School of Information Technology and
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UTILIZATION OF ELECTRICAL AND ELECTRONIC DEVICES, MEASUREMENT AND TESTING INSTRUMENTS, AND INTELLIGENT ELEMENTS IN POWER NETWORKS

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By
Rashad Azimov

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THESIS ACCEPTANCE

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Approved:

Wisam Al-Dayyeni	23.12.2024
(Adviser)	(Date)
Wisam Al-Dayyeni	23.12.2024
(Program Director)	(Date)
Abzatdin Adamov	23.12.2024
(Dean)	(Date)

ABSTRACT

The actual electric power structure of Azerenerji relies only on Conventional Current Transformer (CCT), and this gives a very great chance to start assessing new technologies that could improve the performance of measurement and protection systems. This work represents extended comparative analysis of Fiber Optical Current Transformer (FOCT) and CCT in 110 kV substations with the use of advanced simulation techniques investigating operational characteristics for different electrical situations. In this thesis, the performance of the transformer is simulated in three test case scenarios under a short-circuit condition using DigSilent PowerFactory software. The research investigated the operational characteristics of transformers along the three critical areas of investigation: change in loading conditions, frequency response, and dynamic conditions related to short circuit power. In this regard, the study throws light on the behavior of transformers in complicated electrical scenarios by manipulating generators and load parameters. The most significant differences concerned the frequency response characteristics. FOCTs showed very good performance and allowed high accuracy within a wide frequency range with very small deviation, while conventional Current Transformers showed a strong deterioration of their performance, especially at higher frequencies. With such big differences in performance, potential advantages of FOCT in modern substation systems are implicated, especially in the cases when one needs to get precise and stable measurements under different electrical conditions. Nevertheless, it showed serious implementation challenges. Fiber Optic Current Transformers are quite sensitive to a whole range of environmental factors, including temperature fluctuations and mechanical impact. And that means that despite quite promising perspectives of the measurement technique, serious technological developments are needed before its wide application in critical infrastructure. The implications of the study go beyond immediate technological comparisons. The study provides a basic framework within which the transformative trajectory of existing transformer technologies in electrical power systems can be understood. Thus, the research provides quantitative performance differences that may serve as insight for the engineers, researchers, and infrastructure planners considering technological upgrade alternatives. The simulations revealed that FOCT shows minimal deviations especially under wide range of frequency, although CCT showed considerable deviations during short-circuit event. These findings demonstrate that FOCTs maintain high accuracy in various applications. However, this thesis underscores the demand for further improvement in the FOCTs by considering their temperature and vibration sensitivity.

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
CT	Current Transformer
CCT	Conventional Current Transformer
CIT	Conventional Instrument Transformer
NCIT	Non-conventional Instrument Transformer
EHV	Extra-high voltage
UHV	Ultra-high voltage
HVDC	High Voltage Direct Current
DC	Direct Current
GIS	Gas Insulated Switchgear
FOCS	Fiber Optical Current Sensor
SCADA	Supervisory Control and Data Acquisition
PQ	Power Quality
IT	Instrument Transformer
EIT	Electronic Instrument Transformer
OCT	Optical Current Transformer
SLD	Super Luminescent Diode
LED	Light Emitting Diode
EMT	Electromagnetic Transient
RMS	Root Mean Square

CHAPTER ONE
INTRODUCTION

1.1 Problem statement

Today, development in power grids lead them to utilization of new technologies. With this technological advancement, measurement and protection system within the substation also improves. While CTs plays crucial role in measurement and protection process, in outdated substations, they still use traditional type of CTs. This is the core issue, if we take environmental impacts, measurement accuracy and delayed response into our consideration. Conventional Current Transformers (CCTs) employ electromagnetic effects to step down the current to make it measurable. Due to having magnetic core, they are exposed to saturation at certain conditions. In Azerbaijan, all substations use traditional CTs for current measurement and protection purposes. This slows down triggering speed of protective relays, because of saturation during short-circuit event. Moreover, CCTs have great size and heaviness which makes it not applicable where there is limited space for CT installations. After Azerenerji and Masdar companies agreed and built Garadagh solar power plant, progress in renewable energy sector became more evident. Furthermore, in the liberated areas, smart power grid establishment is planned. Hence, utilization of CCTs will become worse, because new digital technologies requires fast responses and calculations from CTs which easily handled by non-conventional instrument transformers (NCITs).

In response to these challenges, NCITs provide better solutions in various approaches. This study mainly focuses on fiber optical current transformers (FOCTs) which use advanced optical technologies to deliver superior performance. FOCTs have similar design, because they have similar insulation outside of body. Nevertheless, they are smaller in shape than CCTs and lightweight. Due to absence of magnetic core, it becomes suitable for high-voltage applications where delayed response can damage expensive equipment. Moreover, they also provide more accurate measurements which is crucial for Azerenerji's new planned smart power grids for future.

This study investigates shortcoming of CCTs, while highlighting benefits of utilization of FOCTs in new substations at Azerenerji. The research highlights performance, accuracy, saturation characteristics, frequency response during short-circuit event in the simulation.

1.2 Definition of terms

Transient response. The behavior of a system in the event of sudden alteration or disturbance; in other words, a fault or a switching event. For transformers, transient response analysis indicates how rapidly or accurately the transformer becomes settled after such aforementioned events.

Fiber Optic Current Transformer (FOCT). A current-measuring type of NCIT, the principle of operation of which is based on fiber optic technology. Fiber-optic current transformers boast high accuracy, immunity to electromagnetic interference, and improved safety because no conducting parts exist.

Conventional Instrument Transformer (CIT). An electromechanical device used in the step-down process for high voltage or current values in power systems to measurable values feasible for protection, metering, and monitoring applications. A current transformer operates on the principle of electromagnetic induction.

Non-Conventional Instrument Transformer (NCIT). A modern type of instrument transformer using modern optical or electronic sensor technology for measuring current and voltage in power networks. The disadvantages mentioned earlier related to the conventional instrument transformers do not apply for the NCIT: the novel designs are more accurate, much safer, and smaller.

Transformer Saturation. When magnetic flux distorts, and output signals are coming out of a transformer, where the magnetic core has full magnetization. This will result in erroneous current/voltage measurements, especially for fault conditions.

Frequency Response. The size of the output signal for a range of input frequencies. Frequency response tests on transformers have been applied to determine exactly how well a transformer can reproduce an electrical signal faithfully without distortion across a range of frequencies.

Short-Circuit Power. The highest power flowing when a short-circuit condition arises in a power network. It forms a very vital basis upon which the various transformer performances are judged against their faults.

Measurement and Testing Instruments. Voltage, current, power factor, and frequency are instruments used in measuring and analyzing the electrical properties of a power system. Examples are oscilloscopes, multimeters, and power quality analyzers.

Power Networks. The generation, transmission, and distribution of electrical energy to the end user is done using interconnected networks of electrical components. Power system includes substations, transformers, transmission lines, and protective equipment.

Saturation Characteristics. The relation of magnetic flux and current in a transformer core at the point of saturation is important. Such characteristics help identify the operating limits of a transformer.

Simulation. Applications also include mathematical and computational models that represent real-world behaviors or systems for analysis and testing. Regarding this, simulations are useful, especially in forecasting transformer efficacy, analysis of intricate electrical systems without actual experimentation.

Optical Sensors. Devices that depend on light-based technologies, like fiber optics, to make their measurement of an electrical parameter-current or voltage. In most scenarios, optical sensors would be used in NCITs due to offering immunity to electromagnetic interference and a higher accuracy.

Electromagnetic Induction. Principle of operation where a conductor induces a voltage or a current, depending on a variation of a magnetic field. Conventional instrument transformers take this phenomenon as a principle of operation.

Intelligent Elements. Advanced elements are a set of sensors, processors, and communication devices that enable the power system to achieve automation, real-time monitoring, and make better decisions.

Saturation in Current Transformers (CT). A specific case of transformer saturation where a current transformer's core cannot accurately follow rapid changes in primary current, leading to signal distortion and measurement errors.

Accuracy Class. A classification scheme which, for a given application, states the maximum permissible errors of instrument transformers in order to have correct and reliable measurements.

Protective Relaying. A system designed to identify faults or abnormal conditions on power networks and take appropriate control actions, such as the isolation of affected components to protect equipment and ensure the stability of power systems.

Power Quality. A measure showing the consistency and purity of electric power delivered to the end-user. Low power quality may be manifested in terms of voltage sags, harmonic distortions, and other disruptions to affect equipment functionality.

Harmonics. Voltage or current components at frequencies that are integer multiples of the fundamental frequency in the power system. Their impact will be overheating, signal distortion, and loss of efficiency in equipment.

Voltage Stability. Ability of a power system to maintain steady-state voltage levels under normal and abnormal conditions. Voltage instability is the cause of a system collapse or blackout

Fault Tolerance. It enables a system or component to continue its normal operation without disruption if a single or multiple faults or failures occur. In power networks, fault tolerance forms the basis for ensuring reliability and limiting disruptions

Digital Signal Processing (DSP). Electrical signal processing using digital techniques and algorithms; in the case of NCITs, these find wide applications for the correct measurement, filtering, and analysis of electrical parameters

Primary Current. The current through the primary winding of the transformer is proportional to the current in the power network that is to be measured or observed

Secondary Current. Because of this, the available current from the transformer's secondary winding is reduced in proportion to the primary current so that the current magnitudes to the meters and protection relays are safe and measurable

Magnetic Flux. Magnetic flux defines the total quantity of magnetic field passing through the given area of concern, such as a transformer core. It is highly relevant to both conventional and new transformer models.

Current Transformer (CT). The intention of an instrument transformer is to bring high-magnitude primary currents down to lower magnitudes for measurement, protection, and control purposes in electrical power systems.

Conventional Current Transformer. It is a type of current transformer using a magnetic core with windings around it to measure current through electromagnetic induction.

Extra-High Voltage (EHV). Voltage levels in the range of 345 kV to 765 kV used for bulk-power transmission over very long distances within the power systems.

Ultra-High Voltage (UHV). These voltages are above 800 kV. The application is made for a quantity of electrical power transmission across long distances with minimum losses.

High Voltage Direct Current (HVDC). A transmission system of power that uses DC for effectively transmitting energy over a very long distance.

Direct Current (DC). This is in contrast to AC, in which the movement of electric charge periodically reverses direction.

Gas Insulated Switchgear (GIS). Compact switchgear class in which the insulation is usually achieved by a gas, typically SF6, for the electrical conductive part of a high-voltage system.

Fiber Optical Current Sensor (FOCS). A sensor based on fibre-optic technology that measures current with precision, ensuring high performance and immunity to electromagnetic interference.

Supervisory Control and Data Acquisition (SCADA). Design for quick observation, control, and automation of electrical systems and industrial processes.

Instrument Transformer. A transformer steps up or steps down voltage or current levels to quantifiable and safe thresholds, thus serving protective and metering functions.

Electronic Instrument Transformer. A particular class of NCIT uses electronic components and sensors that are applied in measuring electrical parameters accurately and effectively.

Super Luminescent Diode (SLD). A semiconductor light source that combines features of lasers and light-emitting diodes, finding frequent use in optical measurement systems.

Light Emitting Diode (LED). A semiconductor device which emits light when an electrical current passes through it, commonly used in all type of displays and optical detectors.

Electromagnetic Transient. A very short duration, high-frequency event in electric power systems initiated by switching events, faults, or lightening strokes.

Root Mean Square (RMS). A measure of the size of a signal that varies; in electrical terms, it is the root-mean-square value of an AC voltage or current.

1.3 Significance of Study

This research represents the detailed evaluation of Conventional Current Transformers versus Fiber Optic Current Transformers for future applications in Azerenerji substations and generating stations. The results would be useful to show the benefits of FOCT over CCT and update Azerenerji on state-of-the-art measurement technologies.

Higher Measurement Accuracy: FOCTs provide better measurement accuracy as compared to CCTs, especially during dynamic and high current conditions. For ensuring reliable protection, monitoring, and control, precise current measurement is always essential in power systems, which helps to enhance the stability and efficiency of the overall system.

Environmental Advantages: Because of the compact, oil-free design, there are benefits to FOCTs, such as ecological benefits. As compared to the CCTs, there has been a great reduction in leakage risks and also a contribution toward goals related to sustainable infrastructure since it has reduced material usage. Due to this, FOCTs are also more eco-friendly for modern substations.

Cost Efficiency: The cost-reducing possibilities for FOCTs are achieved by simplifying the installation process, reducing maintenance, and extending their lifetime. It is lightweight with a modular design that minimizes labor and resource-intensive processes, thereby optimising economic efficiency.

Future Research Considerations: Though FOCTs realize very significant merits, they are still sensitive to temperature shifts and mechanical vibrations. The present study takes this imbalance in performance and reliability of FOCTs for real applications as the prime consideration for further studies.

Technological: By introducing FOCT technology, the adaptation of both digital substations and smart grid systems will be further facilitated for Azerenerji. In fact, FOCTs offer better acquisition of data, real-time monitoring, and smooth integration with IEDs, all in fashion with the latest trends in the development of power system automation and digitization.

1.4 Limitation of Study

The following thesis gives an in-depth comparison of Conventional Current Transformers and Fiber Optic Current Transformers. However, there must be cited some shortcomings: one of the major issues includes the susceptibility of the FOCT to environmental conditions like temperature and mechanical vibrations. These considerations may affect their measurement accuracy in the worst or under unstable conditions of these factors, therefore demanding more studies to arrive at an effective mitigation strategy.

Besides, simulation-based analysis may be adopted with a view to determine the performance of the FOCTs and CCTs from several aspects such as saturation characteristics, frequency response, and behavior under short-circuit conditions. While all simulations give critical information, performing physical experiments under realistic working conditions would lend more validity to the results and provide fuller insight.

The study also doesn't provide any data about the values of some long-term performance indicators such as insulation durability, ageing effects, stability over long period. These facts are very important for the determination of the general life expectancy and reliability of FOCTs for practical use; on the other hand, practical implementation issues associated with the transition from CCTs to FOCTs-such as compatibility and economic issues-are beyond the scope of this study. Last but not least, performance data on extreme environmental conditions for FOCTs is scarce and may have been one of the limiting factors in the broadness of the analysis. Despite these limitations, there is valuable insight into the relative merit of the FOCT over the CCT. Further research with actual world validation will help in filling these gaps, hence a better understanding and practical implementation of the FOCT technology in power networks.

CHAPTER TWO
LITERATURE REVIEW

2.1 Overview of Non-Conventional Instrument Transformers

In [1], author discusses new process bus in relay protection scheme which can be utilized with non-conventional instrument transformers (NCIT's). NCIT uses Rogowski coil for current and capacitive dividers for voltage measurement. They integrate sensors into GIS and analog signals connect to merging units with passive sensor connection boxes. It has several advantages, such as being small and lightweight, having simple wiring, higher reliability, lower cost, and higher measurement accuracy. Additionally, it causes us to have more compact GIS design, and improved safety in the system.

In [2], the author emphasizes the benefits of NCIT's usage in power systems. They add details about utilizing NCIT's in digital substations. It assists in reducing environmental impacts, increasing operational safety, reduces substation footprint. In addition to all of these, the author mentions that this type of transformer does not require to have analogue-digital conversion to adapt transformer to the system, while conventional instrument transformers require it. They delve into fiber optical current sensor (FOCS) technology in detailed form. FOCS technology causes a phase shift between left and right circular polarized light waves emitted from a fiber optic cable, where the magnetic field travels around the current conductor, Faraday. This phase shift is measured on an interferometer and provides accurate measurement of the electric current without problems such as magnetic saturation faced by conventional current transformers.

In [3], the author aims to compare conventional instrument transformers with non-conventional instrument transformers. He analyzes the construction and operating principles of NCIT's. Performed various laboratory tests on NCIT's to observe how they behave under different conditions. Several advantages have been noted om the article, such as reduced size, weight and cost compared to CT's. Accuracy is at a higher level if we compare two types and has higher immunity to electromagnetic interference and saturation effects. Despite all of these benefits, they have some drawbacks. If the long cable utilized, signal attenuation and noise might occur. Additionally, it has limited overload capacity compared to CT's.

In [4], the author conducted research on development of wide frequency and wide range current transformers using two main techniques: Active and passive compensation. In passive compensation, the main core and compensation core exist which are made of using different materials. Main core is made of nanocrystalline and cold-rolled silicon steel materials to keep B-H curve characteristics. However, compensation core is made of cold-rolled silicon steel which is connected to main core. From all windings (primary, secondary, compensation), magnetic flux cross-linked to reduce error losses. In contrast to passive compensation, active compensation utilize detection winding to improve the accuracy of current transformer angular difference measurement. Both active and passive current transformers were tested and developed in various configurations. While active compensation improves measurement accuracy, passive compensation effectively broadens the current range of rated current and frequency range. Despite the fact that active compensation is better than passive compensation in terms of measurement accuracy, both are superior to traditional transformers.

In [5], researchers from South Ural University and a company named Chelenergopribor made an comprehensive research report about a new type of digital combined voltage and current transformer called TRATON-110 for use in digital substations. TRATON-110 has been tested under different conditions, such as high voltage and thermal imaging control. Main hardware of this type of transformer consists of high voltage sensor and merging unit. For simulation purposes, the Riverbed Modeler software environment has been used. IEC 61580 protocol has been utilized for modeling and simulating integration of the TRATON-110 into digital substation. In contrast to traditional transformers, fire hazards are not being observed in this system. Additionally, the system avoids regular monitoring which was required for traditional CT's. It improves current and voltage measurement accuracy which data is used for control and protection and power quality analysis in digital substations. The system uses IEC 61850 protocol for data exchange withing ethernet networks. Although a higher amount of the initial budget is required, this transformer has 50% less installation costs and 90% less maintenance costs compared to traditional CT's. This paperwork has been successfully implemented and patents have been obtained for technical solutions.

In [6], the author discusses a new type of transformer called TRATON-110. This paper [6] is very similar to 5th paper [5] in some perspectives and one of the authors is same for both paper from South Ural University. Researchers conducted comprehensive research for the development of instrument current and voltage transformers to reduce cost and enhance measurement accuracy compared to using converters. Authors used Riverbed software for simulation and employed experimental studies to evaluate the performance of a new type of transformer. They used IEC 61850 protocol for data transmission to SCADA in the ethernet network. Although simulation is not as effective as real time monitoring, it allows authors to predict future system behavior.[7] Additionally, real world settings have been applied to the system to observe how transformers operate under different conditions. This transformer allows us to reduce the footprint, to improve synchronization and to reduce future costs.[8][9]

In [12], the author conducts research to learn more about traceable measurement of power quality (PQ) when transformers considered in the measurement chain. Frequency has been set to 9 kHz and to achieve realistic PQ disturbances they set up measurement setting to define voltage value and to calibrate it. Researchers also explored potential issues that might occur if they apply all conditions at the same time (temperature, burden, magnetic field) under PQ disturbance. All equipment was sorted and filtered under PQ disturbance, and they defined new PQ accuracy classes and performance indexes considering PQ disturbance. This research assists in filling the knowledge gap which exists in instrument transformer (IT) performance in given conditions. When IT's are used, this methodology improves measurement accuracy for the system. Based on the article, for IT calibrations, all settings are simplified under realistic conditions. Because there are so many possible combinations, it is only possible to analyze the combined influence of two factors at a time when analyzing the impact of multiple factors on IT performance. It may be difficult to meet the target uncertainties for PQ parameter measurement, which are two orders of magnitude smaller than current standards.[10][11]

In [13], an article investigates advantages of electronic instrument transformers (EIT) over conventional ones. Development of instrument transformers made them more compact and more accurate. Conventional instrument transformers produces anologue output, but electronic instrument transformers are type of non-conventional instrument transformers which produces digital output. Electronic instrument transformers work based on set of rules, such as Rogowski Coil, Hall effect, coaxial dividers, and optical. Either it is measuring voltage or current, an appropriate signal is sent to merging unit using secondary converter. Merging units also provide additional protection schemes, even though electronic instrument transformers have a functionality to directly communicate with protection relays. Main component of optical instrument transformers is fiber optic current sensor (FOCS). The core of optical fiber is glass. Fiber optic has cladding, coating, strength member, outer jacket over core element. FOCS sensors use polarized light interacting with magnetic fields to provide accurate measurements crucial for digital substation integration. Their design removes intricate sensor heads and utilizes basic fiber loops, improving ease of installation and operational efficiency. The article also explores Hall Effect Instrument Transformers, which utilize the magnetic characteristics of current-carrying conductors for measurement. These transformers are examined in three different setups: open-loop, closed-loop, and coreless designs. The open-loop and closed-loop configurations utilize a magnetic core, whereas the coreless version circumvents problems with core saturation by using a circular arrangement of Hall sensors to enhance measurement precision. Every setup is meticulously crafted to address particular measurement requirements and operational obstacles, rendering them adaptable in different power usages.

