 1476.6/1476.596 , 1/1
IWC:	mA: 4.508/4.508 , 1/1	Watts: 0.4410/0.441 , 1/1	Cap(pF): 1435.0/1435.019 , 1/1

Now the two measurement results above can be compared by calculating the dissipation power of both measurements. Measurements performed at approximately 10 kV are selected to be compared so that the comparison would be as consistent as possible. Dissipation power can be calculated with the following equation:

$$P_{loss} = UItan\,\delta, \tag{17}$$

where U is the applied voltage, I is the measured current and $Itan\,\delta$ represents the resistive current component under the small-loss-angle approximation.

Thus, the power loss calculated from the measurement results of the Tettex 2877 measurement bridge is:

$$P_{loss,Tettex} = 10.49\ \mathrm{kV} \times 1.59\ \mathrm{mA} \times 0.0962 \approx 1.61\ \mathrm{W}, \tag{18}$$

and, the power loss calculated from the measurement results of the Doble M4100 measuring device is:

$$P_{loss,Doble} = 10.007\ \mathrm{kV} \times 4.642\ \mathrm{mA} \times 0.0493 \approx 2.29\ \mathrm{W}. \tag{19}$$

While both power loss values fall in the same magnitude range, they still exhibit a notable disparity. Power loss measured with Tettex 2877 measurement bridge is approximately 30 % smaller than power loss measured with Doble M4100 measuring device. However, it is an interesting observation that the power value of 1.601 W shown in Table 6 is approximately same as $P_{loss,Tettex}$, which is 1.61 W. This 1.601 W value can be calculated with the equation (17) from the Doble measurement results when the power factor value is used directly without applying the correction factor of 1.43. This suggests that the use of correction factor could explain the observed difference between the two measurement results. The correction factor is used to correct the result measured at the temperature at the time of measurement to a reference level of 20 °C. In the laboratory, temperature was 18 °C during measurements.

The dissipation power can also be calculated directly from the current and voltage waveforms obtained from the IoT measurements by multiplying the instantaneous current and voltage samples point by point. The resulting instantaneous power values are then averaged over the total number of samples. Based on the current and voltage waveforms measured with the IoT device with shunt resistor sensors at 10 kV, the calculated loss power is 0.975 W.

Figure 24 shows result graphs of IoT measurements of the old VT measured using solid-core current transformer sensors. Earth currents measured from secondary terminals are again small and far from sine wave shape similarly as in the measurements of CT with unaged insulation. Again, total current is larger and closer to sine wave so that with that the loss angle calculation could be possible. In this measurement, interference of the Total current signal seems to be stronger than in the solid-core current transformer measurement of the new CT.

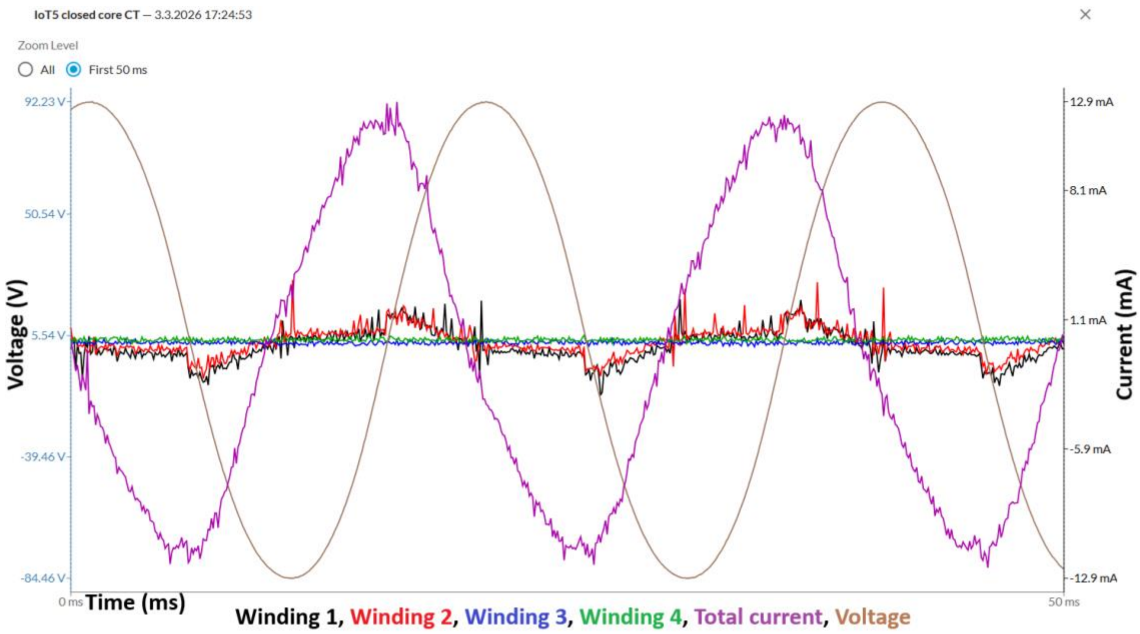


Figure 24. *The old voltage transformer measured with solid-core current transformer sensors at approximately 70 kV RMS voltage.*

IoT measurements of the old VT conducted with split-core current transformer sensors and shunt resistor sensors can be seen in Figures 25 and 26. It must be noted that in Figure 25 phase of the Total current signal is shifted by 180 degrees and appears to be behind the voltage. Same 180 degree shift applies to Split-core signal in Figure 26.