In [14], the paper mainly discuss why conventional instrument transformers are not suitable for today's applications in modern smart grids. They primarily focus on measurement errors that occur on current transformers, due to low harmonics generated by magnetic core. Moreover, parasitic capacitance between each layer of winding causes measurement errors in voltage transformers due to higher harmonics. In addition to all of these, as frequency increases, accuracy deteriorates in the instrument transformers, because magnetic permeability significantly decreases. To avoid these problems, material quality could be improved, however this brings problems such as complexity and cost. In general, the paper suggests that advanced materials should be used and transformer must be redesigned for that purpose.

2.2 Technologies and Compensation Methods for NCITs

In [15], The document investigates sophisticated building methods to enhance the design and precision of present current and voltage instrument transformers. It describes the progression of transformer design from initial analytical methods to contemporary numerical techniques, which currently utilize field calculations to enhance accuracy during the design phases. The research highlights the essential function of instrument transformers in precise current and voltage measurement, vital for both metering and safeguarding in power systems. Employing field computations derived from Maxwell's equations enables a more precise assessment of transformer efficiency. This method greatly decreases the demand for expensive prototypes by allowing designers to model and assess transformer characteristics in virtual settings. These approaches substitute conventional analytical methods with more accurate simulations, particularly suited for managing intricate field interactions within transformers. The creation of novel magnetic substances, like permalloy and nanocrystalline films, has enhanced transformer precision while enabling a decrease in dimensions. These materials possess increased magnetic permeability, improving the efficiency and accuracy of the transformer. Utilizing advanced materials allows transformers to meet higher accuracy levels, which is especially advantageous for applications that demand dependable measurement and protection. New designs like electronic and optoelectronic transformers present promising substitutes for traditional inductive transformers. Though these designs are not yet commonly used, they could improve accuracy in specific applications. For instance, electronic transformers use low signals generated by components such as Rogowski coils, whereas optoelectronic transformers depend on optical fibers and sophisticated concepts like the Faraday and Pockels effects to enhance measurement accuracy. Advanced methods for field-circuit analysis, especially in three-dimensional modeling, facilitate more comprehensive simulations of transformer performance under different operating and fault scenarios. This involves evaluating how transformers react to transient conditions, distorted supply voltages, and open-secondary situations. Using comprehensive 3D field-circuit analysis, designers are able to foresee and improve transformer performance, increasing safety and efficiency even in demanding environments.

In [16], researchers have developed modeling approaches for Optical Current Transformers which helps to have crucial changes in power grid measurement. Optical Current Transformers are able to produce digital output without external equipment that makes it efficient while new grid technologies require digital and analog capabilities. Three distinct modeling approaches discussed and analyzed in this paper are analog, digital and complete. Firstly, analog model uses transfer functions and circuits and achieves 0.41 % maximum error and 1.11 % amplitude in phase for low energy analog model. Knowing all these information, researchers develop digital model based on analog model by transforming it bilinearly. Digital models obtain maximum error of 0.5% and amplitude of 1.5% for phase. The last achievement was a complete model which integrates both optical and electrical components. This model achieves significant accuracy with minimal deviation where the maximum difference is 0.88% and amplitude is 2.41% for phase. This model accomplishes the result by using Jones calculus for optical elements. The importance of this research is beyond model implementation. It proves that various OCT brands can utilize this approach in their product simulations, because they have accuracy better than 1.5% which makes them powerful tools for product simulations. While ensuring safety, reliability, the OCT model provides engineers with relay testing and performance evaluation tools.

In [18], paper suggests that FOCT accuracy is affected by 5 critical state. Junction temperature affects wavelength of broadband control circuits which led to inaccuracies in measurement in super luminescent diode (SLD). Thermistors are used to modify and keep this parameter stable. SLD transmits power which directly influences transformation ratio and phase error. To monitor this parameter's changes photodetector measurements are used. The transmitting optical power of SLD, influenced by drive current and junction temperature, directly affects transformation ratio and phase error. Monitoring can be accomplished either through direct photodetector measurements or indirect current-based calculations. To maintain transformation ratio accuracy which is really crucial is more complex and close loop feedback system is used to analyze and taking action. In this study, environmental factors also considered and observed that relationship between fiber sensing coil and FOCT errors is linear. FOCT error is approximately 0.5% without any compensation circuits across temperatures from -40°C to +70°C. Study showed that regular monitoring is essential, because aging of components leads to reduction in the received optical power of photodetector. These findings play crucial role in design and optimization of new products.

In [19], this paper introduces a new phase modulation technique that use transverse electro-optic effect for FOCTs. To improve sensitivity and stability of transformers, this method is effectively used by integrating Faraday rotators and non-reciprocity modulation. Generally, modulation and demodulation improves and signal noise proportion decreases by using sawtooth wave modulation. Additionally, this method avoids delays which causes accuracy deterioration. It is extremely sensitive, hence error is withing 0.2% across temperature range of –30°C to 50°C. Accuracy level is 0.2S which meets requirements for China standards GB/T 20840.8-2007. System is enough stable, it keeps good performance under different range of external temperature. Its application covers mainly high voltage power systems. Some empirical benefits include better insulation, resistance against electromagnetic interference and compatibility with new power systems. Experiment is launched for current measurement where equipment showed high linearity and accuracy level. Based on these findings, paper suggests that FOCTs have several benefits over traditional ones, such as small size availability, superior insulation and higher resistance against range of temperatures.

In [20], the paper suggests that instrument transformers play vital roles in power network protection. Protective relays are connected to CTs and they should operate in short time periods. However, when electromagnetic transient occurs on CTs, they might cause protective relays operate later than indented period of time. While some high-speed protective overcurrent relays might work before CT saturation happens, in most cases, CT saturation leads to main failures in the system. The article mainly discusses effects of conventional current transformers on numerical relay transients

$$i_s(t) = i_m(t) + i_b(t)$$

$i_s(t)$ here represents secondary current, $i_m(t)$ represents magnetizing current which can be called error current and $i_b(t)$ stands for burden current. CTs do not face saturation until they operate in linear region, because magnetizing current is very low in linear region. However, in non-linear region, magnetizing current becomes very large depending of burden current which is connected to the circuit as shown in Figure 3.4. Breakers are influenced by breaker failure operations done by relays. This is more essential if it is applied in EHV, because there is more risk to severe damage where more critical system elements exist. When breaker triggers, CT secondary current does not reach to zero immediately. For long period, trapped current energy in secondary side exists. Figure 2.1 shows current flow from secondary side after a breaker triggers.

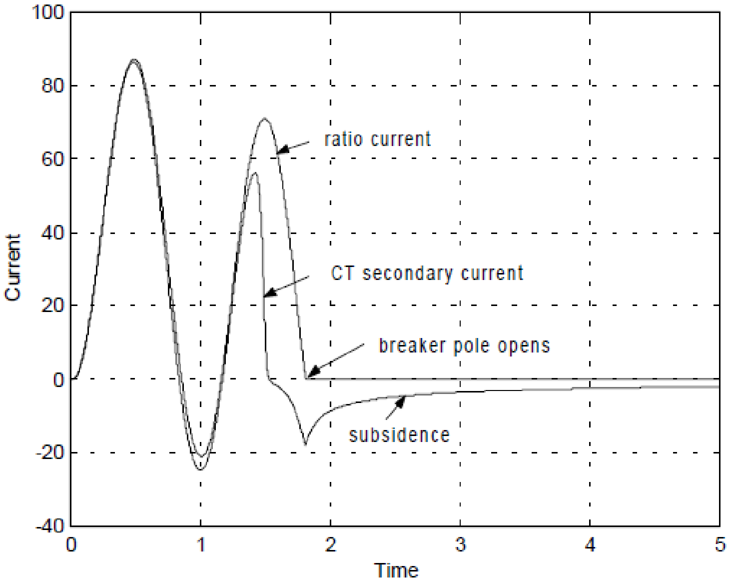


Figure 2.1 Current performance after breaker triggering [20]

The Alpha Plane is the name of the intricate plane that is displayed in figure 2.2. The computed ratio of I_R/I_L moving over time with I_R strongly saturated is represented by the cluster of dots joined by a solid line (I_R = remote relay current, I_L = local relay current). We computed the fundamental phasor ratio of currents to arrive at this number. Both currents come from cosine filters with 16 samples per cycle. Assuming very little line-charging current, the locus of the computed ratio of I_R/I_L would be at the -1 point on the Alpha Plane in the absence of CT saturation.

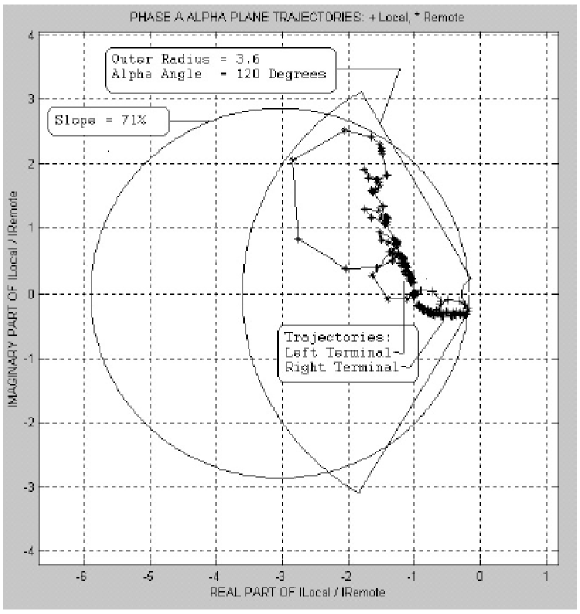


Figure 2.2 CT saturation in Alpha Plane [20]

In summary, this thesis discusses how general misbehaviour affect work of numerical relays and offers new way of designing relays to avoid saturation.

In [21], researchers suggest that how FOCT should be installed in smart substation. They mention that this has always been a main concern for scientists to ensure how reliable system is. This has been tested for high-voltage applications, but due to limitations on vibration and temperature, it had limited applications. However, nowadays, FOCTs are utilized in more and more digital substations. The FOCT application is described in China pilot power plant named Jinnan in this study. They conducted experiments to measure accuracy, ratio and polarity, however, long-term durability and reliability are still considered as unmarked quantities after this research.

In addition to the application of FOCTs, researchers also discuss the working principle of FOCTs. FOCTs work using a Faraday effect. Figure shows schematic design of FOCT in a detailed way. The light source send the light beam to coupler. Coupler obligation is to either separate or join two signals. Ater coupler, light goes through the polarizer and is separated into two axes (X and Y). Polarized light are transformed into 2 circular polarization (left and right) in retarder λ/4. After retarder, circular polarizations get into sensing fiber where Faraday phase shift is created. They are reflected at the end mirror. During the reflection beams are multiplied by two and hence Faraday effect doubles. After reflection, it goes back with another fiber cable and enters to retarder λ/4. In retarder, circulations convert back to polarized lights. Then it goes back to the photodetector and PIN photodetector sends a corresponding signal to signal processing unit. Formula for Faraday rotation angle is $\theta = 4VNI$. V is Verdet constant, N is number of fiber turns, and I is the current.

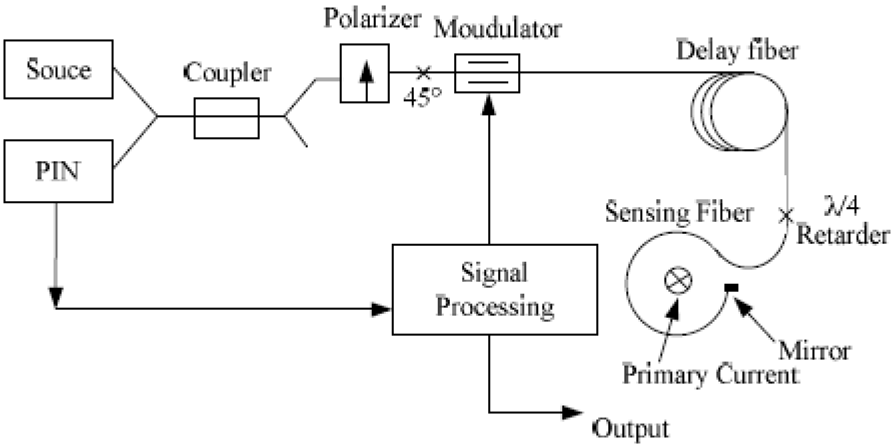


Figure 2.3 Working principle of FOCT [21]

Before utilizing FOCTs in the live plant, field accuracy test is conducted to determine accuracy of FOCT while using CCT as a reference point. It observed that noise causes some errors during measurement. Noise effect on protective relays should be determined. Polarity also checked before installment and many errors mitigated during examination. Noise is fluctuating; however, it does not depend on amount of current on the line. Noise has the effect in three components; Energy metering, protective relays, and error calculations. The paper discusses further details related to these components and also mention integration challenges and limitations. It has been concluded that FOCT has long-time durability if ratio error does not vary by time. In general, it still lacks some empirical knowledge to achieve in the future.

In [22], researchers investigated the topic of wide range current transformers. They claimed that CTs must be environmentally friendly, at first. For all CCTs, gas insulation applies to keep accurate measurements in the system. Nowadays, in a gas-insulated equipment sulfur hexafluoride (SF_6) gas is widely used. However, this gas is not environmentally safe and it causes some future problems. This paper suggests that instead of SF_6, fluoronitrile (C_4F_7N) gas should be used. C_4F_7N is high dielectric and it has lower global warming potential (GWP) than SF_6 has. Researchers did not finish whole study by just replacing gas in gas-insulated equipment, they also offered the way how to handle wide range current variations. They analyze measurement errors during creation of magnetic inductance. The author talks about two types of error compensation, but focuses mainly on active compensation. Figure below shows magnetic potential compensation scheme.

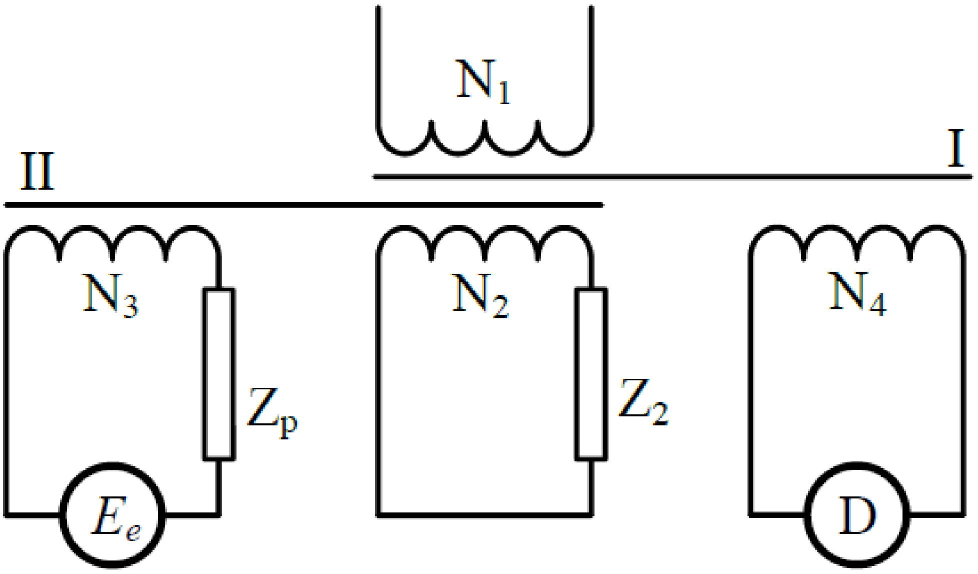


Figure 2.4 Magnetic compensation scheme [22]

In this diagram, N_1 is primary core, N_2 is secondary core. N_3 is compensating winding, while N_4 is winding for the detection. Z_p is leakage impedance and D is a measuring instrument. This scheme is magnetic compensation method which is widely used in today's active current compensation applications.

The author has developed three phase transformer model for analyzing compensation methods, as well as to observe how environmentally and wide range transformer behave during the simulation. Simulation established on two software; Comsol and Simulink. Measurement errors were tested under different conditions, such as varied loads and frequency. Additionally, error compensation method applied to the simulation model and it resulted in reduction of error from 88.8 % to 75 %. In conclusion, researchers supported the idea that new designed transformer model can achieve accuracy standards and it can be used in practical applications.

In [23], this paper discuss about limitations, drawbacks traditional current transformers have such as safety, size, environmental impacts, measurement accuracy. By mentioning this, they offer FOCTs as an alternative way of measuring and protecting network current. FOCTs use Faraday effect to measure current in the system. Additionally, the author mentions that FOCTs have also some limitations such as sensitivity to vibration and temperature and being not applicable to small current applications. Yang X Y has designed double way current transformer in China. Data processing happens according to Marius law. It explains a general overview of working process of FOCTs. They cover the development of two types of current transformers: interference and polarization. As an improvement to FOCTs, researchers talk about new fiber materials, designing special sensor head, and improving temperature, vibration stability. Sensing elements of FOCTs are made of fiber optic material. Hence it exposes itself to linear birefringence. To avoid excessive linear birefringence, new types of fiber optical materials are investigated to upgrade Verdet constant. Data processing is also an ongoing improvement process. However, this increases the initial cost for the new system. Temperature sensitivity affect the system in several ways; it leads to birefringence, it affect wavelength of light source, lastly, delay in phase is affected because of temperature variation. In addition to temperature sensitivity, improvement in vibration sensitivity is also a deal researchers coped with. Vibration causes mechanical stress on fiber material and birefringence effect happens. To escape this issue, they discuss about preparation of new material that is not affected by vibration. Additionally, they built feedback model to receive feedback for further development.

Lastly, advanced data processing models established and utilized for detection and adjustment processes.

2.3 Integration Challenges and Future Research

In [23], researchers state that applications of small current measurement should be included in further researchs. FOCTs are widely used in high voltage applications where there is as well as high current, but it is difficult to use them in small current applications where current is below 1A. Moreover, this technology is not used in the distributed and multi measurement field. For this purpose, signals are received from different sensors, and intelligent units take decision.

In [28], Azerbaijan goes toward modernization and reconstruction in power grids. Azerbaijan aims to reach 5 GW of renewable energy goal until 2030. That will include offshore wind and solar projects, as well as onshore wind projects. The study claims that Azerbaijan has huge potential for renewable energy nearly 200 GW which can be achieved in the future. There are two already ready huge projects, one located at Khizi-Absheron wind plant that has a capacity of 240 MW and one located at Garadagh built by Masdar has a capacity of 230 MW. Garadagh power plant is solar power plant. Authors mention benefits of smart power grids which assists to build a relationship between producer and consumers. However, Azerbaijan’s power grids lack these advantages, because they use outdated technology, hence cannot handle full control over power grids. During grid modernization process, SCADA system are considered to built within power plant and also general infrastructure will be replaced with new technologies. Additionally, Azerbaijan plans to interchange renewable energy capacity with Georgia and Russia in near future which will help to achieve sustainable future. Moreover, researchers. Owning equipment from the Soviet era is main remaining integration challenge for FOCTs. However, by 2028, liberalization of market will occur, and this will allow foreign and private producers to enter the market. Azerbaijan was a host of COP29 and this was one of sign that Azerbaijan took commitment in this sector.

CHAPTER THREE
MATERIAL AND METHOD

3.1 Overview of transformers

Transformers play a crucial role in power systems, facilitating effective transport and spread of electricity. They work by using electromagnetic induction to transfer electrical power between circuits, ensuring that voltage levels are altered to fulfill the system's needs. This procedure reduces energy waste and maximizes grid efficiency. Transformers are mostly two categories when it comes to measuring and safeguarding electricity networks: optical current transformers (OCTs) and traditional current transformers (CCTs). Each of these technologies has unique operational characteristics, design philosophy, and application value. As discussed in Section 3.1.1, conventional current transformers convert high currents into smaller, quantifiable currents by means of magnetic core and coils. Particularly at higher current levels, they have problems including core saturation, limited frequency response, and enormous physical dimensions notwithstanding their general use and dependability in many different sectors.

By means of the Faraday Effect in optical fibers or specific materials for current measurement, optical current transformers—discussed in Section 3.1.2—use in contrast Modern power networks needing accuracy and digital system integration would find OCTs perfect as they are lightweight, nonintrusive, free from magnetic saturation limits.

This section provides a framework for evaluating conventional and modern transformer technologies, therefore enabling in-depth analysis of their advantages, disadvantages, and performance in subsequent talks.

3.1.1 Conventional current transformers

Current transformers are primarily used for metering and protection applications and come in various sizes, shapes, and ratings. CTs have different use principles based on their manufacturing purpose. In this study, 110 kV transformers are tested for both conventional and unconventional types. Typical 110 kV conventional current transformers are shown in Figure 3.1.

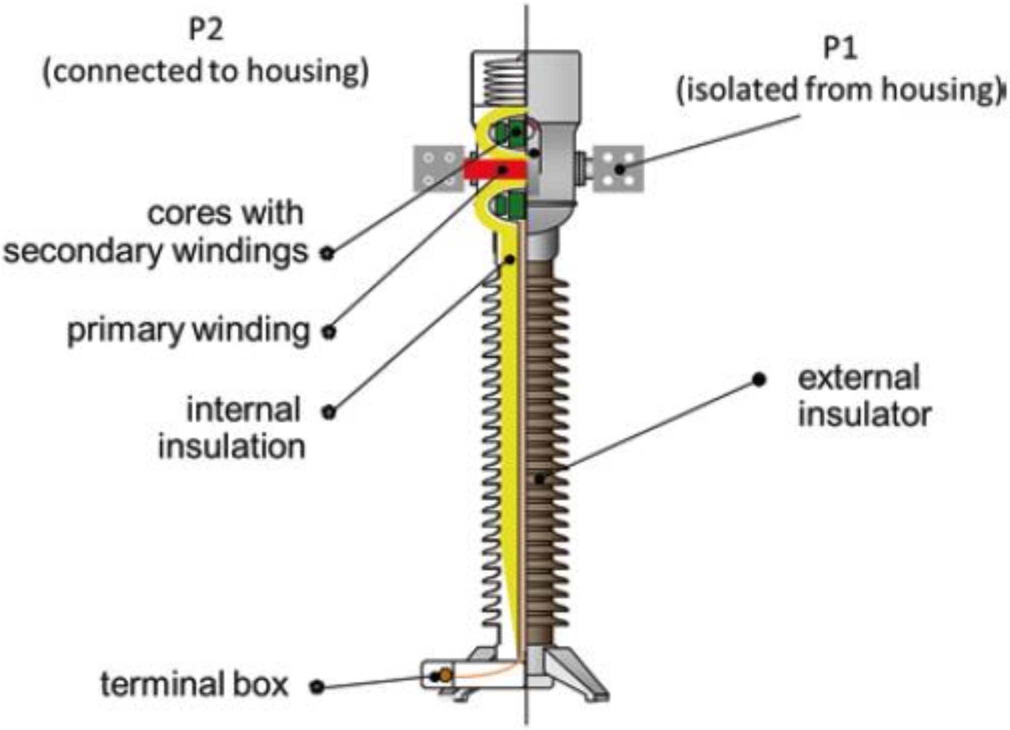


Figure 3.1 Conventional Current Transformer [24]

Main idea of operation of current transformers is to step down current which flows in primary winding and make it safer and measurable for the network. CCTs have 3 essential parts: primary winding, secondary winding and main core. Primary winding is connected to high current side and it assists to measure primary current. Current passes through it generates magnetic field in ferromagnetic core which is proportional to number of turns of primary winding. Secondary winding carries current which is stepped down in a scale of ratio of number of primary and secondary windings. It connects to secondary circuit which is main output for instruments and relays that work with low current. Magnetic core is ferromagnet with high magnetic permeability. Its role is to maintain efficient transformation with minimal energy loss. Additionally, primary winding is made of aliminium. Secondary winding is placed at housing frame. There is an internal insulation applied inside CCTs and as an insulation material SF6 gas is used mostly. However, it can be replaced with C_4F_7N gas to make them more environmentally friendly [22]. Terminals (P1 and P2) are connected to primary current. P1 is isolated from head housing, but P2 is directly connected to it. They have external insulator layer as well to protect them from dangerous electromagnetic fields.CCTs work with a principle of Faraday's law, electromagnetic effect. When current passes through primary side, electromagnetic induction is generated on magnetic core and it produces proportional current to the secondary side. Main applications are for metering and protection purposes in the industry. It works with relays and circuit breakers to detect faults in the network. Several ways of protection exist, such as overcurrent, differential, distance, earth fault protection. Overcurrent protection works under excessive current conditions. This happens during either short-circuit or overloading of power system. Differential protection compares current in multiple pre-selected points and based on final data on it detects and verifies whether fault exists or not. CCTs send produced current to impedance relays and these relays ensure efficient and smooth information transfer to identify defects from the distance (substation). Lastly, earth fault protection checks for residual current within the system and this helps to find and prevent ground faults, leakage. Additionally, CCTs are used for measuring and monitoring. It assists in preventing future problems by monitoring load sharing by equipment. Moreover, in high-voltage industries where direct measurement is not appropriate, CTs are employed. Furthermore, it is useful for harmonic analysis of the system to aid power quality. Load shedding is controlled by CCTs as well. It disconnects loads that is no longer necessary and connects new loads to the system. It has several advantages, like cost-effectiveness, and reliability. It is cost-effective, because they have low maintenance costs and there are enough professional workers to provide services. Moreover, it has been used for a long time, it has been proved technologically, so it does not carry any risk. They are easily integrated into traditional electrical systems; hence it does not require expensive redesigning for the installation process. CCTs do not consume active power from the network due to their passive components. When selecting an appropriate current transformer, several aspects are taken into account. Firstly, current transformers have error tolerance which is shown in the label, for example, class 0.5. Secondly, they cannot handle exceeded magnetic flux due to having magnetic core. Hence, knee point voltage is considered to know when saturation will begin in this transformer. [22]

3.1.2 Non-conventional current transformers

In this study, as a non-conventional current transformer, the fiber optical current transformer (FOCT) is used. The optical current transformer, which is based on a completely passive optical transducer, is an extremely accurate optical current transformer for high voltage applications. In the upcoming generation of high voltage digital substations, the optical current transformer offers a digital measurement solution for protection and metering applications.
FOCTs consist of 6 key components.

1. Optical Fiber
2. Sensing element
3. Light source
4. Photodetector
5. Signal processing unit
6. Interrogator unit

Optical fiber is mostly made of plastic and its role is to transmit polarized light signal to sensing element. Sensing element is made of elements containing crystal due to increase Faraday effect. It is an essential component, because it measures current by utilizing Faraday effect. Light source is LED that is widely used in computer screens nowadays. It constantly beams and this makes interaction with the magnetic field. Photodetector is getting light after sensing element and its function in the system is basic. It provides its basic functionality and converts optical signals into electrical signals. Mainly, photodiode is used as a photodetector because of its high sensitivity. Signal Processing Unit (SPU) behaves like Central Processing Unit (CPU) and participates in processing, and calculation process. Hence, it is called “brain” of the FOCTs. It receives electrical signals from photodetector and produces corresponding output based on input. Interrogator unit attend in two separate processes. Firstly, it is a power unit for whole FOCT. Secondly, it builds communication between FOCT and external system and ensures smooth and reliable communication. [28]

The Faraday Effect is the foundation for how the optical sensor works. When a linearly polarized optical signal passes through a magnetic field, its polarization state rotates. The angle of rotation of an optical signal moving over a closed path is proportional to the current that the path encloses. Interferometrically, the rotation of the light's polarization state is determined by measuring the phase difference between circularly polarized optical signals that circle a fiber coil enclosing the primary in opposite directions as shown in Figure 3.2.

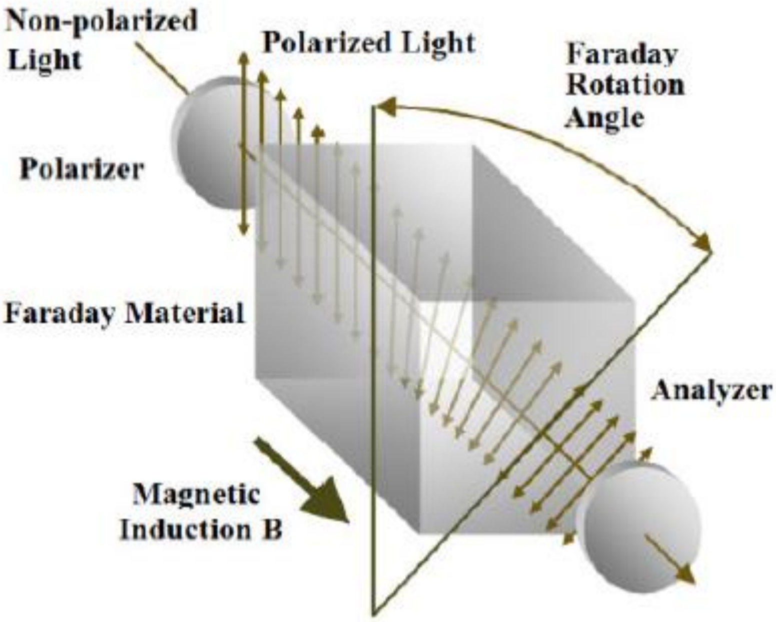


Figure 3.2 Working principle of FOCT [17]

Rotation angle (φ) is directly proportional to magnetic induction intensity. Then, analyzer analyzes this Faraday rotation angle and calculates magnetic field intensity and current based on that. Relationship between the Faraday rotation angle and current is given by this formula:

$$\varphi = V\int_{l} H \cdot dl = VN_{L}I$$

where I is the conductor's electric current, N_L is the number of optical fibre loops, H is the magnetic induction strength, V is the optical medium's Verdet constant, and l is the light's propagation distance within the medium. FOCT has been designed to fit in small area thanks to Spun Highly-birefringent fibre optic cable. Hence, it is excellent solution for measurement and protection. Applied current to FOCTs can be 8-10 times more than rated current. Therefore, it has some huge advantages over traditional transformers. There is no saturation concerns for FOCT, because there is no iron core installed into it. To observe how good transient characteristics FOCT has, in Xi'an High Voltage Apparatus Research Institute, test results has been generated based on empirical data and it is shown in table 3.1.

Table 3.1 Transient table for FOCT [17]

	Operation	Symmetrical short-circuit current /kA	Peak current /kA	Maximum instantaneous error current /kA	Transient error /%
1	C-0.1s-O	46.8	131.6	1	1.5
2	0.5s				
3	C-0.1s-O	45.7	128.5	1.3	2

“C-01s-O” here is first power on state for FOCT. It represents “close-01s-open”. “0.5s” represents shutdown process. The system is going to shut down process for 0.5 seconds and then restarts itself. In first power on state, symmetrical short-circuit current is 46.8 kA and peak current is 131.6 kA. For all of three states, decaying time constant is 100ms. System is turned off for 0.5s and after that second power on state starts. From the table, it is easily seen that transient error for both operations is too low, 1.5% and 2% correspondingly. Figure 3.3 shows a general view of FOCTs. [17]

Figure 3.3 View of FOCT in the field [25]

Unlike CCTs, FOCTs are suitable for extra-high voltage (EHV) and ultra-high voltage (UHV), because of its compact size. Compact size also makes it appropriate for gas insulated switchgear applications. Fiber optical current transformers offer several benefits, such as linear performance, improved dynamic response, integration and insulation, and ease of use in digital systems. These devices are more linear, as consequence, they have very high accuracy and very wide range with minimal saturation. Certainly, these devices are more expensive than traditional devices, however, to achieve as low saturation as optical current transformer has costs more money if traditional current transformer used. Another achievement is obtaining by using optical type current transformer, is improved dynamic response. During transient period, this type of current transformer is not affected by capacitance and inductance, unlike conventional current transformers. Additionally, they are easily integrated into measurement and communication systems. This happens using help of fiber optics and eventually, this results in enhanced insulation and reduced weight. Moreover, NCIT’s provide digital output directly to without demand for additional equipment installed at the network for this purpose. In this study, it is also revealed that optical current transformers do not tend to have saturation while increasing loads of the network due to having no magnetic core available in these transformers. They also achieved high performance in frequency response in absence of magnetic core. Hence, frequency response is also dependent on magnetic saturation transformer has. Short-circuit power test is also maintained in this study. Optical current transformers achieve high performance on this test for higher short-circuit powers. This occurs because they do not have magnetic core. Unlike optical current transformers, when magnetic flux exceeds limits, magnetic saturation occurs in traditional current transformers. However, they also have limitations. Initial cost is too high for materials, and maintenance. FOCT technology is still developing and hence there is no standardized technology compared to CCTs.

3.2 Key elements of the simulation

In this simulation, several elements beside transformers are used. Generators, busbars, circuit breakers, line differential relay, power grid, lines and connectors are used in this simulation as shown in Figure. Generator utilization is for providing back-up electricity over the circuit during outages to provide uninterrupted power flow. Additionally, in the study, it is employed to increase short-circuit power. Busbars and circuit breakers are elements that are mainly used in circuits for maintaining connections and providing protection for the system. Busbars play the role of hubs helping to minimize connections and complexity. Circuit breakers are designed to protect against short-circuit and overload. During these events, circuit breakers separates a part from the grid. Power grid is an element that covers main demand for electrical supplements. It assists maintaining realistic load to have superior simulation. Line differential relay is used to provide additional protection for the network. It works by comparing two current these are ingoing and outgoing. Moreover, if fault condition occurs, it alerts on monitoring system (SCADA) to observe modifications on the system. Lines and connectors are main components to build connections between other elements. An electrical power network model that is dynamic and realistic is produced by integrating these components into the simulation. In order to replicate operating situations ranging from typical load circumstances to fault incidents, each component is made to work in tandem with the others. The simulation also mirrors contemporary grid management techniques, where real-time monitoring and control are essential for operational dependability and efficiency, by integrating a SCADA monitoring system. A thorough examination of system behavior is made possible by this all-encompassing methodology, which also offers insights into performance under a variety of circumstances, such as malfunctions, overloads, and equipment failures. Generators, relays, and breakers are included to guarantee that the simulation not only depicts a functional power system but also emphasizes the preventative and remedial actions necessary to preserve stability.

3.3 Mathematical modeling

This section covers mathematical models for both CCTs and FOCTs. These equations assist to calculate secondary current, excitation voltage and magnetic flux for both delta and wye connections. These provide accurate results to analyze and compare results from the simulation. The EMT simulation model uses instantaneous values instead of complex phasors used in load current, short circuit calculations and Root Mean Square (RMS) simulation. Saturation is considered with nonlinear magnetizing conductance. The equivalent circuit is shown in Figure 3.4. Saturated and unsaturated magnetic inductance, as well as, burden resistance, and burden inductance are calculated as written below for conventional current transformers [26].

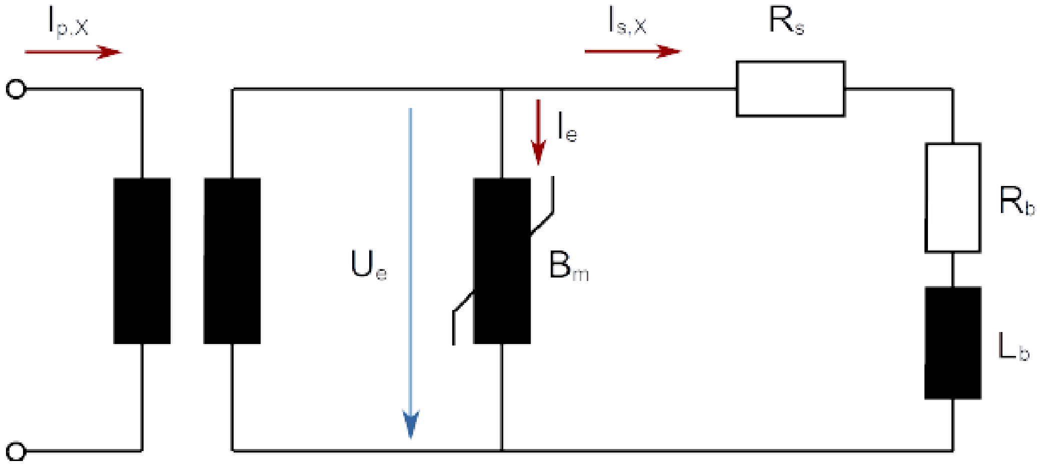


Figure 3.4 EMT simulation model for CT [26]

$$B_m = \frac{i_e}{Z_r} \tag{3.1}$$

$$B_{m,sat} = \frac{y_{sat}}{Z_r} \tag{3.2}$$

$$R_b = Z_b \times \cos\ \varphi_b \tag{3.3}$$

$$L_b = \frac{Z_b \times \sqrt{1 - \cos\ {\varphi_b}^2}}{2 \times \pi \times f_N} \tag{3.4}$$

Where:
i_e is the excitation to the rated current ratio in p.u.
Z_r is the rated burden
y_{sat} is the saturated admittance in p.u.
Z_b is the magnitude of the actual burden
$cos\varphi_b$ is the power factor of the actual burden
f_N is the nominal frequency of the network in Hz

In next section, for both delta and wye connected transformers, secondary current, excitation voltages and magnetic flux are calculated. Magnetic flux is calculated so that the transformer core's behavior for changing conditions could be ascertained. This would give an idea about the magnetic performance of the core at saturation and transient conditions. The derived equations allow for the exact representation of the flux linkage within the transformer core.

Estimation of excitation voltage is rather necessary in order to analyze the magnetizing requirements of the transformer. Such calculations underpin the relationship between the applied voltage and the resulting magnetic field strength, taking into account the nonlinear characteristics of core magnetization in saturation. Since in wye-connected CCTs the phase-to-neutral connections should be considered for derivation of mathematical relations of primary and secondary quantities, therefore, the secondary current, excitation voltage, and magnetic flux for wye configuration can be expressed with. Calculation of secondary current for wye connected transformers are as follows.

$$I_{s,A} = \frac{1}{ratio} \times I_{p,A} - I_{e,A} \tag{3.5}$$

$$I_{s,B} = \frac{1}{ratio} \times I_{p,A} - I_{e,B} \tag{3.6}$$

$$I_{s,C} = \frac{1}{ratio} \times I_{p,C} - I_{e,C} \tag{3.7}$$

$$3I_{s,0} = I_{s,A} + I_{s,B} + I_{s,C} \tag{3.8}$$

Excitation voltages:

$$U_{e,A} = I_{s,A} \times (R_s + R_b) + \frac{d}{dt} I_{s,A} \times L_b \tag{3.9}$$

$$U_{e,B} = I_{s,B} \times (R_s + R_b) + \frac{d}{dt} I_{s,B} \times L_b \tag{3.10}$$

$$U_{e,C} = I_{s,C} \times (R_s + R_b) + \frac{d}{dt} I_{s,C} \times L_b \tag{3.11}$$

Magnetic flux:

$$\frac{d}{dt}\psi_A = U_{e,A} \tag{3.12}$$

$$\frac{d}{dt}\psi_B = U_{e,B} \tag{3.13}$$

$$\frac{d}{dt}\psi_C = U_{e,C} \tag{3.14}$$

For the delta-connected CCTs, the mathematical model considers phase-to-phase relations as well as circulating currents. For a delta configuration, the secondary current, excitation voltage, and magnetic flux can be described by the following equations:
Delta-connected current transformers:
Secondary currents:

$$I_{D0} = \frac{1}{3 \times ratio} \times (I_{p,A} + I_{p,B} + I_{p,C}) - (I_{e,A} + I_{e,B} + I_{e,C}) \tag{3.15}$$

$$I_{s,A} = \frac{1}{ratio} \times I_{p,A} - I_{e,A} - I_{D0} + I_{s,B} \tag{3.16}$$

$$I_{s,B} = \frac{1}{ratio} \times I_{p,B} - I_{e,B} - I_{D0} + I_{s,C} \tag{3.17}$$

$$I_{s,C} = -(I_{s,A} + I_{s,B}) \tag{3.18}$$

$$3I_{s,0} = 0 \tag{3.19}$$

Excitation voltages:

$$U_{e,A} = (I_{s,A} - I_{s,B}) \times (R_s + 3R_b) + \frac{d}{dt}(I_{s,A} - I_{s,B}) \times 3 \times L_b \tag{3.20}$$

$$U_{e,B} = (I_{s,B} - I_{s,C}) \times (R_s + 3R_b) + \frac{d}{dt}(I_{s,B} - I_{s,C}) \times 3 \times L_b \tag{3.21}$$

$$U_{e,C} = (I_{s,C} - I_{s,A}) \times (R_s + 3R_b) + \frac{d}{dt}(I_{s,C} - I_{s,A}) \times 3 \times L_b \tag{3.22}$$

Magnetic flux:

$$\frac{d}{dt}\psi_A = U_{e,A} \tag{3.23}$$

$$\frac{d}{dt}\psi_B = U_{e,B} \tag{3.24}$$

$$\frac{d}{dt}\psi_C = U_{e,C} \tag{3.25}$$

$I_{p,X}$ is the primary current, phase X in A
$I_{s,X}$ is the secondary current, phase X in A
$3I_{s,0}$ is the secondary zero sequence current in A
$U_{e,X}$ is the excitation voltage, phase X in V
$I_{e,X}$ is the excitation current, phase X in A
Ψ_X is the magnetic flux, phase X in Vs
R_s is the secondary winding resistance in Ω
R_b is the burden resistance in Ω
L_b is the burden inductance in H
ratio is the transmission ratio ratio $= \frac{I_{tap,p}}{I_{tap,s}}$
$I_{tap,p}$ is the selected primary current in A
$I_{tap,s}$ is the selected secondary current in A
Table 3.2 is designed for signals and states in EMT simulation.