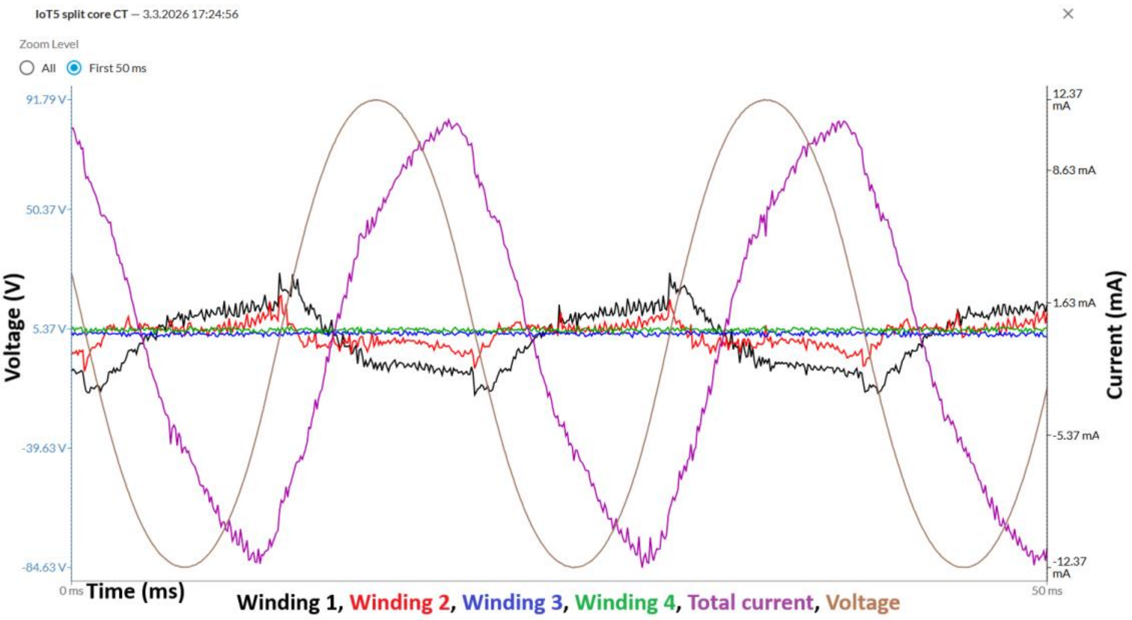


Figure 25. *The old voltage transformer measured with split-core current transformer sensors at approximately 70 kV RMS voltage.*

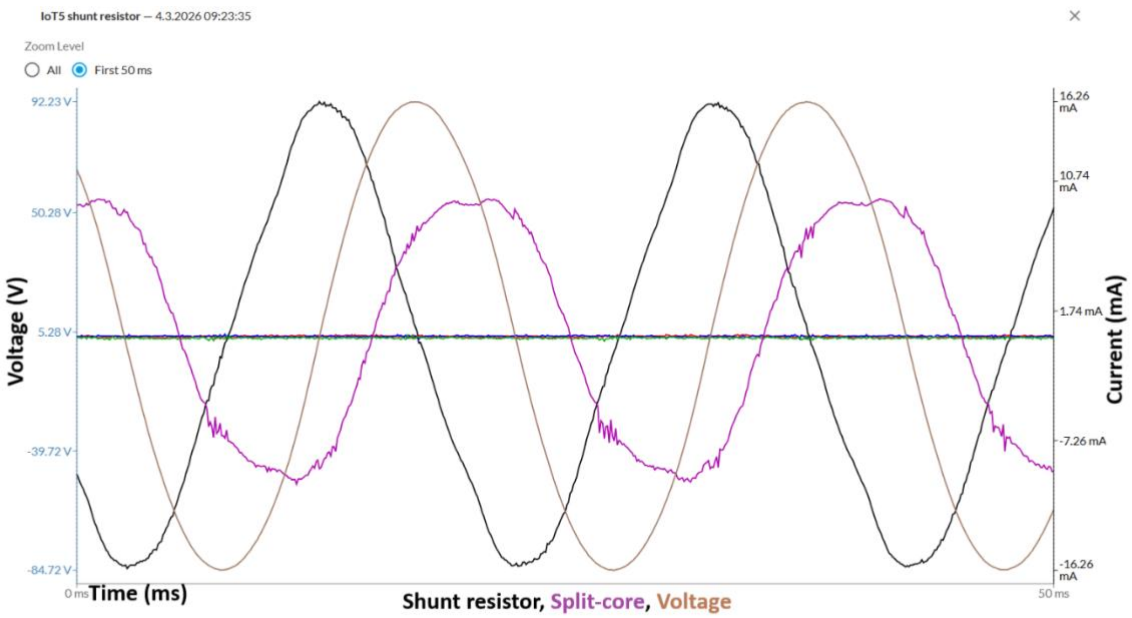


Figure 26. *The old voltage transformer measured with shunt resistor sensors at approximately 70 kV RMS voltage.*

IoT device measurements of the old voltage transformer at approximately 70 kV RMS voltage were also analyzed with Python, using cross-correlation and fast Fourier transform (FFT) methods. Table 7 presents the analysis results and compares them with tan δ values obtained with the Tettex 2877 device.

Table 7. *Results of the Python analysis of old VT IoT measurements at 70 kV RMS voltage.*

Measurement	Phase-dif. xcorr	Phase-dif. FFT	Tan δ xcorr	Tan δ FFT	Tan δ Tettex
solid-core CT	105	104.32	-0.2679	-0.2553	0.0844
split-core CT	127.5	126.39	-0.7673	-0.7371	0.0844
shunt resistor	85.5	85.40	0.0787	0.0805	0.0788

It can be again observed from the analysis of results that both solid-core CT and split-core CT have a phase difference clearly over 90 degrees and negative tan δ values. Tan δ values measured with shunt resistor and calculated with both cross correlation- and FFT-based methods appear to be close to the tan δ value measured with Tettex.

For the old VT, additional measurements were performed using a precision shunt resistor and an oscilloscope from Tampere University. The oscilloscope had two channels: one channel measured the voltage waveform, while the other measured the current waveform. The measurements were conducted at approximately 70 kV RMS, and the recorded waveforms were analyzed using Python. The results of the analysis are presented in Table 8.

Table 8. *Results of the laboratory measurements with a shunt resistor and an oscilloscope.*

U_{rms}	I_{rms}	P_{loss}	Tan δ
70.14 kV	5.11 mA	27.34 W	0.0765

The results in Table 8 show that the obtained tan δ value is in good agreement with the values presented in Table 7, where the measurements were performed using the IoT device with a shunt resistor and the Tettex measuring bridge. This supports the conclusion that the implemented IoT-based measurement method can produce results that are consistent with established measurement arrangements. The dissipation power is 27.34 W which is significantly higher than the values obtained at 10 kV in the previous calculations in this chapter. This difference is mainly explained by the higher test voltage.

4.6 Old voltage transformer from Tampere University

The last IT to be measured is an old VT from Tampere University manufactured by Messwandler-Bau (NUE0110a) in 1962. The secondary winding of the VT is divided into two parts, one of which also has two intermediate taps. Measurement arrangement used can be seen in Figure 27.

Figure 27. *Measurement arrangement for VT from Tampere University.*

Now the measurement arrangement is different than in the previous measurements. Reference voltage is now taken from the same VT that is being measured.

4.6.1 Results and analysis

Measurement results measured with Tettex 2877 measurement bridge can be seen in Table 9.

Table 9. *Results of the VT from Tampere University measured with Tettex 2877 measurement bridge.*

U_{rms}	I_{cx}	Tan δ	C_x
10.48 kV	934 µA	0.249	275.4 pF
65.16 kV	6.51 mA	0.172	304.3 pF
71.45 kV	6.82 mA	0.175	300.9 pF
73.18 kV	7.00 mA	0.176	299.9 pF

Tan δ values are around 17–18 % at operating voltage which is significantly greater than in previous measurement of the old VT with defective insulation. High age of this VT is clearly shown in the condition of its insulation.

Figure 28 shows IoT measurements measured using solid-core current transformer sensors, Figure 29 using split-core current transformer sensors and Figure 30 using shunt resistor sensors. It seems that the worse the insulation condition, the more noisy the earth current signals are. This may be because partial discharges can occur in poor insulation, causing disturbances and nonlinearity in the current curve. Secondary terminal earth currents have often bigger magnitudes in these cases but the signals are significantly interfered so fitting a sine wave on top of those becomes infeasible. Phase-shift of 180 degrees can be seen again in the Total current signal of solid-core measurement in Figure 28 as well as in the Shunt resistor measurement in Figure 30.

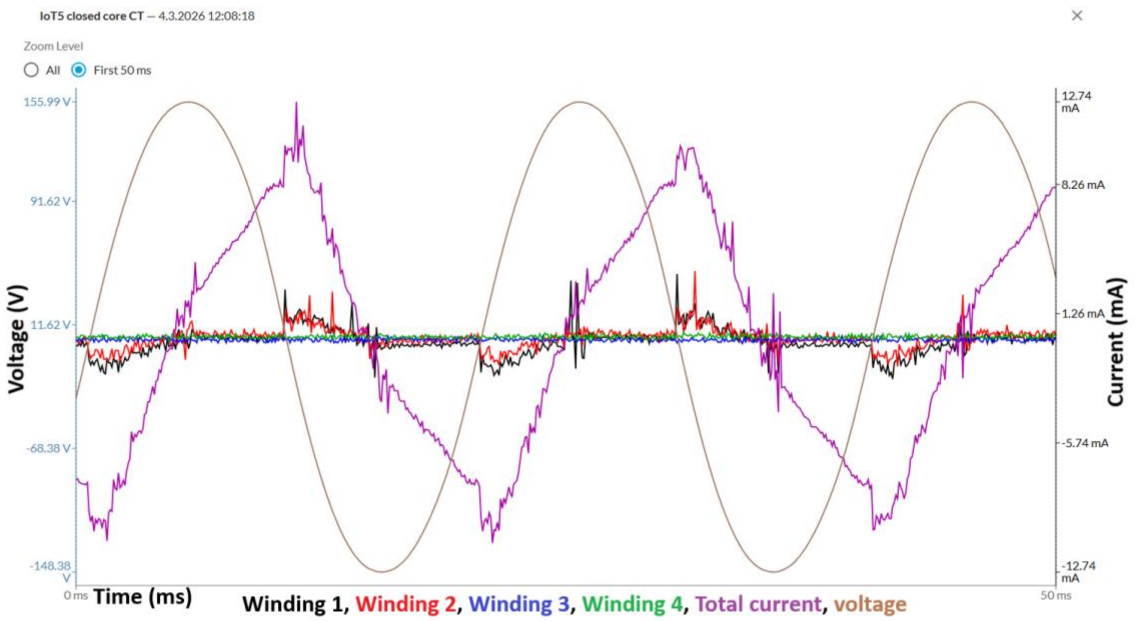


Figure 28. *VT from Tampere University measured with solid-core current transformer sensors at approximately 70 kV RMS voltage.*