Table 3.2 Signal description for CCT [26]

Signal	Description	Unit	Type
LA	Primary Current A	p.u.	IN
I_B	Primary Current B	p.u.	IN
I_C	Primary Current C	p.u.	IN
I2r_A	Secondary Current A	A	OUT
I2r_B	Secondary Current B	A	OUT
I2r_C	Secondary Current C	A	OUT
I0x3r	3*10	A	OUT
I2r_A:dt	Secondary Current, derivative A	A/s	OUT
I2r_B:dt	Secondary Current, derivative B	A/s	OUT
I2r_C:dt	Secondary Current, derivative C	A/s	OUT
I0x3r:dt	3*10, derivative	A/s	OUT
psim_A	Mag. Flux	Vs	STATE
psim_B	Mag. Flux	Vs	STATE
psim_C	Mag. Flux	Vs	STATE
psim_A:dt	Mag. Flux, derivative	Vs/s	d/dt
psim_B:dt	Mag. Flux, derivative	Vs/s	d/dt
psim_C:dt	Mag. Flux, derivative	Vs/s	d/dt

In the next part, the mathematical model of Fiber Optic Current Transformers is presented. The equations are derived in terms of the determination of the secondary current, considering the special characteristics of FOCTs. These models are developed to highlight the improved accuracy and reduced magnetization dependence of the FOCTs for direct comparison with the results obtained from Conventional Current Transformers.

Wye-connected current transformer:

$$I_{s,A} = \frac{1}{ratio} \times I_{p,A} \tag{3.26}$$

$$I_{s,B} = \frac{1}{ratio} \times I_{p,A} \tag{3.27}$$

$$I_{s,C} = \frac{1}{ratio} \times I_{p,C} \tag{3.28}$$

$$3I_{s,0} = I_{s,A} + I_{s,B} + I_{s,C} \tag{3.29}$$

Delta-connected current transformer:

$$I_{s,A} = \frac{1}{ratio} \times (I_{p,A} - I_{p,B}) \tag{3.30}$$

$$I_{s,B} = \frac{1}{ratio} \times I_{p,B} - I_{p,C} \tag{3.31}$$

$$I_{s,C} = \frac{1}{ratio} \times I_{p,C} - I_{p,A} \tag{3.32}$$

$$3I_{s,0} = 0 \tag{3.33}$$

Where:

$I_{p,X}$ is the primary current, phase X in A

$I_{s,X}$ is the secondary current, phase X in A
$3I_{s,0}$ is the secondary zero sequence current in A
ratio is the transmission ratio ratio $= \frac{I_{tap,p}}{I_{tap,s}}$
$I_{tap,p}$ is the selected primary current in A
$I_{tap,s}$ is the selected secondary current in A
Signal information table is shown below in table 3.3 for optical current transformer system.

Table 3.3 Signal description for FOCT [26]

Signal	Description	Unit	Type
LA	Primary Current A	p.u.	IN
LB	Primary Current B	p.u.	IN
LC	Primary Current C	p.u.	IN
I2r_A	Secondary Current A	A	OUT
I2r_B	Secondary Current B	A	OUT
I2r_C	Secondary Current C	A	OUT
10x3r	3*10 Secondary Current	A	OUT

These are major differences: operating principles and complexities of CCT and FOCT mathematical models. Indeed, CCT involves characteristics like a magnetic core, saturation effects, and burden impedance; hence, in CCT, complicated equations are involved that relate the magnetic flux and excitation voltage. In the case of FOCT, however, the mathematical model is quite simple and straightforward since the optical sensing principle involves only one relationship with the primary current of the optical output. The difference in mathematical representation implies a big difference of the physical realities: CCTs are indeed electromagnetic devices, which thus suffer from saturation and core losses, whereas magnetic effects do not affect FOCTs.

These relations of CCT bring out the interdependence of the relations of the secondary current, magnetic flux, and excitation voltage, which vary interdependently with changes in one respecting others, and more under transient conditions and faults. The presence of a burden impedance and core saturation characteristics complicates the modeling of the CCT; again, this is essential for faithful representation. In the FOCT model, the relation of primary current to output signal is more direct, without consideration of magnetic core effects or burden. This mathematical simplicity in the relationship would immediately suggest a possibility for greater accuracy of measurement, especially at the high-current fault conditions where the CCTs would likely saturate.

These theoretical differences and their practical implications will be discussed in detail in the following sections with the aid of simulation results, which provide a comparison of performances of both types of transformers under various operating conditions.

3.4 Digsilent PowerFactory

DIgSILENT PowerFactory is a popular software tool that is widely used by electrical power professionals for the simulation and analysis of power system networks. The product has been developed by DIgSILENT GmbH since the founding in 1976; the first release of PowerFactory was in 1997. With more than 10,000 licenses being utilized in more than 140 countries, it has established itself as a leading instrument in the sector [29]. DIgSILENT GmbH is the core company that owns this software (PowerFactory) used in this study. PowerFactory is one of the leading software in the industry and it is one of the main competitors of ETAP software. It offers several benefits, such as real-time performance monitoring, real-time simulation, data analysis etc. In this study, PowerFactory 2022 version is used to analyze the data, to work with charts.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

Accurate measurement of electric parameters is crucial in contemporary power systems. Traditional current transformers have widely been used as a standard device for current measurement in power systems for decades, and their performances are satisfactory in many applications. However, current transformers face several issues, such as saturation under high fault currents, limited frequency response, and relatively large size that may affect their efficiency in the modern grid system. Instead, NCITs emerged with novel optical or Rogowski and other sophisticated measurement methodologies to find a way out of this limitation. It purports to do performance studies of conventional and unconventional current transformers using simulation methods. The three salient features under study are saturation characteristics, frequency response, and short-circuit power. This work, therefore, attempts to bring out the advantages of unconventional current transformers over conventional ones for applications requiring higher accuracy, faster response time, and reduced size by studying the variation of these three parameters. The simulation results give a sufficient insight into operational properties of both types of transformers, with a view to a deeper understanding of various ways NCITs may reinforce or replace conventional CTs in Azerenerji power plants. The thesis represents a highly needed study for advancing the performance of measurement schemes in power networks.

4.1 Simulation setup

The current transformer shows similar responses if there is no short-circuit in the network. However, when a short-circuit occurs, two different transformers show different responses. For that reason, the short-circuit event is defined to observe changes during simulation. Simulation representation is illustrated in Figure 4.1

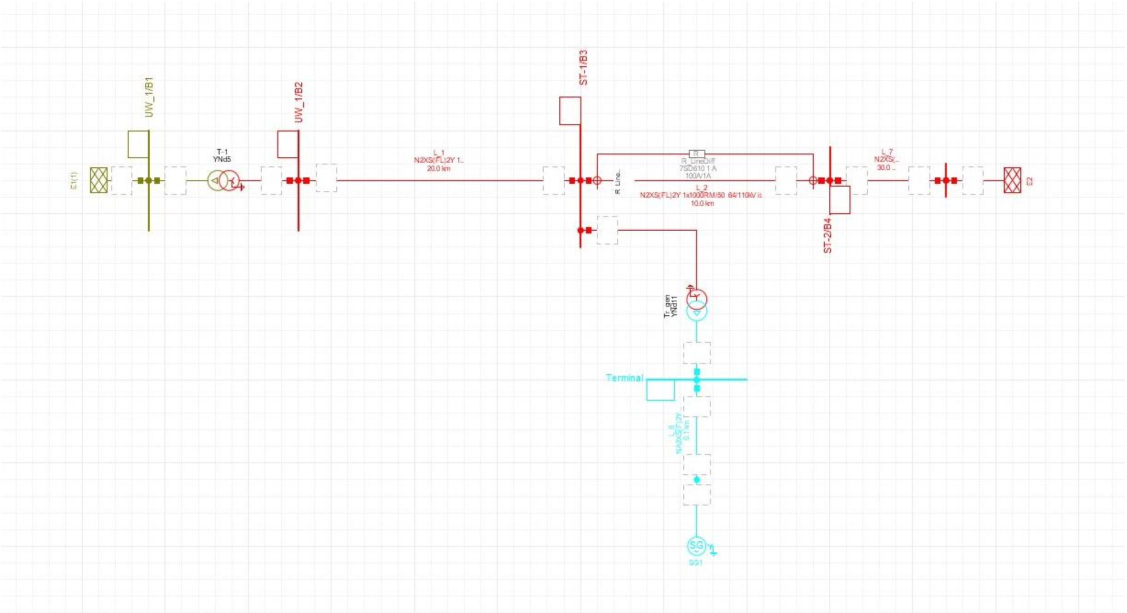
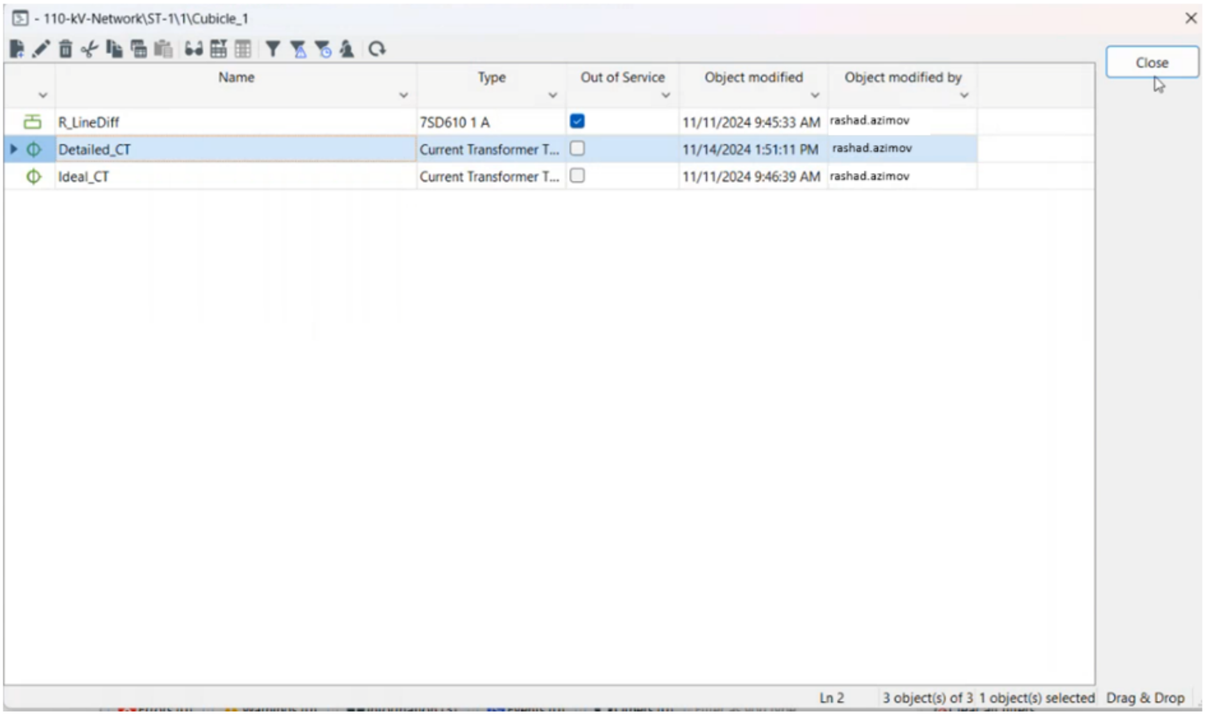


Figure 4.1 Simulation model for CTs

In the network, 2 main elements have been used for the simulation. Detailed_CT which stands for conventional transformers, and Ideal_CT which stands for optical type current transformers as shown in Figure 4.2. In this simulation, line differential relay is used for making network more complex and more realistic.



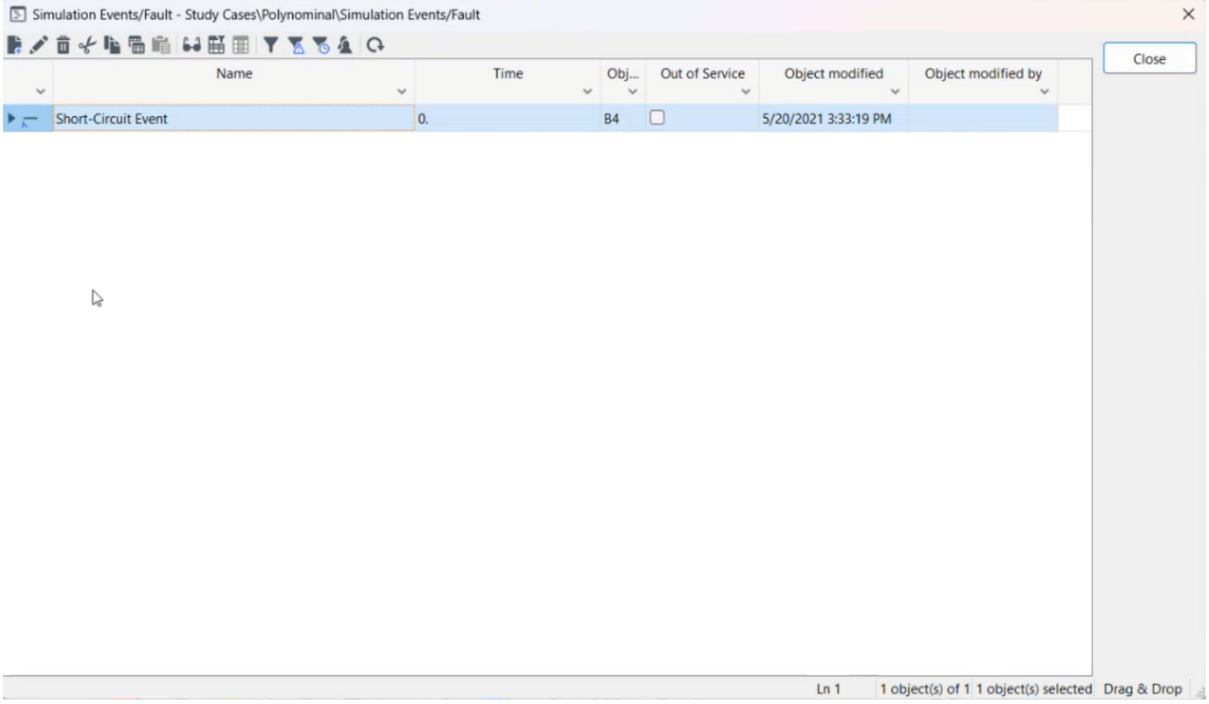
- 110-kV-Network\ST-1\1\Cubicle_1

Name	Type	Out of Service	Object modified	Object modified by
R_LineDiff	7SD610 1 A	☑	11/11/2024 9:45:33 AM	rashad.azimov
Detailed_CT	Current Transformer T...	☐	11/14/2024 1:51:11 PM	rashad.azimov
Ideal_CT	Current Transformer T...	☐	11/11/2024 9:46:39 AM	rashad.azimov

Ln 2 3 object(s) of 3 1 object(s) selected

Figure 4.2 Defining transformers

I have only one event available, which is short-circuit event as shown in Figure 4.3. I defined this event to observe misbehavior on the network.



Simulation Events/Fault - Study Cases\Polynominal\Simulation Events/Fault

Name	Time	Obj...	Out of Service	Object modified	Object modified by
Short-Circuit Event	0.	B4	☐	5/20/2021 3:33:19 PM	

Ln 1 1 object(s) of 1 1 object(s) selected

Figure 4.3 Defining short-circuit event

Created 2 transformers and defined the short-circuit event; now, the network is set to be examined under 3 conditions: saturation characteristics, frequency response, and response change by varying the short-circuit power.

Understanding operating dynamics, such as in magnetic components like transformers, current transformers, and inductors, is really based on characteristics of saturation. All these devices depend on the magnetic core's ability to convert electrical energy into magnetic energy and vice versa in a linear fashion. The linear conversion does have a limit due to inherent properties of the core material, especially the magnetic saturation limit. Beyond that point, the core cannot support the further increase of magnetic flux density, and nonlinearities begin to appear in system performance. The above described phenomenon is called saturation.

In power systems, saturation mostly occurs in current transformers, which are rendered critical in measurement and protection applications. The current transformers were designed to step down the high current level for the purpose of relaying and metering. The CT operates in normal conditions within the linear range, thus enabling accurate current transformation. If high fault currents or overloading, the core of the CT gets saturated, and secondary currents get distorted. The presence of distortion can result in malfunctioning protective relays hence unsafe and unreliable operation. Magnetic saturation general behavior is represented by a normal B-H curve where magnetic flux density, B, is plotted versus magnetic field strength, H. The graph is a straight line at the initial stages, which is because the magnetic domains are in state of perfect alignment in the same direction as that of the magnetic field. It eventually flattens out horizontally due to the material reaching its saturation limit, where shifting the strength of the magnetic field beyond this value no longer results in considerable variation of flux density. This is a saturation region where the core needs much more energy for a small increase in flux, thus creating very high magnetizing currents. Saturation characteristics depend upon lots of factors that include but are not limited to core material, geometry and operation conditions. High permeability materials such as silicon steel support higher saturation limits and therefore are suitable in power transformers and current transformers. Operating frequency and applied voltages have a direct impact on saturation-overvoltages, or system transient conditions may easily drive the core into saturation and affect the stability and performance of the system.

Saturation is not only an inaccuracy in measurement but can lead to serious heating of the core by eddy currents and hysteresis losses, which in turn will degrade the material of the core in due course of time and thus reduce the life span of the transformer or current transformer.

Additional harmonics generated by saturation may also spread into the network, interfere with sensitive equipment, and increase system losses.

Understanding and mitigating saturation is crucial in the design and operation of power systems. The manufacturers often use an air gap in core designs to minimize the effect of saturation or make use of a better quality core material that can handle saturation limits. In addition, protection engineers should provide saturation while setting the thresholds of relays to ensure correct detection of faults under severe conditions. Simulation and testing of saturation characteristics under various scenarios help engineers predict and overcome challenges for reliable and effective system operations.

The CT is after the busbar called ST-1/B3, as shown in Figure 4.4. It is connected to line differential relay for additional protection in the network. This line differential relay measures current flow from two connected points and then outputs the corresponding result based on the calculation model written in it. We placed a short-circuit event in the second busbar, now called ST-2/B4, in order to observe how our system will behave under such conditions.