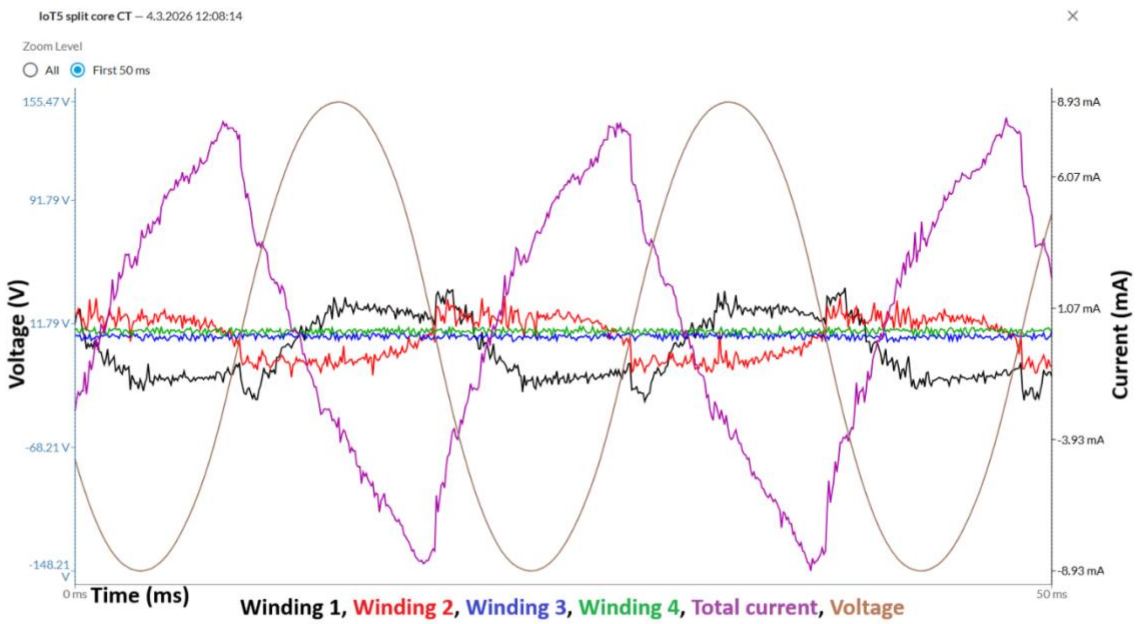


Figure 29. *VT from Tampere University measured with split-core current transformer sensors at approximately 70 kV RMS voltage.*

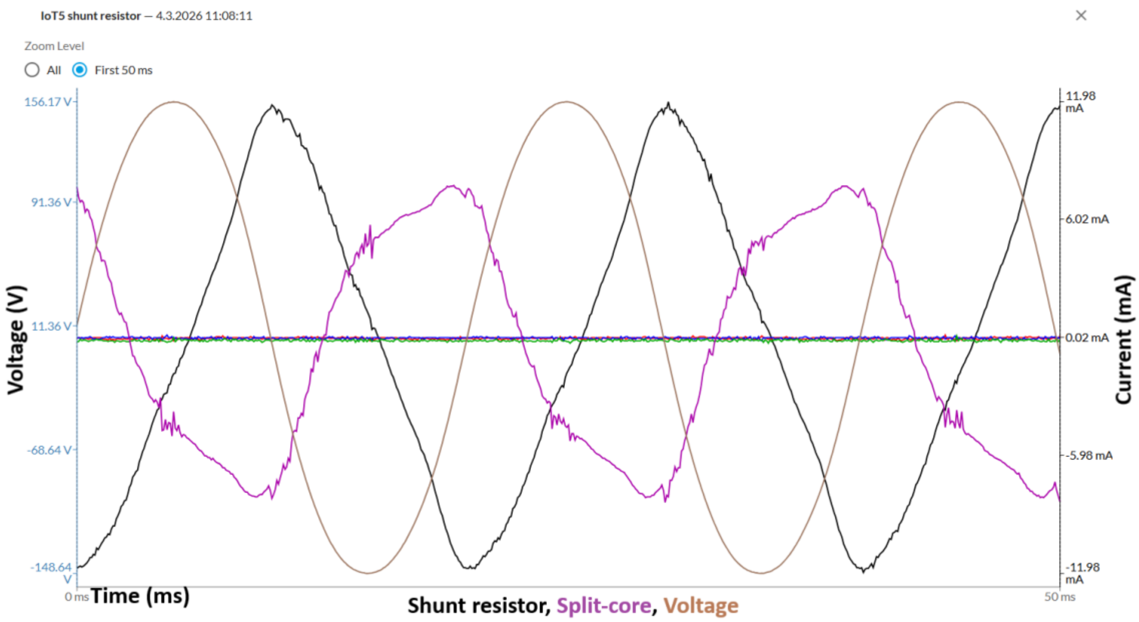


Figure 30. *VT from Tampere University measured with shunt resistor sensors at approximately 70 kV RMS voltage.*

Python analysis was conducted for the measurements of old VT from Tampere University at approximately 70 kV RMS voltage similarly as for the new CT and old VT. Table 10 presents the analysis results and compares them with tan δ values obtained with the Tettex 2877 device.

Table 10. *Results of the Python analysis of old VT from Tampere University IoT measurements at 70 kV RMS voltage.*

Measurement	Phase-dif. xcorr	Phase-dif. FFT	Tan δ xcorr	Tan δ FFT	Tan δ Tettex
solid-core CT	97.5	96.92	-0.1317	-0.1213	0.175
split-core CT	124.5	123.94	-0.6873	-0.6729	0.175
shunt resistor	79.5	80.19	0.1853	0.1729	0.170

As in previous similar analysis conducted, both solid-core CT and split-core CT have a phase difference clearly over 90 degrees and negative tan δ values. Again, tan δ values measured with shunt resistor and calculated with both cross correlation- and FFT -based methods appear to be close to the tan δ value measured with Tettex.

4.7 Summary of the laboratory measurements

One of the most important observations made in the laboratory measurements is the large difference between substation and laboratory measurements in the magnitudes of the secondary terminal earth currents. At the substation, the measured earth currents were big. One explanation for this could be that the measured current contains a significant capacitively coupled component, which arises from long and unprotected secondary circuits and travels through the ground to the measurement point. The measured earth currents in the laboratory were very small and strongly distorted which means that conducting reliable phase angle and loss angle analysis based on these signals is not possible. In the ITs with poor insulation condition, the earth currents measured from individual secondary terminals were often larger than in a device with good insulation, but the signals were also more heavily interfered with. This suggests that as the insulation deteriorates, the magnitude of the measurement signals may increase, but at the same time the signal quality may deteriorate, making it difficult to calculate the loss angle reliably. The capacitive current component should remain roughly constant and the observed increase in signal magnitude is therefore more likely explained by a growing resistive current component and by partial discharge activity.