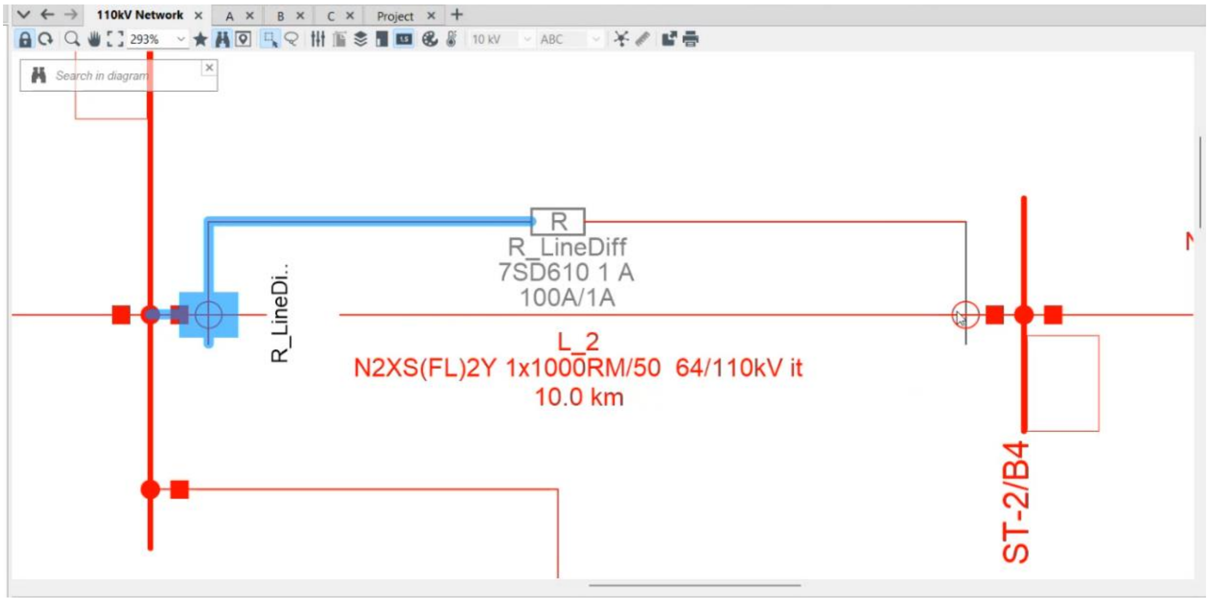
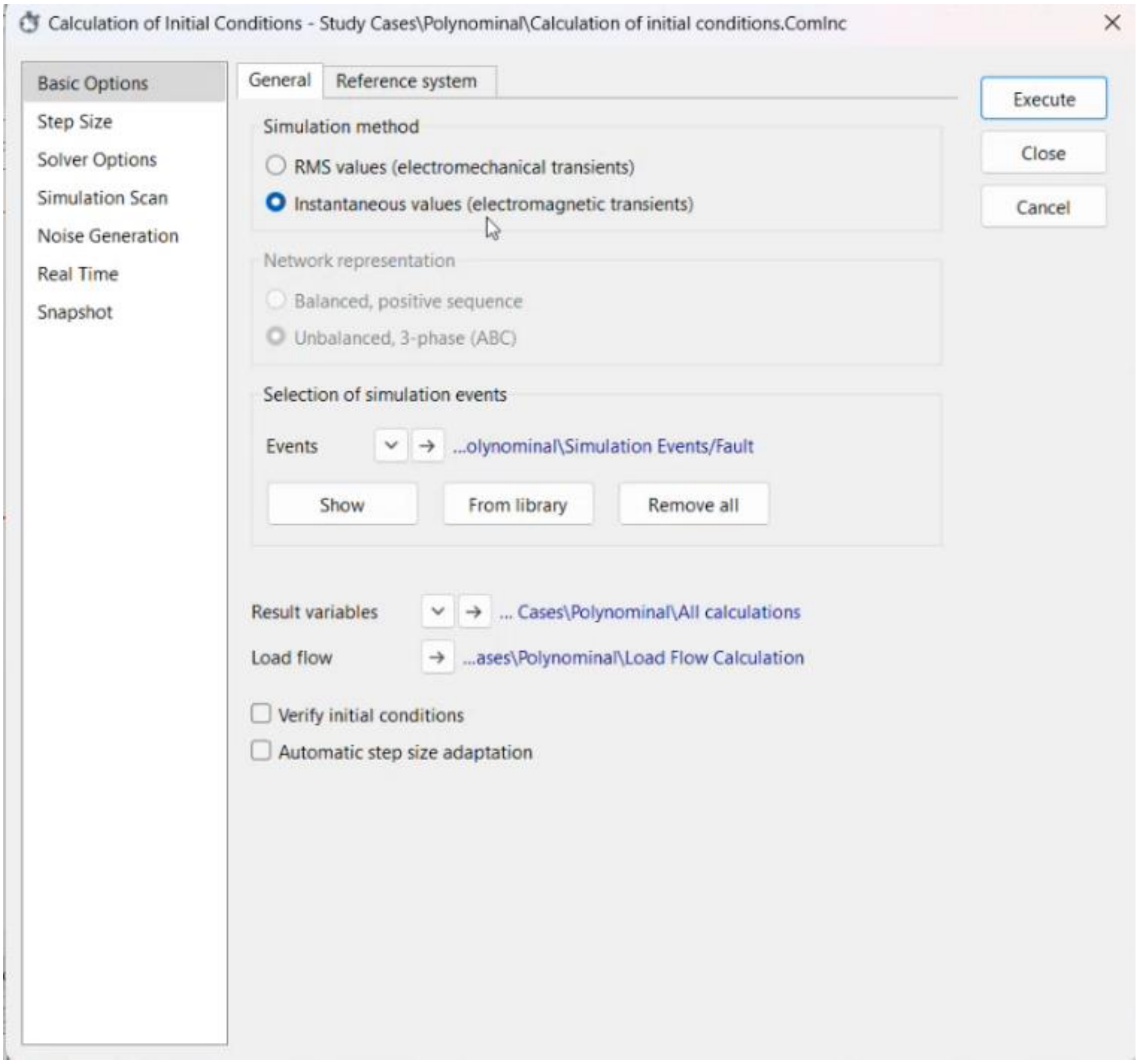


Figure 4.4 Close view of CT

Once the simulation model is configured and completed, then for pre-determined conditions short-circuit event is launched and simulation is started. From figure 4.5, we should opt instantaneous values (electromagnetic transients) over Root Mean Square (RMS) values (electromechanic values), because we are making transient analysis of the system. For that reason, the simulation is named Electromagnetic Transients (EMT) simulation. Let's delve into the topic and figure out their differences and why EMT simulation is used over RMS simulation in this study.

In today's world, global oil and gas companies such as BP, Schlumberger, SOCAR etc. tend to become energy companies. This process is a result of tendency toward renewable energy in the whole world. This tendency brings its own characteristics and EMT, RMS simulation are becoming more and more popular. Electromagnetic transients occur when sudden change happens in the network, such as faults, spikes, as well as short-circuit. These transient leads to insulation issues, damage to generators, transformers, and misbehaviour in general. To apply EMT simulations, first of all, we start short-circuit event in the system and EMT simulations solve differential equations by applying different techniques by analyzing instantaneous values of current and voltage in time domain. Capturing these values makes this simulation model appropriate for analyzing fast transient. On the other hand, RMS simulation uses similar techniques to analyze transient, however, it solves differential equations in the phasor domain. This study is superior approach if experiment continues for long periods. For this reason, system must be in steady state and quick transient must not happen during the test period.

EMT simulation is preferred for this study, because we need to analyze fast transient in time domain that makes deterioration easy to distinguish in the system. In Figure 4.5, "Calculation of initial conditions" pop-up window appear. From this window, we select instantaneous values (electromagnetic transients) and click on execute button.



Calculation of Initial Conditions - Study Cases\Polynominal\Calculation of initial conditions.ComInc

Simulation method

○ RMS values (electromechanical transients)

● Instantaneous values (electromagnetic transients)

Network representation

○ Balanced, positive sequence

● Unbalanced, 3-phase (ABC)

Selection of simulation events

Events ...olynominal\Simulation Events/Fault

Result variables ... Cases\Polynominal\All calculations

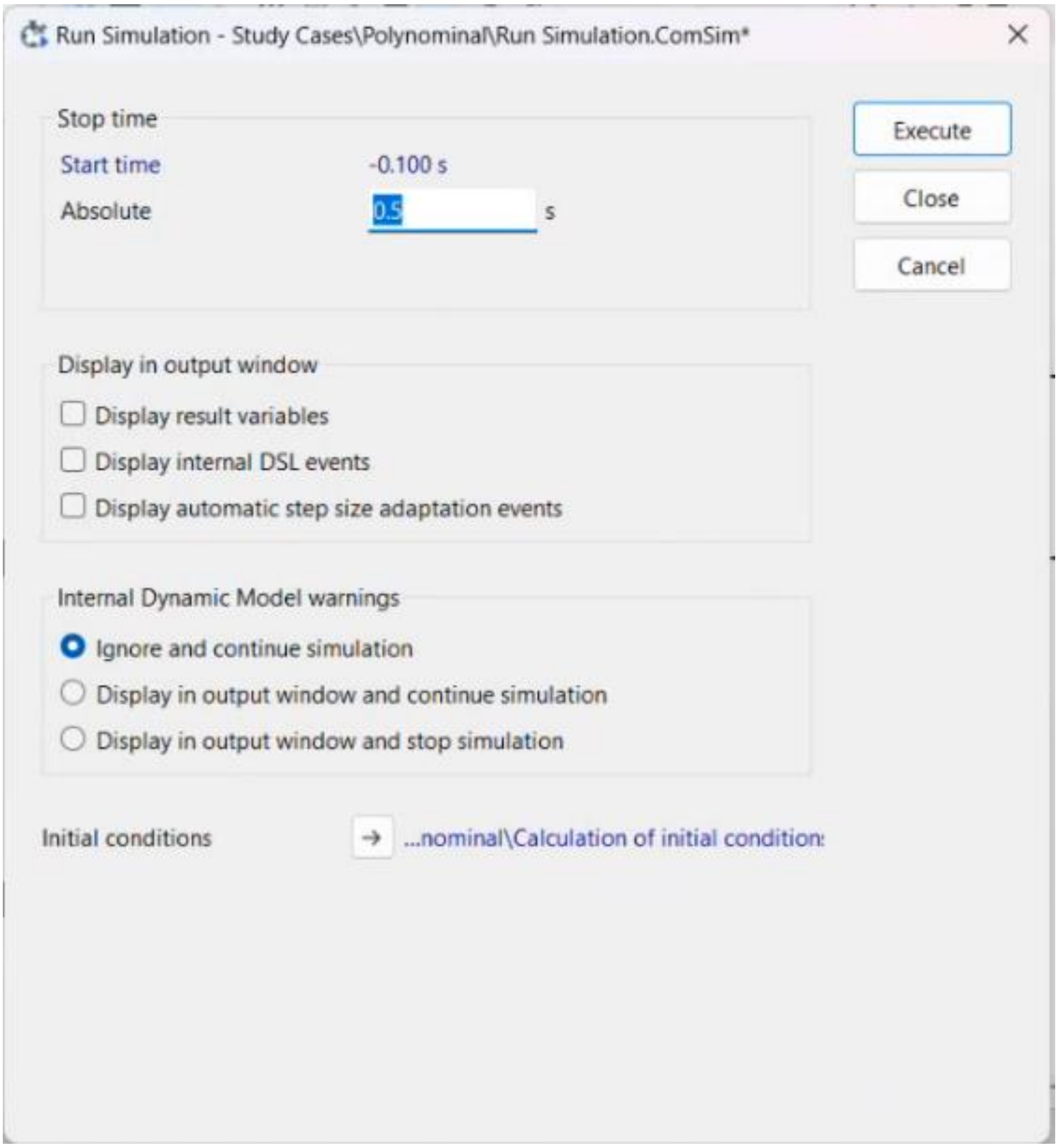
Load flow ...ases\Polynominal\Load Flow Calculation

☐ Verify initial conditions

☐ Automatic step size adaptation

Figure 4.5 Setting electromagnetic transients

In the "Run Simulation" window (Figure 4.6), various settings and options that control the simulation could be seen. The simulation will run for 0.5 seconds because the "Absolute" which is total elapsed time is set to 0.5s. The specific details of the work and the use of the simulation should be selected in this windows, this includes whether display result variables, DSL events and automatic step size adaptation events or not, The "Internal Dynamic Model warnings" section provides options for the software to handle any warnings that arise during the simulation, such as ignoring and continuing the simulation, displaying the warnings in the output window and continuing, or stopping the simulation. In this study, firstly, “Display in output window and continue simulation option selected. However, after reaching warning free state, for final version “Ignore and continue simulation option opted” . Lastly, initial conditions section allows to specify initial conditions for the simulation. Specific initial conditions are not defined in this window, because they are pre-defined in Figure 4.5. In summary, the simulation setup window has a lot of options and controls for running a power system simulation.



Run Simulation - Study Cases\Polynominal\Run Simulation.ComSim*

Stop time

Start time -0.100 s

Absolute 0.5 s

Display in output window

☐ Display result variables

☐ Display internal DSL events

☐ Display automatic step size adaptation events

Internal Dynamic Model warnings

● Ignore and continue simulation

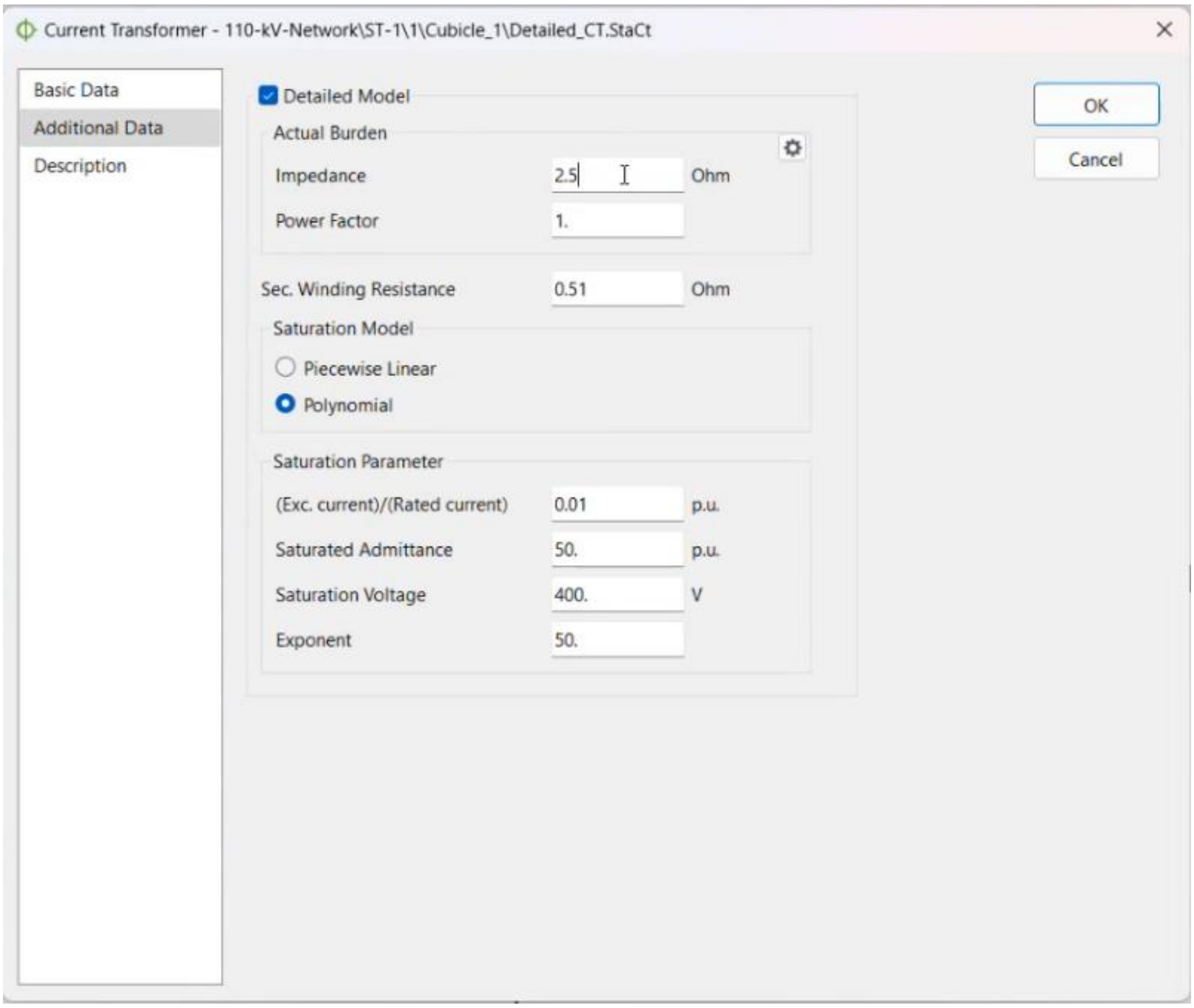
○ Display in output window and continue simulation

○ Display in output window and stop simulation

Initial conditions → ...nominal\Calculation of initial condition:

Figure 4.6 Execution of the simulation

In this study, response of transformers is analyzed under 2 specific conditions. Firstly, system response is evaluated with 2.5 Ohm impedance (impedance here represents load of transformer in real conditions) as shown in Figure 4.7. Power factor, secondary winding resistance, rated current, saturated admittance, saturation voltage and exponent are defined as 1, 0.51 Ohm, 0.01 p.u., 50 p.u., 400 V, and 50 respectively. These values are retrieved from real working parameters of transformers to ensure study is effective.


Current Transformer - 110-kV-Network\ST-1\1\Cubicle_1\Detailed_CT.StaCt

☑ Detailed Model

Actual Burden

Impedance 2.5 Ohm

Power Factor 1.

Sec. Winding Resistance 0.51 Ohm

Saturation Model

○ Piecewise Linear

● Polynomial

Saturation Parameter

(Exc. current)/(Rated current) 0.01 p.u.

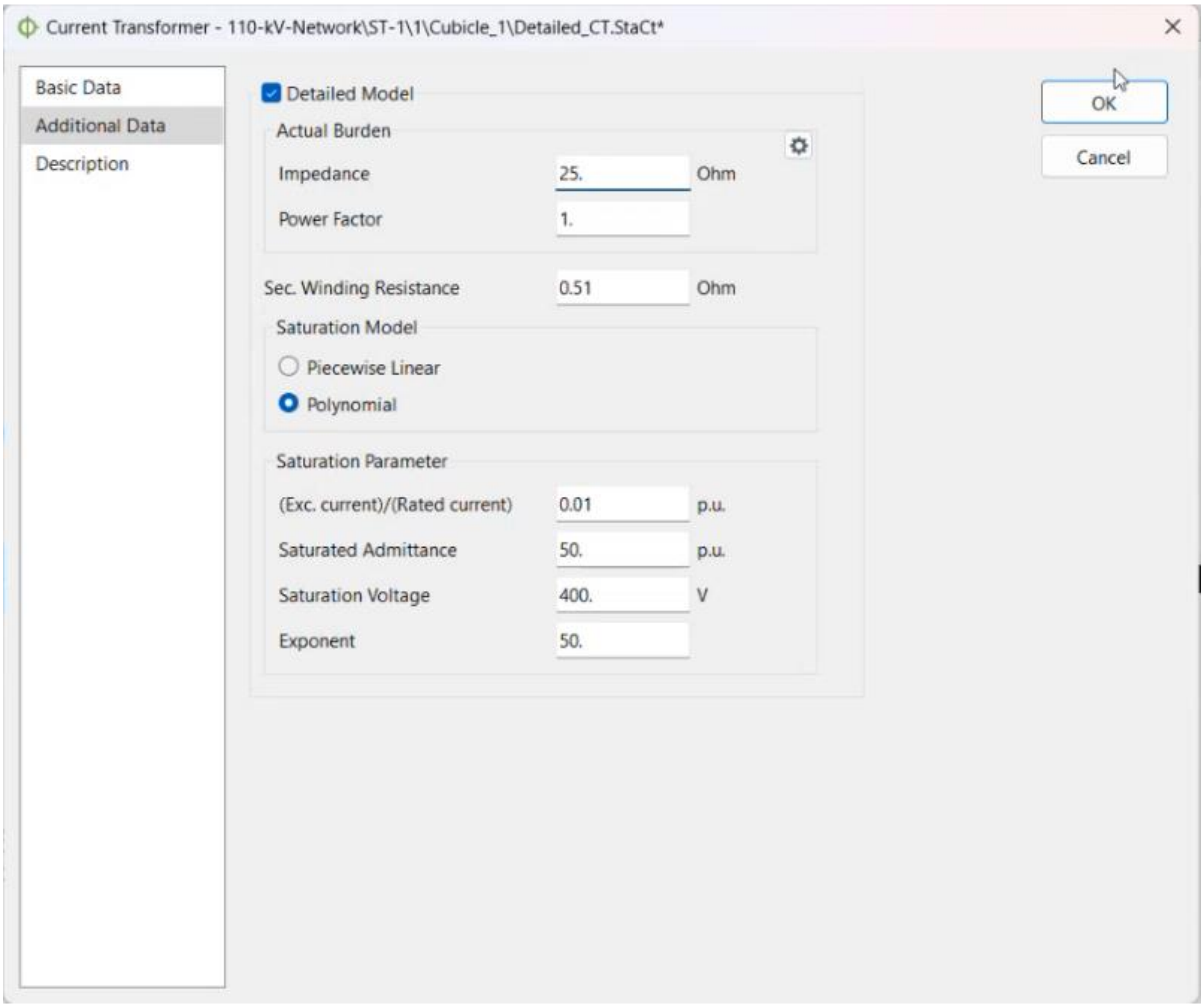
Saturated Admittance 50. p.u.