Measuring the total earth current which includes sum of all the secondary terminal earth currents and the current flowing through the IT frame, gives a current signal that is larger and closer to sine wave. This raises the question that if good earth current signals are only obtained as total currents that includes the current from IT frame, how well can the internal insulation loss angle be measured from the total current signal. On the other hand, the analysis of measured total currents gave different phase difference and tan δ values from different instrument transformers and the values were of the same order of magnitude as expected. This can be considered a positive result in favor of this total current measurement method.

The reference measurements done with Tettex 2877 measurement bridge showed clear differences between the insulation conditions of different instrument transformers. The new Arteche current transformer showed a low tan δ value of 0.2 %, which indicates that the insulation is in good condition. In contrast, the measured voltage transformers showed significantly higher tan δ values. The old Arteche voltage transformer had tan δ values approximately in the range of 8–10 % while the Messwandler-Bau voltage transformer from Tampere University had values approximately in the range of 17–18 %. These values clearly indicate a deteriorated insulation condition. The old Arteche current transformer could not be measured at operating voltage levels because there occurred a breakdown when the voltage was increased above approximately 20 kV RMS. This indicated a severely degraded insulation condition.

It was observed that both solid-core and split-core current transformer sensors caused significant phase errors in the measurements. A likely reason for these large phase errors is that the current ranges of the used CT sensors (75 A for split-core and 4 A for solid-core) are very large compared to the measured earth currents, which are only in the milliampere range. As a result, the sensors operate at a very unfavourable part of their operating range, where the phase error caused by the magnetizing current is likely at its largest. The measured phase difference of current and voltage was always clearly over 90 degrees with these sensors. This led to negative tan δ values in the analysis which is not physically possible for insulation. Based on the results, these current transformer sensors are not suitable for loss angle measurements without accurate compensation or calibration of the phase error. Alternatively, current transformer sensors with a rated current range better matched to the measured currents would likely reduce both the phase angle error and the measurement noise and could thus improve the reliability of the loss angle determination. However, if solid-core and split-core sensors used in the measurements are compared, it seems that solid-core is a better option due to the less noisy signal it produces as well as the phase difference which is closer to 90 degrees.

On the other hand, the shunt resistor seems to work much better than the current transformer sensors. The tan δ values analyzed with shunt resistor measurements corresponded well to the Tettex 2877 reference measurements in all cases where the analysis could be performed reliably. These results indicate that the IoT5 device combined with a suitable current measurement method, has potential for loss angle measurement applications.

The analysis of the IoT measurements was conducted using two different methods, cross correlation and FFT-based method. The FFT-method proved to be particularly useful when analyzing small loss angles. Its smaller angle resolution is more useful than the cross correlation method used. Problem with the cross correlation method is that it gives the phase difference in 1.5 degree steps which is too coarse, especially when tan δ is small. Due to this e.g. in the case of the new CT measurement using shunt resistor, cross correlation method gave tan δ value of 0, whereas FFT-method gave 0.0010 which is closer to Tettex results. However, cross-correlation can be useful in noisy signals if its resolution and implementation are improved.

5. FUTURE IMPROVEMENT POSSIBILITIES

The laboratory measurements showed that the proposed online loss angle measurement method has potential, especially when the current measurement is implemented with a suitable sensor. However, several technical and analytical challenges must still be addressed before the method can be applied reliably in practical substation environments. Based on the results from the laboratory and the substation, the formation of the measured earth current, the selection of the sensor type, signal processing and long-term substation validation are particular key areas for further development. The main future improvement should not be only to improve the numerical accuracy of individual tan δ values, but to develop the method into a reliable trend monitoring tool that can detect long-term changes in instrument transformer insulation condition.

One of the most significant issues to remain open and to be studied in the future is to find out why the earth currents measured from secondary terminals are significantly higher at the substation than in the laboratory. Idea of capacitively coupled component was mentioned in the summary of the laboratory measurements but it is not a completely certain thing. Future tests could examine the contribution of different current components causing the measured current. This could be researched further at the substation e.g. by inspecting the possible effect of secondary cabling on the measurement results. Grounding arrangements or external interference could be also researched further.

Regarding different current sensing methods, there are basically two different routes for future development work. If current transformer sensors (solid-core and split-core) are still wanted to be used, phase error calibration methods need to be researched. First, the phase error caused in them should be determined accurately and then compensated in the measurement system or in the analysis. The shunt resistor sensor performed better in laboratory measurements, giving more accurate phase angle results and therefore tan δ values. Therefore, it would be worth focusing further development on the IoT device using a shunt resistor sensor, although some practical challenges must be considered. Since a CT secondary must never be open circuited, a protection circuit needs to be built across the shunt, and the installation is also more laborious than with a split-core sensor. The research work also revealed that the phase angle error can vary between sensors. In further development, a check measurement could be made for each sensor before installation, so that these phase angle error variations between the sensors can be calibrated out.

Another development area in the future would be improving signal processing and data analysis of the measurement results. The FFT-based method was found to be more suitable than the cross-correlation method, especially when the loss angle was small. Therefore, focus on the analysis development could be in further development and validation of the FFT-method. Important development areas include also taking into account the influence of various interference components and environmental conditions. The analysis algorithm should be able to distinguish insulation related changes from short-term disturbances caused by external conditions. Environmental conditions can also change significantly at the substation throughout the year, which is also important factor to be considered in the analysis algorithm. As has been pointed out earlier in the thesis, the analysis tool should be built in such a way that the focus is not on absolute tan δ values, but on monitoring changes as a function of time.

Long-term changes could not be tested in the laboratory but must be implemented at the substation. The prototype installation at the substation should be repaired and carefully documented for conducting new tests in which all the different observations made are considered. The new measurement implementation should take into account the issues mentioned earlier in this chapter like inspecting different current components and the effect of secondary cabling. The measurements should be conducted with shunt resistor sensors or compensated current measurement sensors. Also, the total current measurement should be included in substation measurements to see if it gives as promising results as in the laboratory. The test monitoring should be a long period, including different weather and load situations.