Saturation Voltage 400. V

Exponent 50.

Figure 4.7 Setting impedance to 2.5 Ohm for simulation

In the second part of the study, impedance value is set to 25 Ohm to examine saturation characteristics of transformer in this condition. As illustrated in the figure 4.8 below, all parameters remained unchanged. This represents a case where the system has 10 times more load which allows us to analyze results and investigate network further. Higher impedance affects saturation voltage and excitation current (secondary current) behavior. Due to containing magnetic core of conventional current transformers, it is exposed to saturation in higher loads. This condition influences excitation current that is required to magnetize main core. Such an approach shows the importance of why testing current transformers under varying load conditions is important.



Current Transformer - 110-kV-Network\ST-1\1\Cubicle_1\Detailed_CT.StaCt*

☑ Detailed Model

Actual Burden

Impedance 25. Ohm

Power Factor 1.

Sec. Winding Resistance 0.51 Ohm

Saturation Model

○ Piecewise Linear

● Polynomial

Saturation Parameter

(Exc. current)/(Rated current) 0.01 p.u.

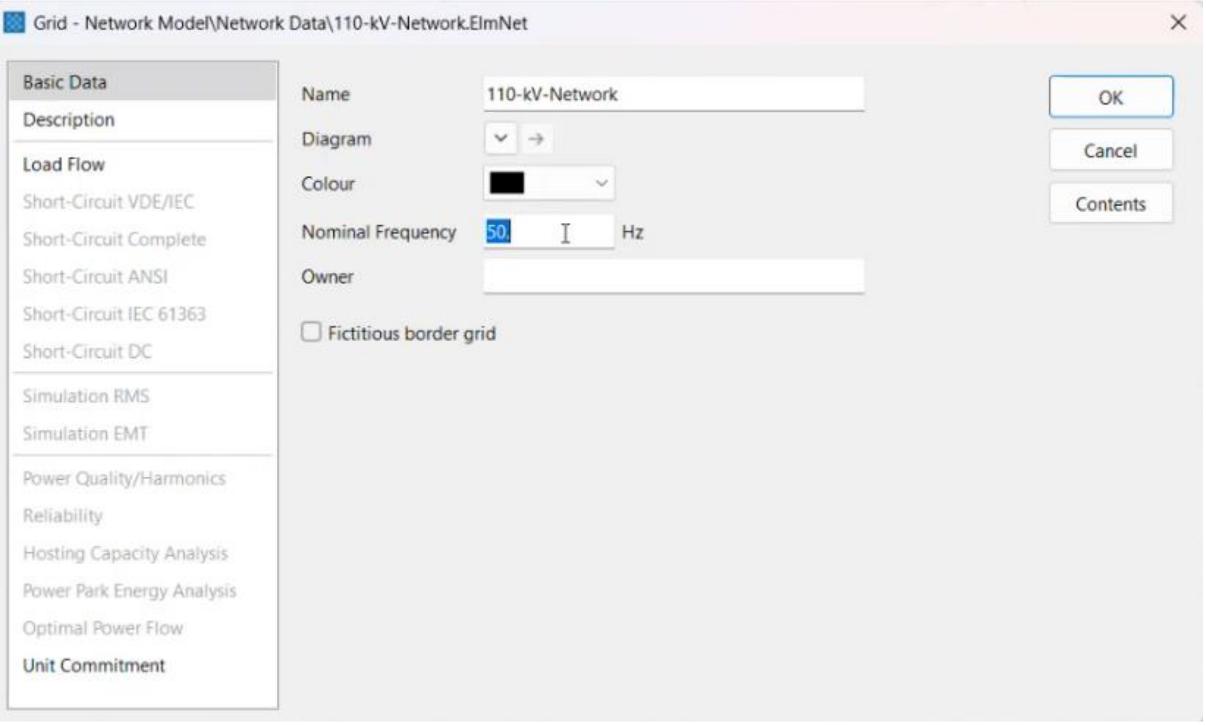
Saturated Admittance 50. p.u.

Saturation Voltage 400. V

Exponent 50.

Figure 4.8 Setting impedance to 25 Ohm

Second part of this simulation study includes frequency response test for both transformers. Firstly, as frequency is 50 Hz which is standard frequency for this application, no any problems occurred and result was same in Figure 4.9, because while implementing saturation characteristics test, frequency was set at 50 Hz. Hence, in this study, it is already known that system is stable for both transformers under 50 Hz frequency. However, test cases are not limited to a case, network tested under 3 conditions (1st, 5th, and 11th harmonics).


Grid - Network Model\Network Data\110-kV-Network.ElmNet

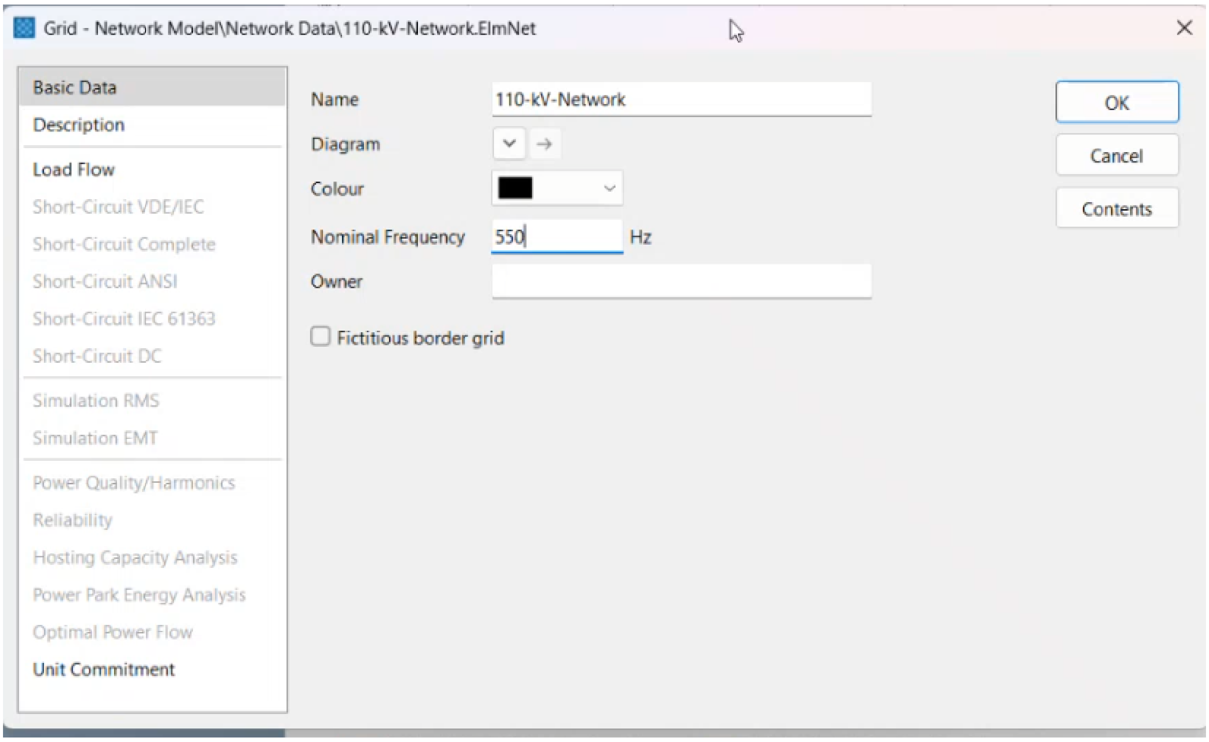
Name: 110-kV-Network

Nominal Frequency: 50. Hz

☐ Fictitious border grid

Figure 4.9 Setting frequency to 50 Hz

The grid standard frequency changed to 550 Hz corresponding to 11th harmonic was changed to check the performance of both OCT and CCT as shown in Figure 4.10. Also, the investigation covers higher order harmonic frequencies as they are becoming common in today's modern power networks owing to analysis of responsiveness of these transformers. The eleventh harmonic is chosen here to simulate high-order harmonic distortions generated by power electronic and nonlinear loads in practical scenarios. Most traditional current transformers are subjected to huge challenges while being excited by such high-order harmonics as the eleventh harmonic. A conventional current transformer has a magnetic core, which at these high-order harmonic frequencies, tends to get saturated and nonlinear, hence causing waveform distortions and incorrect current measurements. This effect, however, should not affect the measurement accuracy of an OCT that has a non-magnetic construction, hence further emphasizing suitability for modern power systems. A second objective of the 550 Hz experiment will be to investigate harmonic distortion effects on saturation and phase errors. These two are so fundamental in determining the reliability of the metering and protection functions of the system. Higher-order harmonic frequencies in the current serve to accentuate phase shifts and saturation phenomena in CCTs and this may short-circuit the effectiveness of such protection. A relative performance comparison is made here by comparing the results of the 11th harmonic to those obtained with the fundamental frequency of 50 Hz and the 5th harmonic. It is expected that the CCT will exhibit more distortion and less reliability with increased harmonics, while OCT will behave in a predictable matter with all three levels of frequency.



Grid - Network Model\Network Data\110-kV-Network.ElmNet

Name 110-kV-Network

Colour ■

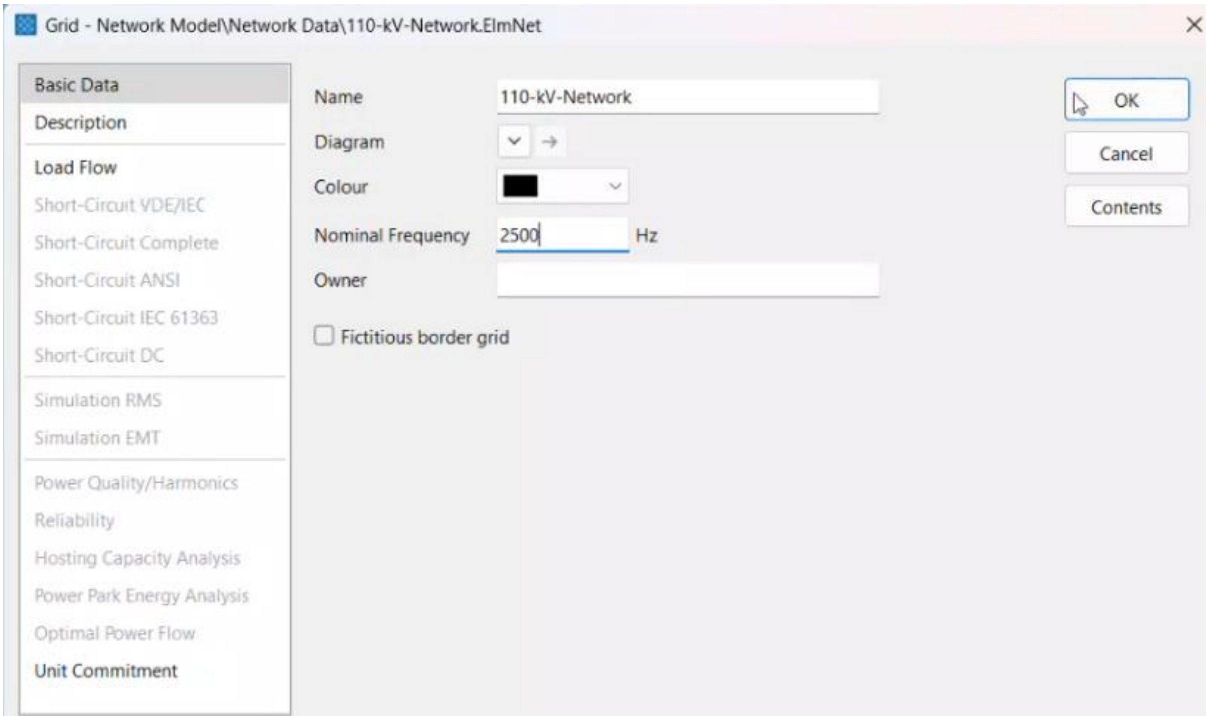
Nominal Frequency 550 Hz

Owner

☐ Fictitious border grid

Figure 4.10 Setting frequency to 550 Hz

Comparative analysis of standard and optical current transformers reveals unique performance qualities in response to high-frequency harmonics. During testing at 550 Hz (11th harmonic), one transformer showed a steady sinusoidal waveform with a peak-to--peak amplitude of about 40 units; the other transformer had distortion, sharp spikes, and inconsistent behavior at peaks and troughs, therefore producing a lower amplitude. Extending the research to 2500 Hz (50th harmonic) tests the operational limits of both transformers, therefore offering vital information on their high-frequency capacity. Setting value to 2500 Hz is illustrated in Figure 4.11. Modern power systems especially depend on this extensive frequency testing since power electronic devices and non-linear loads cause rising frequency of harmonics. Harmonic performance has to be considered when choosing transformers for applications with clearly high-frequency components; this is evidenced by the appreciable variation in waveform quality between the two transformer types at these frequencies. This observation directly affects protective systems, harmonic analysis, and power quality monitoring in the modern electrical networks.



Grid - Network Model\Network Data\110-kV-Network.ElmNet

Name 110-kV-Network

Diagram

Colour

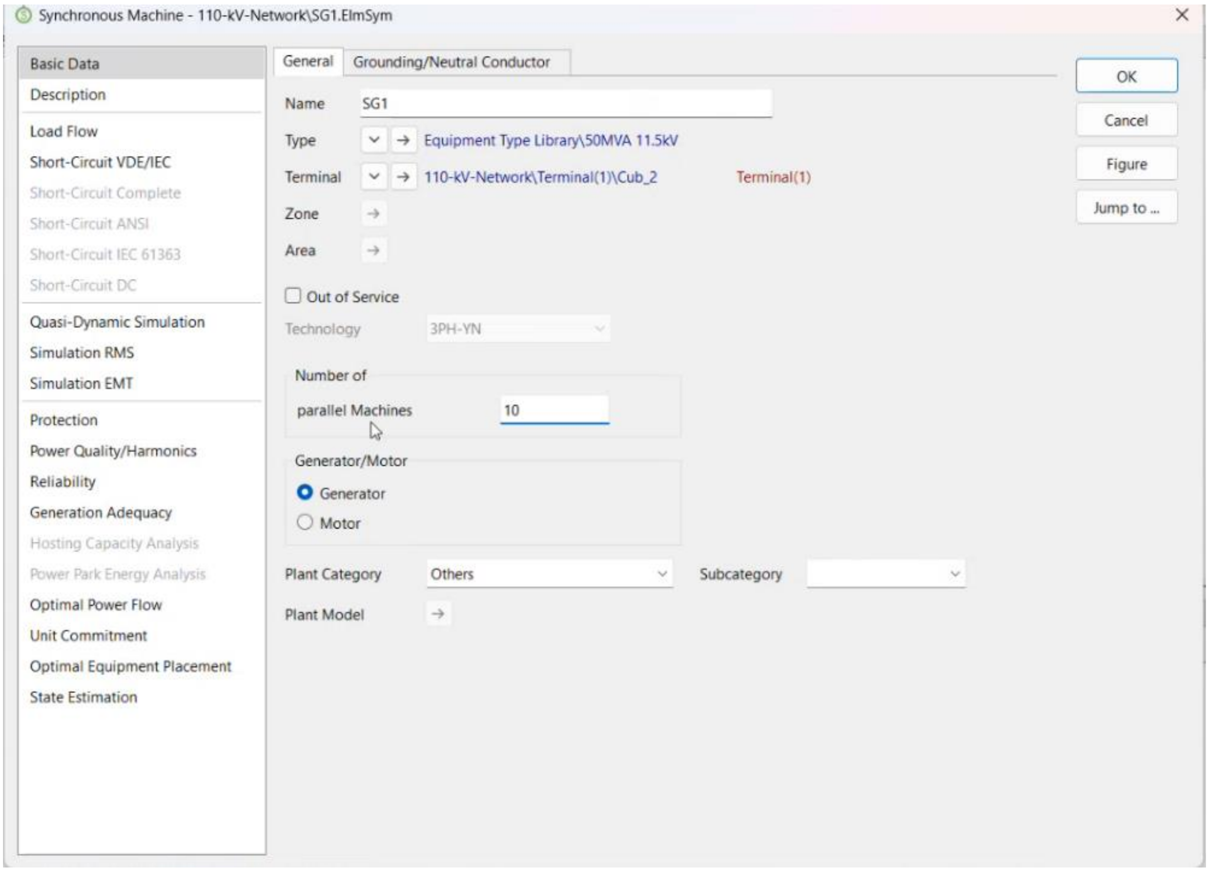
Nominal Frequency 2500 Hz

Owner

☐ Fictitious border grid

Figure 4.11 Setting frequency to 2500 Hz frequency

This work investigated the network behavior for variations in short-circuit power achieved through the systematic variation of numbers of generators. This provided much-needed information about the effects of system strength. In the process, transformers and generators used a one-to-one matching strategy to ensure effective power delivery without tampering with the network structure in research. This change in generator count made systematic variations in short-circuit power, having significant impacts in key network elements. Voltage stability characteristics and the magnitude of fault current became related to each other with each additional generator-transformer added to the already robust system. From this relation, invaluable conclusions could be drawn regarding the variation of performance of current transformers with network strength. Additional units, when connected in parallel, reduce the impedance of the system, which in turn affects the magnitudes and characteristics of fault current in the network. Varying the number of generators greatly changed the response characteristic of the dynamic network. From a performance evaluation viewpoint, the number of generators became an important variable because the way in which the system responded to disturbances was strongly dependent on the number of generators present. The study presented here has been performed for a configuration of 10 paralleled generators operating at 110 kV, supported by transformers rated for 50 MVA each, therefore providing a total transformation capacity of 500 MVA. In Figures 4.12 and 4.13 is shown. Such a study was performed to understand the influence of network strength on effective performance while maintaining symmetry in the system. The comprehensive analysis thus made meaningful conclusions on the influence of system strength, both on conventional and optical current transformers' behavior. Their contribution will go to the establishment of the boundaries of performance within different network configurations, hence bringing forth useful insight into the design and operation of power systems. Such results are of great importance in modern power grids, where variation in system strength and complex network arrangements are increasingly the critical elements for reliable performance.