While the IoT measurement method is being improved at the substation, traditional loss angle measurement could also be conducted for the devices in question. This would give valuable data to be compared and analyzed. At the moment, the substation measurements are only conducted for CTs but given the laboratory measurements gave as promising results for VTs and CTs, the new test implementation at the substation should also include VT measurements. Due to the fact that the laboratory measurements gave surprising results compared to expectations, it might be sensible to carry out new laboratory measurements before making the new substation implementation. This would provide an even better understanding for development work at the site, and validate the observations made in this thesis. These new laboratory measurements could also be designed to be more extensive. For example, a compressed gas capacitor with a known, very small tan δ and a highly stable and accurately known capacitance could be measured with the different methods. In addition, various signals could be generated and analyzed with different measurement devices to compare their performance. The effects of larger partial discharges and the possibility of detecting them as spikes in the current signal could also be investigated.

6. CONCLUSIONS

The main objective of this thesis was to examine whether the online loss angle measurement method tested at the substation could be developed into a reliable solution for continuous insulation condition monitoring of instrument transformers. Another objective was to identify suitable technologies and measurement arrangements that could support the implementation of such solution. The motivation for this thesis arises from the increasing need for condition-based maintenance in modern power systems, where efficient use of the grid and security of electricity supply are becoming increasingly important.

By combining theoretical background, laboratory measurements and comparison with reference bridge measurements, this thesis evaluated both the feasibility and the limitations of the proposed online loss angle monitoring method. The research part involved measurements in a high voltage laboratory, where IoT-based measurement devices were tested with different current measurement sensors. Measurements were made on instrument transformers of different conditions and compared to reference measurements made with a measuring bridge. The main contribution of the thesis is the experimental evaluation of the measurement concept and the identification of current sensing, earth current formation and signal analysis as key factors affecting the reliability of the method.

The results of the thesis show that the proposed online measurement method can produce results comparable with reference measurements when a suitable current sensing method is used. Among the tested alternatives, the shunt resistor provided the most reliable phase angle and tan δ values. In contrast, the solid-core and split-core current transformer sensors introduced significant phase errors, which led to negative tan δ values in the analysis. Thus, these sensors are not suitable for loss angle measurement without separate calibration. The determination of absolute tan δ values with the proposed method remains challenging, but the method shows potential as a trend monitoring tool, where the focus is on detecting long-term changes in insulation condition.

The results also show that online loss angle measurement of instrument transformers is technically challenging. Due to the small capacitance of instrument transformer insulation, the earth currents to be measured are very small and therefore sensitive to external interference. In substation conditions, the measured current may be affected by capacitive coupling and grounding arrangements, which makes the interpretation of the results more complex. As a result of these issues, the measured current signal is also not exactly sinusoidal, especially when the insulation condition is poor.

Further research is required to improve the practical applicability of the measurement method. Development work should include gaining a better understanding of earth current formation in substation environments. Other key development areas include implementing an improved measurement arrangement at the substation which would make long-term field testing under real operating conditions possible. In addition, the FFT-based analysis method could be developed further. The results showed that it is better suited for small loss angle values than the implemented cross-correlation method, but its reliability should still be improved under noisy and distorted signal conditions. Ultimately, online loss angle measurement represents a promising method for monitoring instrument transformers and has the potential to support efficient and proactive maintenance strategies in the future.

REFERENCES

[1] "Main grid development plan 2026-2035," Fingrid. Accessed: Apr. 26, 2026. [Online]. Available: https://www.fingrid.fi/en/grid/development/Main-grid-development-plan/

[2] O. A. Tobar-Rosero, O. D. Díaz-Mendoza, P. A. Díaz-Vargas, J. E. Candelo-Becerra, H. A. Florez-Célis, and L. F. Quintero-Henao, "Digital Substations: Optimization Opportunities from Communication Architectures and Emerging Technologies," *Sci*, vol. 7, no. 2, p. 63, Jun. 2025, doi: 10.3390/sci7020063.

[3] J. Elovaara, *Sähköverkot 2: verkon suunnittelu, järjestelmät ja laitteet*. Helsinki: Otatieto, 2011.

[4] Wm. T. McLyman, *Transformer and Inductor Design Handbook*. Milton, UNITED KINGDOM: Taylor & Francis Group, 2011. Accessed: Sep. 05, 2025. [Online]. Available: http://ebookcentral.proquest.com/lib/tampere/detail.action?docID=1446498

[5] "What is a Current transformer," Accuenergy. Accessed: Sep. 04, 2025. [Online]. Available: https://www.accuenergy.com/support/reference-directory/what-is-a-current-transformer/

[6] L. Hewitson, *Practical power system protection*, 4th ed. Oxford ; Elsevier/Newnes, 2004.

[7] S. Clou, "The safety risks of open CT secondary circuits," Smart Energy International. Accessed: Sep. 09, 2025. [Online]. Available: https://www.smart-energy.com/industry-sectors/components/the-safety-risks-of-open-ct-secondary-circuits/

[8] A. T. Joy, "Voltage Transformer - Working Principle," Tameson.com. Accessed: Sep. 09, 2025. [Online]. Available: https://tameson.com/pages/voltage-transformer

[9] "Non conventional current and voltage transformers - Electra." Accessed: Oct. 30, 2025. [Online]. Available: https://www.e-cigre.org/publications/detail/elt-059-2-non-conventional-current-and-voltage-transformers.html

[10] G. W. Day, P. D. Hale, M. Deeter, T. E. Milner, D. Conrad, and S. M. Etzel, "Optical power line voltage and current measurement systems: Volume 1, Limits to the precision of electro-optic and magneto-optic sensors: Final report," National Bureau of Standards, Washington, DC (USA); Electric Power Research Inst., Palo Alto, CA (USA), EPRI-EL-5431-Vol.1, Sep. 1987. Accessed: Oct. 30, 2025. [Online]. Available: https://www.osti.gov/biblio/6238816

[11] "State of the Art of Instrument Transformers - Technical Brochures." Accessed: Sep. 22, 2025. [Online]. Available: https://www.e-cigre.org/publications/detail/394-state-of-the-art-of-instrument-transformers.html

[12] J. H. Harlow, *Equipment types, Electric power transformer engineering*, 1st ed. in The electrical engineering handbook. Boca Raton: Taylor & Francis, 2003. doi: 10.1201/b12110.