Synchronous Machine - 110-kV-Network\SG1.ElmSym

Name: SG1

Type: Equipment Type Library\50MVA 11.5kV

Terminal: 110-kV-Network\Terminal(1)\Cub_2 Terminal(1)

Zone

Area

☐ Out of Service

Technology: 3PH-YN

Number of

parallel Machines: 10

Generator/Motor

● Generator

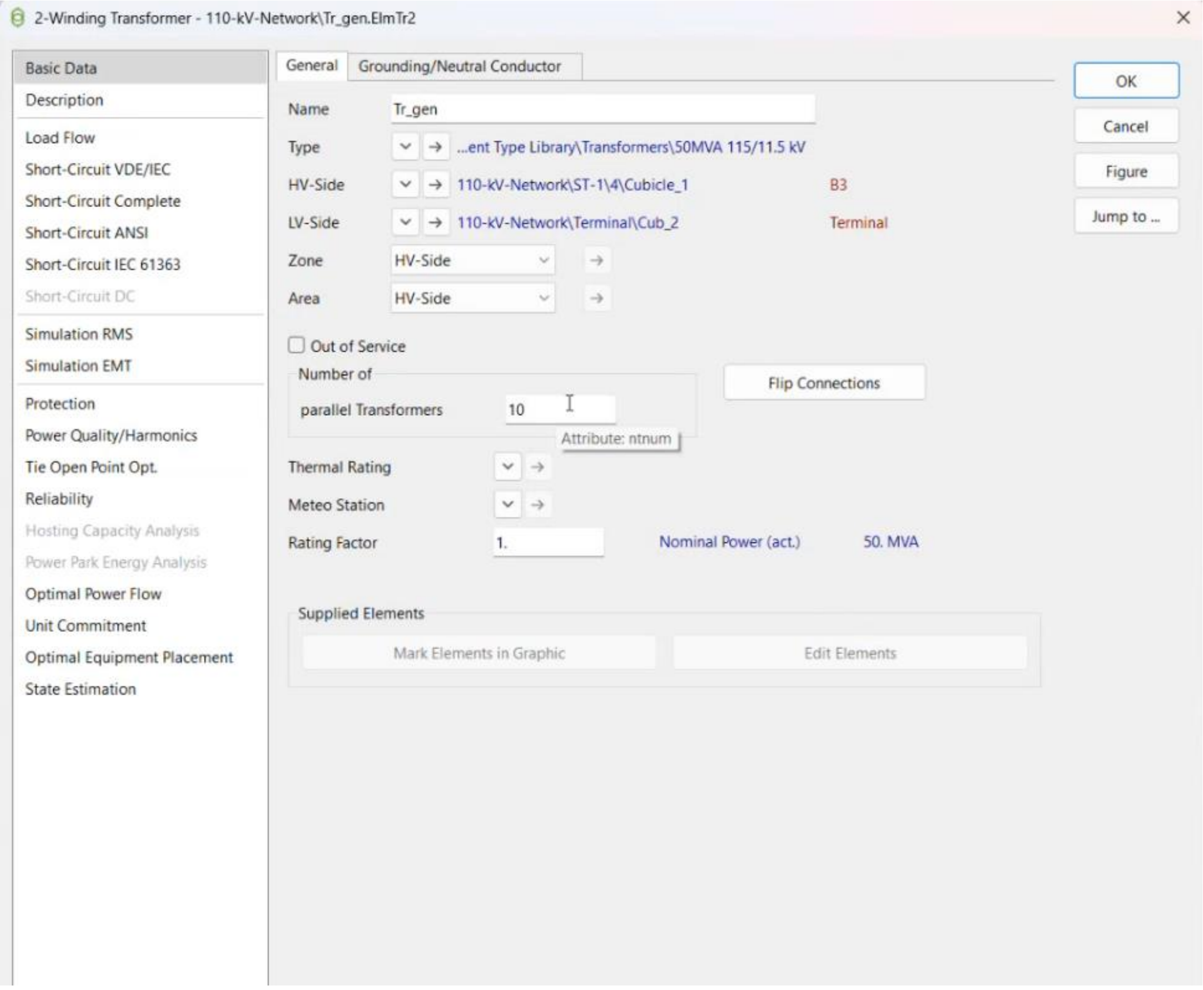
○ Motor

Plant Category: Others

Subcategory

Plant Model

Figure 4.12 Setting number of generators to 10



Name: Tr_gen

Type: ...ent Type Library\Transformers\50MVA 115/11.5 kV

HV-Side: 110-kV-Network\ST-1\4\Cubicle_1 B3

LV-Side: 110-kV-Network\Terminal\Cub_2 Terminal

Zone: HV-Side

Area: HV-Side

☐ Out of Service

Number of parallel Transformers: 10

Rating Factor: 1.

Nominal Power (act.) 50. MVA

Figure 4.13 Setting number of transformers to 10

4.2 Results of simulation

Operating performance was investigated for FOCT and CCT models under different conditions. The main focus of the given study is concentrated on harmonic frequencies, short-circuit power variation, and load changes in order to investigate the accuracy, reliability, and limits of both transformer types.

Firstly, it is required to look at graphs related to saturation characteristics under 2.5 Ohm (light load) and 25 Ohm (heavy load) and for all other cases except frequency response, frequency is set to 50 Hz. For first case, as shown in Figure 4.14, when impedance is set to 2.5 Ohm, simulation results show no significant variations. In case, graph inspected closely, phase difference between two waveforms could be observed.

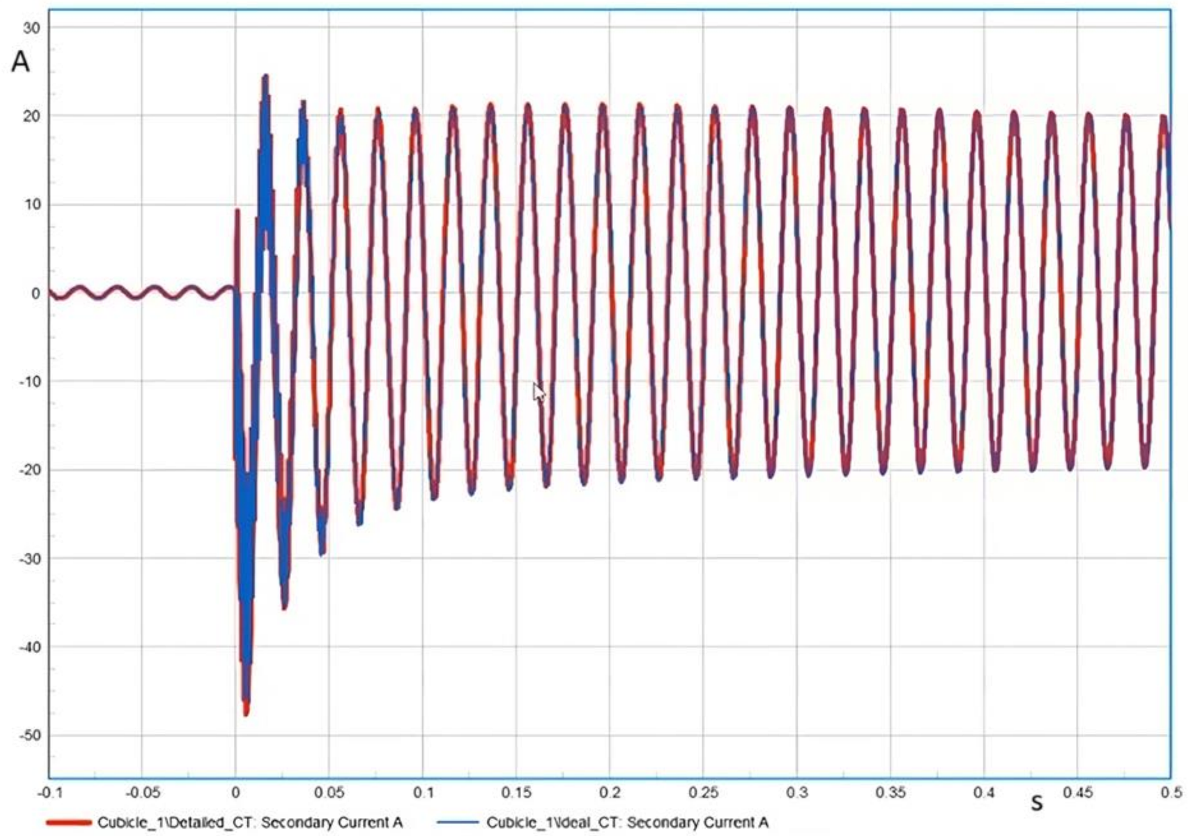


Figure 4.14 Comparison of transformers under light load (x-axis: Time(seconds), y-axis: Current (Amperes))

After discussion of behaviour of conventional current transformer (CCT) under light load, to observe the difference test case is organized under heavy load. Figure 4.15 below illustrates waveform of secondary current for both types of transformers under 25 Ohm impedance (load). This case allows us to understand the difference between light and heavy load conditions deeply. Core saturation causes significant distortions in the waveform of CCT. This distortion is most noticeable in areas with higher current levels, demonstrating the core material's non-linear characteristics. Furthermore, the difficulties of saturation in traditional transformers are evident through sharp clipping and decreased accuracy during peaks. Even in the face of increased load impedance, the blue optical current transformer exhibits its linear performance by maintaining a virtually perfect sinusoidal shape. The advantages of this type of transformers in providing accurate current readings under a range of operating situations are demonstrated by the absence of saturation effects.

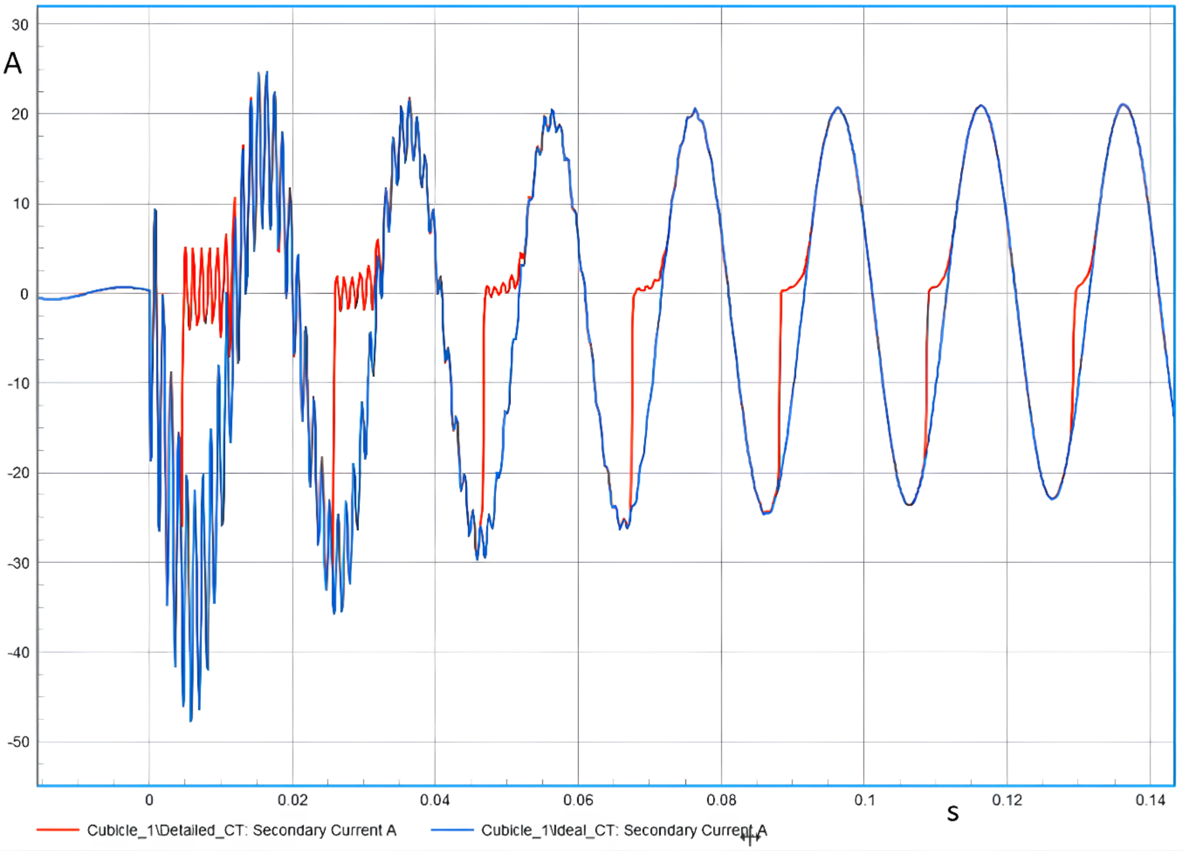


Figure 4.15 Comparison of transformers under heavy load (x-axis: Time(seconds), y-axis: Current (Amperes))

Proceeding to the next study, both transformers are tested under wide range of frequency. As written in previous section, first, eleventh and fiftieth harmonics are utilized as test condition for the frequency response. In the first harmonic, there is minimal deviation observed, as shown in Figure 4.14, because during saturation characteristic test during load variation, frequency was set to 50 Hz. Figure 4.16 below shows transformers' behaviour under 550 Hz frequency (eleventh harmonics). In this condition, especially, the red waveform (CCT) shows sharp peaks and erratic patterns at peak points of the cycle, really indicating that the respective transformer has a frequency-dependent limitation or a saturation phenomenon either in the optical sensor system-in the case of FOCT-or in the magnetic core-in the case of CCT-at 550 Hz. Since the phase is what matters with respect to the response of each transformer to the input current at this frequency, the phase difference between the two waveforms shown in Figure 4.10 is a good measure. After a brief period around the time marker of -0.005 where both transformers make the transition from a steady state to the harmonic test case, the test begins. After that, a repetition occurs, with both of these kinds of responses being given by both kinds of transformers.

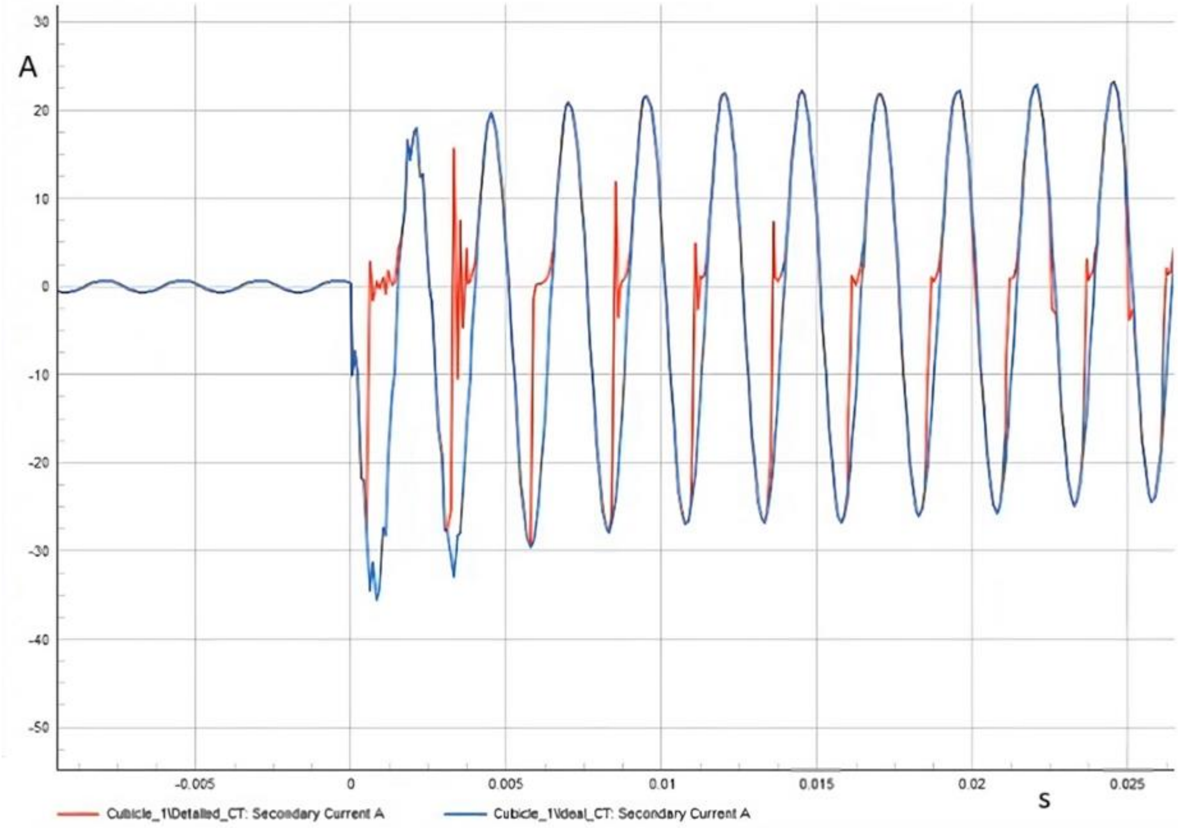


Figure 4.16 Comparison of transformers under 550 Hz frequency (x-axis: Time(seconds), y-axis: Current (Amperes))

Then the test is conducted under 2500 Hz (fiftieth harmonics). The transformers' performance differs significantly when the 2500 Hz (50th harmonic) response is examined in Figure 4.17. Over the course of the measurement time, the amplitude of the blue waveform steadily decreases from an initial peak of about 45 units to about 25 units, demonstrating a noticeable damping effect while maintaining a sinusoidal shape. This dampening property implies that at this high frequency, frequency-dependent losses become more noticeable. The changes in the red waveform's behavior are considerably more pronounced than those at 550 Hz. In contrast to the blue waveform, it exhibits narrow, sharp spikes at regular intervals with a somewhat smaller amplitude. High-frequency current fluctuations can be followed but, as demonstrated by the obvious distortion in the response and the rapid return to values near zero between peaks, the capability is seriously limited. That it may be hard to get accurate measurements at the higher harmonic frequencies is further evidenced by the progressive degradation in signal clarity present at 2500 Hz, particularly in the response of the red waveform. This fact has immense consequences in applications where measurements of high-frequency currents of small values are required, such as power quality assessment and system protection in modern power grids with substantial harmonic contents.

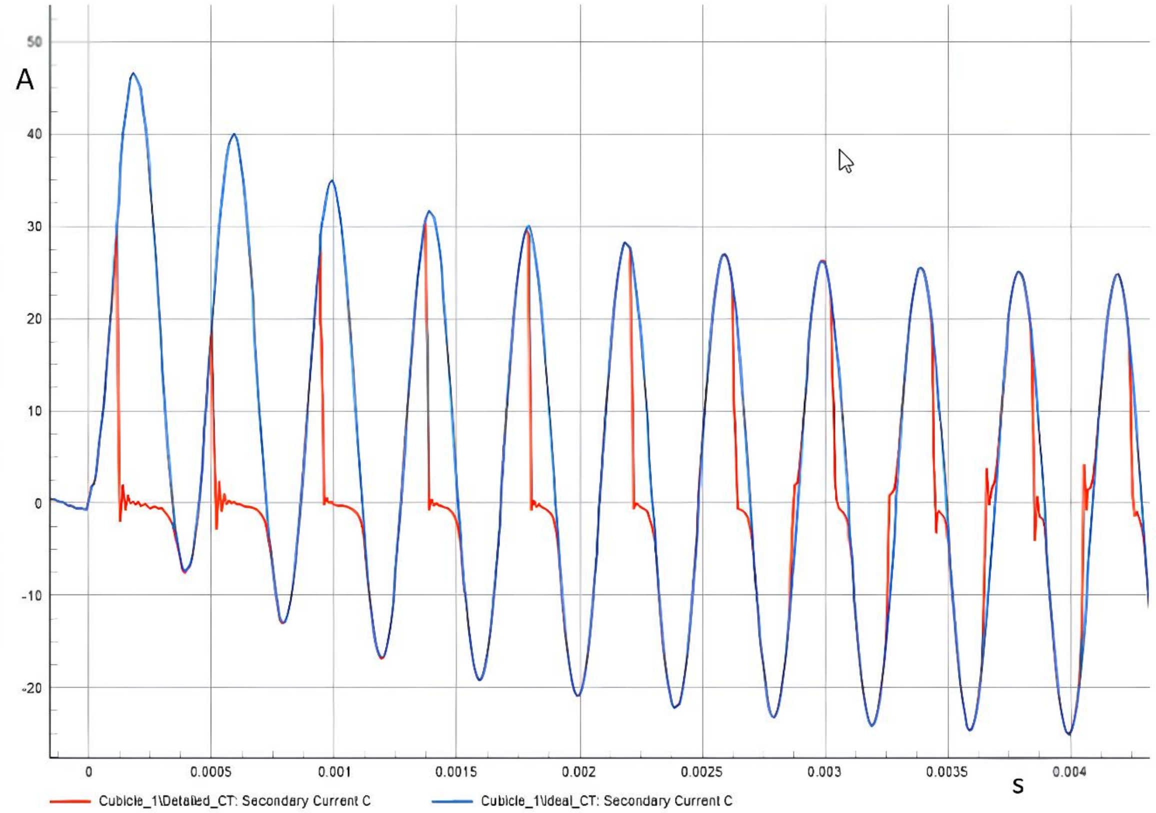


Figure 4.17 Comparison of transformers under 2500 Hz frequency (x-axis: Time(seconds), y-axis: Current (Amperes))

Lastly, transformers' behaviour is analyzed under different short-circuit power. During low short-circuit power, system shows resistance with minimal deviation as shown in Figure 4.14, because previous both tests are conducted using 1 generator as it is in this case. When the waveform response of such a network configuration including 10 generators is analyzed, the difference in the properties of traditional and optical current transformers stands out. The blue waveform by the optical current transformer reaches about 100 units both in the positive and negative, showing a wide response with great fluctuations. Oscillations, particularly during transitional phases, show sudden fluctuations in current that the robust network can sense via an optical transformer. In comparison, oscillations from a conventional current transformer are shown as the red wave, which has a very different response: much smaller amplitude of variation, with highly constrained behavior. Although its peak values do obviously oscillate during periods of stability, these oscillations are much lower compared to the ones occurring with the optical transformer. The core saturation effect becomes more dominating when higher-order short circuit powers along with higher amplitude current ramps come into play, which may partially explain the poor performance of conventional transformers. A conceptual comparison between them is provided in Figure 4.18.

The output of the optical transformer shows constant high-amplitude oscillations, indicating that in such a case, when 10 generators together supply the total short-circuit power, a much stronger network state is given. This difference in response characteristics, for conventional versus optical technology, is underlined most precisely for high values of short-circuit power and really points to enhanced capability for the optical transformer in tracking fast current variations in resilient networks. Currently, measurement in networks containing more than one parallel generating source is not normally possible due to the ordinary transformer narrow response.

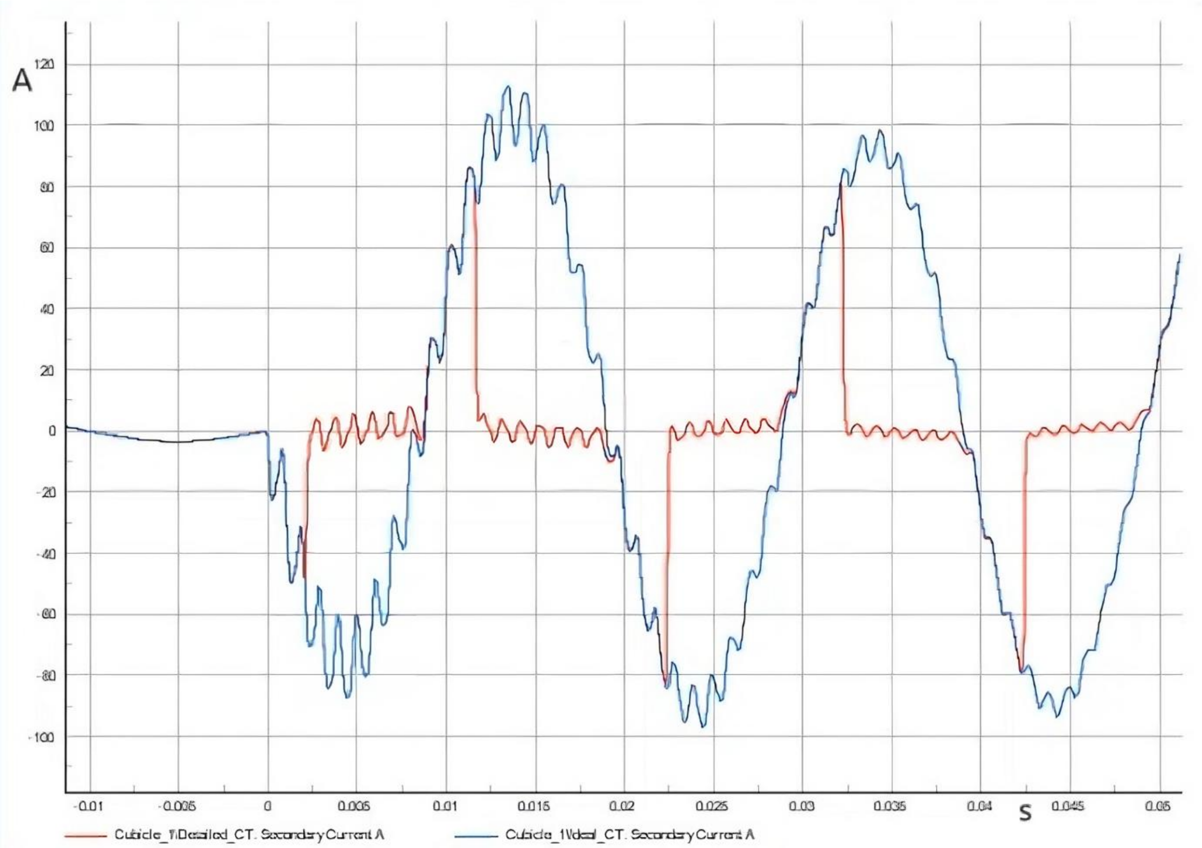


Figure 4.18 Comparison of transformers under high short-current power (x-axis: Time(seconds), y-axis: Current (Amperes))

It is quite evident from the simulation that there exist clear performance distinctions between FOCT and CCT in different operating scenarios. In this regard, each of these types of transformers can be examined in detail. These observations are discussed in detail in the subsequent sections; first, FOCT in Section 4.2.1 and then CCT in Section 4.2.2, and their detailed comparison in 4.2.3.

4.2.1 Fiber Optical Current Transformers

The conditions imposed yielded great results for the FOCT, proving the advantages this device has over those based on traditional technologies. For example, at the 11th harmonic of 550 Hz, the FOCT maintained an absolutely perfect sinusoidal waveform with highly consistent peak-to-peak amplitude of about 40 units and without any distortion. This proves one of the very essential capabilities of the FOCT-to-keep waveforms intact even under conditions whereby, based on frequency, the normal operation of conventional transformers is disrupted. In the 50th harmonic at 2500 Hz, frequency-dependent losses become pronounced, and the response of the FOCT is a damped sinusoid in which the amplitude decreases slowly from approximately 45 to 25 units. Thus, even with such damping action, the structure and accuracy of the waveform were preserved-a proof that the FOCT is capable of handling high-frequency components with no compromise in performance.

Moreover, the FOCT operated very effectively during tests under conditions of short-circuit power. The system is designed with 10 generators and their relevant transformers, simulating a stronger network. In transient events, the FOCT exhibited high-amplitude oscillations peaking at about 100 units. These indeed prove the strong structure of the FOCT in capturing fast and dynamic variations of current with remarkable precision. Such characteristics make FOCT indispensable in modern power systems for which reliable measurement during transient and fault conditions is necessary. Unlike conventional transformers, FOCTs demonstrate the flexibility and resilience required for complex and high-powered grid systems.

The performance revealed by the FOCT when subjected to different loading was very commendable. At a relatively lower load of, say, 2.5 MVA, the FOCT maintained almost an ideal sine waveform with minor fluctuations thus guaranteeing an accurate measurement.

Even when increased to an increased load of 25 MVA, the FOCT continued to provide distortion-free and reliable outputs with ease, adapting to the fluctuating current. This adaptability underlines the strength of the FOCT in versatility, considering demands in modern grids that intrinsically work under variable loads. Its reliability through all these differing load scenarios underlines its suitability for modern power systems, which are becoming increasingly dependent on flexible and robust measurement technologies. Beyond the technical performance of the installation, the adoption of FOCTs fell perfectly in line with the modernization of the energy grid in Azerbaijan. Intelligent devices clearly enable transition in a context of a liberalizing energy market, which accelerates investment in renewable energy.

They avoid one of the most important problems of CCTs-core saturation. In modern renewable energy systems that increasingly contain high-frequency components, the FOCTs can provide the accuracy and stability that are needed for dynamic current changes. Equipped with integrated FOCTs, Azerbaijan will have the opportunity to solve the challenges brought in by obsolete grid infrastructure and enable its pathway toward a future-proof power system capable of supporting ambitious renewable energy targets. With the high degree of accuracy that they deliver, waveform integrity maintained, and adaptability to various conditions, the technology is in a privileged position to answer the changing needs of Azerbaijan. In this ongoing process for market liberalization, Azerbaijan is well-placed to attract investment in modern grid technologies like FOCTs. The deployment of FOCTs will replace traditional current transformers and help the country enhance grid reliability, cut down measurement errors, and evade saturation issues in future applications.

These substitutions will be very important to satisfy a digital, decarbonized energy infrastructure and to keep the electric grid of Azerbaijan robust, efficient, and at international energy standards. These FOCTs are unequalled in highly dynamic and high-frequency environments, representing a paradigm shift in existing measurement technology. These deployments will modernize not just the Azerbaijan grid but provide the cornerstone for achieving the 2030 target of 5 GW renewable energy and prepare the nation's power system to meet the challenges that lie ahead [30].

4.2.2 Conventional Current Transformer

Under the described test conditions, CCTs performed poorly, clearly showing their unsuitability for modern power systems. Analyzing the power spectrum under these conditions, severe waveform distortions with sharp spikes and erratic behavior can be seen at 550 Hz, corresponding to the 11th harmonic. These defects originated from core saturation and frequency-dependent anomalies by which the ability of the CCT to provide accurate current measurements was severely degraded. At higher harmonic frequencies, especially around 2500 Hz (50th harmonic), the performance deterioration was even more pronounced. It showed that the pronounced, slender spike distortions and markedly diminished amplitude of the CCTs were not sufficient for good monitoring of waveform integrity at high frequencies, underlying a limiting factor in systems with dynamic current fluctuations and high harmonic content.

Further short-circuit power variations underlined the failures of the CCTs.. With the increase in short-circuit power, the oscillatory response of the CCT became clearly weaker, with lower amplitude and stronger fluctuations. Such behavior, aggravated by core saturation, rendered the CCT unstable under fast-changing load conditions. That kind of instability suggests that CCTs cannot handle sudden current surges in modern power systems, especially in larger networks with greater short-circuit power contributions, where precision and reliability are must-haves.

This inability to adapt to dynamic conditions creates a risk to the stability and efficiency of power systems that rely on such archaic technology. The performance issues were even more visible under dynamic load conditions. Thus, at low loads of 2.5 MVA, slight distortions in the output of the CCT became dominant with increasing harmonic content. If the loads are increased to 25 MVA, these distortion effects worsened, hence proving that in such conditions, the CCTs cannot appropriately track the exact current variations under dynamic and heavy-load conditions. All these results underline the limited suitability of CCTs for modern power grids under highly variable operating conditions with exact monitoring and control required. A case illustrating the inconveniences of old grid technologies, such as CCTs, is really epitomized by the energy landscape of Azerbaijan. Even though, in 2016, it achieved 100% electrification, its reliance on outdated infrastructure obstructed the very modernization required. The generation mix, with 94% dependent on gas and only 6% renewables, has really resulted in years passing without much infrastructure reconstruction. It had contributed to the dependency on old legacy systems and, subsequently, the ongoing use of technologies like CCTs, ill-equipped for the demands now placed on modern, renewable-based power systems. The fact that CCTs keep being in use mirrors the more extensive issue of the energy transition within the country—outdated infrastructure holding Azerbaijan back. The inability of the CCTs to handle high harmonics, sudden load changes, and short circuit power variations poses risks to system reliability and efficiency.

With Azerbaijan aspiring to integrate 5 GW of renewables by 2030, on top of exporting electricity through large projects such as the Black Sea Submarine Cable, CCT limitations will be increasingly intolerable. Thus, by the implementation of these novel technologies, no other devices are able to perform the functions required by modern smart grid systems as FOCTs can. With FOCTs providing increased precision, better performance in extreme conditions, and capability for integration of renewable energy, they are very vital in the upgrade of Azerbaijan's grid to achieve its renewable energy goals. These results show the need for a transformation in the paradigms of energy infrastructures in Azerbaijan. This will be upgrading from conventional technologies like CCTs to new systems such as FOCTs, which is not technology upgrade but a grid necessity for reliability and efficiency, meeting the new needs of energy.

4.2.3 Comparison of transformers

Until now, some comparative studies on the measurement performance of OCT and CCT for a few harmonic orders, short-circuit power levels, and under different load conditions have presented striking differences, which are very relevant when explaining the acceptability and reliability of these two types of transformers while working in modern power systems.

Moreover, as further evidenced by our frequency response simulations, the frequency range at which FOCT yields better linearity and accuracy is much larger. The system behaves well even at high frequencies, being a testimony to its robustness against phenomena of phase errors and saturation of the core. Moreover, performances of FOCT result in being very robust against electromagnetic interference, being extremely suitable for environments with high harmonic distortion. Of course, performance at higher frequencies was found to be low in our tests due to core saturation and eddy current losses. This yielded high-amplitude phase shifts and strong distortions, hence limiting dependability in systems which may have dynamic frequency fluctuations or are rich in harmonics. Under those conditions where short-circuiting took place, it was seen that this corelessness construction did not result in any loss of accuracy in FOCT. The large dynamic range allowed for the accurate measurement of current in faulty conditions-a key component for successful fault detection and protection of the system. On the one hand, where the CCT performance was drastically degraded in our tests during short-circuit events, core saturation warped its output signal and degraded its capability for correct fault analysis. This limitation evidences its relatively reduced reliability during such high-stress conditions. The additional influence of load fluctuations further cinches our conclusions on the better reliability of FOCT. Within our simulations, the measurements derived from FOCT were independent of load impedance, hence always providing accurate results regardless of the load connected. The sensing mechanism of the optical effectively reduced the influence of the conditions of external circuits, hence enhancing its reliability. However, due to the burden effect, the accuracy of CCT in our simulations was highly dependent on the load impedance. In case of increasing the load, there appeared errors due to core behavior, as saturation and hysteresis, which made its measurement unreliable.

Our analysis has proved that FOCT is more resistant from the viewpoint of general stability and reliability in our opinion. The material showed great thermal stability in our test, in which it did not change with the temperature-induced change of its magnetic properties; secondly, it is light and compact, which eased the installation and integration in modern power systems. On the contrary, a simulation has revealed that CCT will be vulnerable to thermal fluctuations, which was affecting the magnetic core negatively, resulting in inaccuracies in the measurement under severe conditions. Besides that, the more bulky design made installation in smaller areas difficult. The results obtained from our simulations bring serious evidence that in all scenarios, FOCT outperforms CCT in accuracy, stability, and reliability. Even though CCT can be quite useful in traditional power systems, shortcomings regarding frequency fluctuation handling and situations with short circuits or changes in loads make it less fit for current needs. Based on our conclusions, improved performance of FOCT is able to provide full compatibility with digital systems, making it the best choice for today's and perspective power networks.

At harmonic frequencies, the OCT outperformed the CCT by maintaining a stable sinusoidal waveform with minimal distortions. At the 11th harmonic (550 Hz), the OCT achieved a peak-to-peak amplitude of approximately 40 units without experiencing any waveform irregularities. In contrast, the CCT exhibited substantial distortion, including sharp spikes and reduced amplitude, indicating core saturation and limitations in handling high-frequency signals. At the 50th harmonic (2500 Hz), the OCT demonstrated a damped sinusoidal response, gradually decreasing in amplitude but maintaining waveform integrity, while the CCT displayed severe waveform degradation with narrow, distorted spikes and significantly diminished amplitude. When the short-circuit power was increased by adding 10 generators and transformers, the OCT continued to deliver consistent high-amplitude oscillations during transient periods, with peak values reaching approximately 100 units. This robust performance illustrates its ability to accurately track rapid current changes in strong networks. On the other hand, the CCT struggled under the same conditions, showing constrained oscillations and lower peak amplitudes due to core saturation effects. The CCT's limited ability to handle the increased fault current levels and rapid variations highlighted its vulnerability in high short-circuit power scenarios. Load variation further underscored the differences between the two technologies. The OCT reliably tracked current variations at both low (2.5 MVA) and high (25 MVA) load conditions, maintaining waveform integrity and ensuring accurate measurements. In contrast, the CCT displayed performance degradation as the load increased, with noticeable distortions and an inability to accurately capture current variations under higher loads. This behavior suggests that the OCT is better equipped to handle dynamic operating conditions in modern power networks. In the table below, it shows complete differences between both of them.

Table 4.1 Comparison of CTs

Characteristics	**CCT**	**FOCT**
Frequency Response	Performance deteriorates at higher frequencies due to core saturation and eddy current losses.	Superior linearity and accuracy across a wide frequency range. Immune to electromagnetic interference.
Short-Circuit Handling	Accuracy is affected by core saturation, leading to distorted output during faults.	Maintains accuracy and stability under fault conditions. No core saturation
Load Variation	Accuracy is burden-dependent; performance degrades with increased load.	Independent of load impedance, ensuring consistent and reliable measurements.
Thermal Stability	Susceptible to thermal variations, causing measurement errors.	Unaffected by temperature variations, maintaining high accuracy.
Installation	Bulkier and heavier, challenging to install in limited spaces.	Lightweight, compact, and easy to install in modern systems.
Suitability	Suitable for conventional power systems but less adaptable for modern needs.	Ideal for modern smart grids and digital integration.
Transient characteristics	Magnetic saturation	No saturation

Overall, the comparison demonstrates the FOCT’s superior adaptability and performance across all tested scenarios. Its ability to maintain accuracy under high-frequency harmonics, increased short-circuit power, and varying loads makes it a more reliable choice for power quality monitoring and protection systems. While the CCT was suitable for lower frequencies and less demanding conditions, it showed significant limitations in modern power systems because of their complex and dynamic operational environment. That means a primary focus on FOCT technology is exceedingly relevant when high accuracy and reliability are required.

CHAPTER FIVE
CONCLUSION AND FUTURE WORK

5.1 Conclusion

The current transformer performance review has been done in this article by considering the major challenges, advances, and hence the potential opportunities. For a very clear understanding of the limitations and future prospects that come with the FOCTs, we shall discuss in detail the resolved issues: saturation in FOCT, its light weight, compactness, and the ability to operate over a wide range of frequency. The insights articulated underscore the significance of, which continues to be crucial in tackling both present and forthcoming challenges. The improvements mentioned, such as the optical technology used in the existing CT industry that is yet to be applied at Azerenerji electrical stations, together with the improved performance of FOCTs in handling different operational scenarios - high short-circuit power and variable frequencies - are just indicative of the progress realized towards the imminent replacement of old conventional CTs with modern optical types at Azerenerji substations. Yet, despite these advances, the challenges of vibrations and temperature-related problems remain very active, and therefore, further studies, innovations, and interdisciplinary collaborations are called for. These shortfalls could have been corrected, and better solutions facilitated if an atmosphere that encourages interdisciplinary initiatives was fostered among the participants.

Moreover, this thesis demonstrated that the material should either be replaced with one that resists stress or one should prepare a fiber polarization rotor for enhancing robustness in FOCTs. Indeed, the use of tools will provide not only resistance to temperature and vibration but also opportunities for new areas in research that had previously remained untouched. The emerging technologies and strategies looking toward the future will bring a very promising avenue for the existing barriers. As the field is continuously changing, this will make the scientists' involvement quite vital. Continuous research and investment in collaboration will therefore be very important in developing more accurate and less harmful equipment to the environment.

In all, even though there are still challenges, the progress that this article has identified does constitute increasing momentum toward meaningful and genuinely transformative change. Putting emphasis on innovation, flexibility, and collaboration, together we can work toward a future where environmental concern and technological development go hand in hand. Such a process would meet present needs and create a framework for long-term success in service of generations to come.

5.2 Future research recommendations

This study provided the detailed view towards FOCT technology and its use at Azerneerji substations. However, there are still some uncompleted works need to address in the future. In this study, we covered the simulation using only DIgSILENT PowerFactory software for obtaining insights on FOCT performance under certain conditions. Nevertheless, in future, AI driven tools can be used for further analyzing their non-linear and dynamic characteristics. AI tools can improve efficiency and enhance accuracy in detailed analysis. While this work focuses on investigation on theoretical and simulation parts, there is also demand for further validation in the experimental set-up. This will also be useful to measure disturbance of temperature and vibration caused by environmental factors on FOCTs. Long-term reliability is another ongoing research area, because the optical technology is new, and it still requires confirmation from that perspectives. Additionally, although this technology is superior than old technology used in CTs, cost-benefit analysis needs to be considered before implementation at Azerenerji substations. It is proven that maintenance and operational costs reduces using FOCTs, however, initial cost is higher than conventional methods that needs to be considered. Moreover, integration into renewable energy technologies needs to be investigated. Future research can explore how FOCTs behaves after integration into renewable energy systems and smart power grids.

By addressing this issues, future research can contribute to power grids and this investigation can assist Azerenerji to build long-lasting

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