[13] J. Lehtinen, "Fingrid Oyj Expert interview," 2025.

[14] P. Minder, "Operation reliability of high voltage instrument transformers," vol. 76, SEV Bulletin, 1985, pp. 509–512.

[15] "Technical basis for minimal requirement for composite insulators - Electra." Accessed: Oct. 30, 2025. [Online]. Available: https://www.e-cigre.org/publications/detail/elt-088-3-technical-basis-for-minimal-requirement-for-composite-insulators.html

[16] M. Aro, J. Elovaara, M. Karttunen, K. Nousiainen, and V. Palva, *Suurjännitetekniikka*, 4. korj. ja täydennetty p. Helsinki: Otatieto, 2015.

[17] P. Hyvönen, *Prediction of insulation degradation of distribution power cables based on chemical analysis and electrical measurements*. Teknillinen korkeakoulu, 2008. Accessed: Dec. 15, 2025. [Online]. Available: https://aaltodoc.aalto.fi/handle/123456789/4498

[18] "Dielectric characteristics comparison of insulating babaçu's grain vegetable oil and transformers mineral oil - ISH Collection." Accessed: Jan. 30, 2026. [Online]. Available: https://www.e-cigre.org/publications/detail/ish2017-251-dielectric-characteristics-comparison-of-insulating-babacus-grain-vegetable-oil-and-transformers-mineral-oil.html

[19] G. Zhou, Y. Shi, Q. Wang, and X. Chen, "Research on AC and High Frequency Breakdown Characteristics of Oil-paper Insulation of 220 kV Current Transformers," in *2021 IEEE 5th Conference on Energy Internet and Energy System Integration (EI2)*, Oct. 2021, pp. 3740–3743. doi: 10.1109/EI252483.2021.9713229.

[20] "Natural Esters for Green Transformers: Challenges and Keys for Improved Serviceability." Accessed: Dec. 15, 2025. [Online]. Available: https://www.mdpi.com/1996-1073/16/1/61

[21] C. Perrier and A. Beroual, "Experimental investigations on insulating liquids for power transformers: Mineral, ester, and silicone oils," *IEEE Electr. Insul. Mag.*, vol. 25, no. 6, pp. 6–13, Nov. 2009, doi: 10.1109/MEI.2009.5313705.

[22] S. A. Azli, M. Hezri Fazalul Rahiman, Z. M. Yusoff, N. Fadzilah Razali, S. S. Abd Wahid, and M. Sufian Ramli, “A Review on Alternative Oils as Dielectric Insulating Fluids on Power Transformer,” in *2019 IEEE 15th International Colloquium on Signal Processing & Its Applications (CSPA)*, Mar. 2019, pp. 198–201. doi: 10.1109/CSPA.2019.8695983.

[23] H. P. Gasser, C. Krause, and T. A. Prevost, “The aging characteristics of laminated pressboard and laminated wood in oil cooled power transformers,” in *Conference Record of the 2006 IEEE International Symposium on Electrical Insulation*, Jun. 2006, pp. 403–407. doi: 10.1109/ELINSL.2006.1665343.

[24] I. Rytöluoto, M. Ritamäki, A. Gitsas, S. Pasanen, and K. Lahti, “Morphology Development, Structure and Dielectric Properties of Biaxially Oriented Polypropylene,” *Proc. Nord. Insul. Symp.*, no. 25, Oct. 2017, doi: 10.5324/nordis.v0i25.2359.

[25] “State of the art in insulation of gas insulated substations: main issues, achievements, and trends.” Accessed: Dec. 04, 2025. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/7552373

[26] *Regulation (EU) 2024/573 of the European Parliament and of the Council of 7 February 2024 on fluorinated greenhouse gases, amending Directive (EU) 2019/1937 and repealing Regulation (EU) No 517/2014 (Text with EEA relevance)*. 2024. Accessed: Jun. 13, 2026. [Online]. Available: http://data.europa.eu/eli/reg/2024/573/oj

[27] “Ageing of cellulose in mineral-oil insulated transformers - Technical Brochures.” Accessed: Sep. 29, 2025. [Online]. Available: https://www.e-cigre.org/publications/detail/323-ageing-of-cellulose-in-mineral-oil-insulated-transformers.html

[28] M. R. Meshkatodd, “Aging Study and Lifetime Estimation of Transformer Mineral Oil,” *Am. J. Eng. Appl. Sci.*, vol. 1, no. 4, pp. 384–388, Apr. 2008, doi: 10.3844/ajeassp.2008.384.388.

[29] Ch. Krause, L. Dreier, A. Fehlmann, and J. Cross, “The degree of polymerization of cellulosic insulation: Review of measuring technologies and its significance on equipment,” in *2014 IEEE Electrical Insulation Conference (EIC)*, Jun. 2014, pp. 267–271. doi: 10.1109/EIC.2014.6869389.

[30] V. M. Montsinger, “Loading Transformers By Temperature,” *Trans. Am. Inst. Electr. Eng.*, vol. 49, no. 2, pp. 776–790, Apr. 1930, doi: 10.1109/T-AIEE.1930.5055572.

[31] *IEC 60076-7 Loading guide for oil-immersed power transformers*.

[32] “IEEE Guide for Loading Mineral-Oil-Immersed Transformers - Corrigendum 1,” *IEEE Std C5791-1995Cor 1-2002*, pp. 1–16, Jun. 2003, doi: 10.1109/IEEESTD.2003.94283.

[33] K. B. Liland, M. Kes, M.-H. Glomm Ese, L. E. Lundgaard, and B. E. Christensen, “Study of oxidation and hydrolysis of oil impregnated paper insulation for transformers using a microcalorimeter,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 18, no. 6, pp. 2059–2068, Dec. 2011, doi: 10.1109/TDEI.2011.6118644.

[34] L. E. Lundgaard, W. Hansen, D. Linhjell, and T. J. Painter, “Aging of oil-impregnated paper in power transformers,” *IEEE Trans. Power Deliv.*, vol. 19, no. 1, pp. 230–239, Jan. 2004, doi: 10.1109/TPWRD.2003.820175.

[35] P. Wedin, “Electrical breakdown in dielectric liquids-a short overview,” *IEEE Electr. Insul. Mag.*, vol. 30, no. 6, pp. 20–25, Nov. 2014, doi: 10.1109/MEI.2014.6943430.

[36] M. Poljak and B. Bojanić, “Method for the reduction of in-service instrument transformer explosions,” *Eur. Trans. Electr. Power*, vol. 20, no. 7, pp. 927–937, 2010, doi: 10.1002/etep.375.

[37] “Measurands capacitance and dissipation factor.” Accessed: Nov. 20, 2025. [Online]. Available: https://www.highvolt.com/en/calibration/accreditation-scope/measurands-capacitance-and-dissipation-factor

[38] C. F. Ten, M. A. R. M. Fernando, and Z. D. Wang, “Dielectric properties measurements of transformer oil, paper and pressboard with the effect of moisture and ageing,” in *2007 Annual Report - Conference on Electrical Insulation and Dielectric Phenomena*, Oct. 2007, pp. 727–730. doi: 10.1109/CEIDP.2007.4451521.

[39] H. Wu, L. Liu, T. Liu, Z. Peng, X. Lv, and J. Liao, “The effect of moisture and temperature on the oil-immersed-paper used in EHV converter transformer,” in *2016 IEEE International Conference on Dielectrics (ICD)*, Jul. 2016, pp. 577–580. doi: 10.1109/ICD.2016.7547670.

[40] P. Werelius, M. Ohlen, J. Cheng, and D. M. Robalino, “Dielectric frequency response measurements and dissipation factor temperature dependence,” in *2012 IEEE International Symposium on Electrical Insulation*, Jun. 2012, pp. 296–300. doi: 10.1109/ELINSL.2012.6251476.

[41] “What is Megger Test and How it is performed?” Accessed: Dec. 10, 2025. [Online]. Available: https://electricalampere.com/what-is-megger-test-and-how-it-is-performed/

[42] J. Golarz, "Understanding Dissolved Gas Analysis (DGA) techniques and interpretations," in *2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, May 2016, pp. 1–5. doi: 10.1109/TDC.2016.7519852.
[43] "Schering bridge," *Wikipedia*. Nov. 26, 2021. Accessed: Jan. 19, 2026. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Schering_bridge&oldid=1057196005
[44] "Schering Bridge: Know Circuit Diagram, Loss Factor, Advantages & Application." Accessed: Feb. 05, 2026. [Online]. Available: https://testbook.com/electrical-engineering/schering-bridge
[45] Technomax_wp, "Tan Delta Test And Capacitance Measurement In UAE | Technomax." Accessed: Apr. 21, 2026. [Online]. Available: https://www.technomaxme.com/tan-delta-test/
[46] J. H. Harlow, *Ancillary Topics, Electric power transformer engineering*, 1st ed. in The electrical engineering handbook. Boca Raton: Taylor & Francis, 2003. doi: 10.1201/b12110.
[47] "Digitaalinen kunnonvalvontajärjestelmä tuotantokäyttöön sähköasemille," Fingrid. Accessed: Dec. 12, 2025. [Online]. Available: https://www.fingrid.fi/ajankohtaista/tiedotteet/2023/digitaalinen-kunnonvalvontajarjestelma-tuotantokayttoon-sahkoasemille/
[48] S. Kornhuber, S. Markalous, H. M. Muhr, T. Strehl, and C. Sumereder, "Comparison of Methods for the Dissipation Factor Measurement at Practical Examples: 16th International Symposium on High Voltage Engineering," *Proc. 16th Int. Symp. High Volt. Eng.*, pp. 144–144, 2009.
[49] M. Rhodes, A. Khan, J. Wold, G. Zweigle, and J. Bestebreur, "Voltage Transformer Failure Prediction With Synchrophasor Data," presented at the 49th Annual Western Protective Relay Conference, Spokane, Washington: Schweitzer Engineering Laboratories, Inc, 2022.
[50] M. Kivistö, "ionSign Oy CEO interview," 2025.
[51] S. Staboulis, "Luoto Company Full Stack Data Scientist interview," 2025.
[52] "CR8400 Series.pdf." [Online]. Available: https://www.crmagnetics.com/Assets/ProductPDFs/CR8400%20Series.pdf
[53] "CR3100 - CR3113 Series1.pdf." [Online]. Available: https://www.crmagnetics.com/Assets/ProductPDFs/CR3100%20-%20CR3113%20Series1.pdf
[54] F. Adams, "Current Transformers: An Analysis of Ratio and Phase Angle Error," CR Magnetics, Inc., 2001.
[55] "High Voltage Laboratory," Tampere universities. Accessed: Feb. 11, 2026. [Online]. Available: https://www.tuni.fi/en/research/high-voltage-laboratory
[56] T. Shen, H. Li, M. Li, Q. Zhang, and Y. Shen, "A simple multiple cross-correlations phase delay estimator," in *2017 29th Chinese Control And Decision Conference (CCDC)*, May 2017, pp. 408–412. doi: 10.1109/CCDC.2017.7978129.
[57] "What is FFT ? : A Short Intro to the Fast Fourier Transform - Keysight Oscilloscope Glossary - Keysight Technologies." Accessed: Jun. 01, 2026. [Online]. Available: https://www.keysight.com/used/us/en/knowledge/glossary/oscilloscopes/what-is-a-fft-fast-fourier-transform