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ANALYSIS AND CLASSIFICATION OF INSTRUMENT TRANSFORMERS FOR MODERN DC APPLICATIONS.

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ABSTRACT

This thesis explores DC Instrument Transformers. The research addresses the gap between the rising use of DC power sources and the limited advancements in instrumentation for DC signal measurement. A comprehensive classification of DC instrument transformers has been developed based on voltage levels, electrical parameters, and technological frameworks.

The analysis covers 8 types of DC ITs, including Fiber Optic Current Sensors (FOCS), Hall Effect Current Transformers (open and closed loop, as well as coreless), Pockels Optical Voltage Sensors, closed-loop Hall Voltage Sensors, shunt resistor current transformers, and resistive voltage divider transformers. Each transformer's operational principles and circuit representations are examined, leading to the identification of 15 key performance parameters such as electromagnetic compatibility, linearity, accuracy, sensitivity, size, and reliability. A comparative analysis using a 15x8 matrix highlights that the FOCS outperforms others by meeting 11 of the 15 parameters, with closed-loop Hall sensors and resistive voltage dividers also showing strong performance.

In addition, the thesis investigates the market dynamics for instrument transformers, focusing on regional trends and forecasts in Asia Pacific (APAC), North America, Latin America, Europe, and the Middle East and Africa (MEA). The APAC region emerges as the leading market due to rising electricity demand and renewable energy integration, while North America offers significant investment opportunities. In Europe, a consolidation trend suggests a shift towards market dominance by fewer firms. Overall, global market growth for instrument transformers is expected to maintain a compound annual growth rate (CAGR) below 10%. The findings enhance the understanding of DC instrument transformers, their performance, and market dynamics, thereby supporting informed decision-making in the power industry and promoting the adoption of efficient measurement solutions.

DEDICATION

I dedicate this thesis to my loving family, especially to my mom, Mrs. Rose Mwinisin, who, despite lacking any formal education, laid a solid foundation for me to thrive academically. I dedicate this thesis to her as an expression of gratitude for providing me with formal education.

To my brothers, Mwinisin Roger, Dominic, and Emmanuell, I am forever grateful for your unwavering support throughout my journey in higher education. Allow me to extend a special mention to our elder brother, Roger, for believing in me and investing in my ability to reach this milestone.

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A special acknowledgment is extended to the Italian Ministry of Foreign Affairs and International Cooperation for their substantial investment in covering my tuition fees and living expenses in Italy. Without this support, the realization of this thesis would have remained a distant dream. Your assistance not only provided financial relief but also propelled my educational and professional journey while exposing me to the vibrant and diverse Italian culture.

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CHAPTER 1

GENERAL INTRODUCTION

This introductory chapter encompasses a broad overview of the topic: Analysis and Classification of Instrument Transformers for Modern DC Applications. It consists of an introduction whose purpose is to provide an opening to the research by assessing the status quo of the topic and providing a clear path for the next steps of action. The problem statement driving the need for this research is also presented in this chapter. Herein, the research aim and objectives are defined according to the expected outcomes. Finally, facilities used, research methodology, the thesis organization and execution timeline of the work are presented.

1.1 Background

Power Quality (PQ) measurements are becoming increasingly important as a result of the rising use of solid-state electronic devices (switching power converters), whose presence distort significantly the waveform of the distribution voltage further away from a pure sine wave. The growing demand for energy and increasing environmental consciousness has led to a substantial surge in the demand for renewable energy sources (RESs) in recent years. However, the power electronic device (inverters) necessary to link renewable energy sources to the distribution grid, on the other hand, increase the number of grid-injected disruptions. Power quality deterioration incurs major expenses for business and consumers hence its accurate measurement is therefore crucial for grid monitoring [1]. Ensuring the reliable operation of grid-connected renewable Distributed Generation systems presents a complex task. This complexity arises from power quality issues associated with the intermittent nature of environmental factors and the inherent technological disparities between renewable distributed generation systems and the constant energy supply offered by fossil fuel-based systems [2]. PQ measurements are performed using Instrument Transformers (ITs), particularly at high and medium voltage levels of the power network [3]. The commencement of power systems development for electricity generation, transmission and use marks the birth of production and incorporation of instrument transformers. This explains the vital role that instrument transformers play when it comes to measurement of system parameters of the power networks: both AC and DC systems. Beside power quality measurement, the need for instrument transformers concerns the transformation of voltages or currents with high degree of accuracy for measuring consumption for billing purposes or for protection by coupling it to protective devices such as relays. For instrument transformers (particularly high-voltage and high-current), the focus on construction and calculation issues, which are also faced in the design of other converters and electrical devices, is intensified by their metering and protection activities[4].

Considering the pivotal role instrument transformers play in the utility grid, their classification and performance analysis has become vital for reliable operation and safety of personnel working around it. While instrument transformers are not particularly expensive components in the utility grid, their failure or breakdown might result in significant additional expenses. As a result, utilities all around the world are looking for ways to assess the status of their equipment performance, aging and inaccuracies under normal and off-normal conditions [5]. International standards have been formulated to assess the accuracy and performance of these devices giving their crucial role in power networks. Although these standards are defined for both AC and DC power, the majority of research continues to be intensified on the traditional AC power despite the fast emergence and incorporation of DC power into the traditional AC power network. The International Electrotechnical Commission (IEC) defines the worldwide standards (IEC 61869-X series) for instruments transformers for different voltage and frequency levels. For instance, the newly published standard, IEC 61869-1:2023 specifies the general requirements for newly manufactured instrument transformers whose secondary side provides either digital or analogue signal for protection, measuring and control functions. It is applicable in situations where the nominal voltage is greater than 1kV AC and 1.5 kV for DC and valid for frequencies ranging from 15Hz to 400Hz (AC). For low voltage (nominal voltage less than 1kV AC or 1.5 kV DC) applications, the IEC 61869-201 of the IEC 61869-X series specifies the general requirements of ITs. Similarly, for the different types of instrument transformers available and various voltage levels and frequency ranges, the IEC standard formulates a unique procedure for testing the performance of ITs. While these standards are very comprehensive in nature, it obviously cannot capture all important aspects of the operational performances of ITs. Some authors have identified uncovered sections of the international standards. For example, in [3] the authors realized there is no international standard yet that specifies the procedure for testing the errors that the instrument transformers themselves introduce during its operations in power quality measurements. Also [6] pointed out that the available standards do not provide a methodology for assessing the performance of ITs under combined effects of the factors that influence their performance. The standard only focuses on one effect at a time. However, in realistic operations conditions, the measuring instruments are known to be subjected to different effects simultaneously.

The point here is that, while standards are available and discussions about them are ongoing, efforts are concentrated in one part (AC). While the growth of DC power presents an exponential trend, the research on research on ITs for this network and its growth does not corollate. For now, let’s consider the two major DC power systems: Solar and Wind. As at the end of 2018, the total global installed wind energy capacity was almost 600 GW while in the past two decades it was 18GW [7].

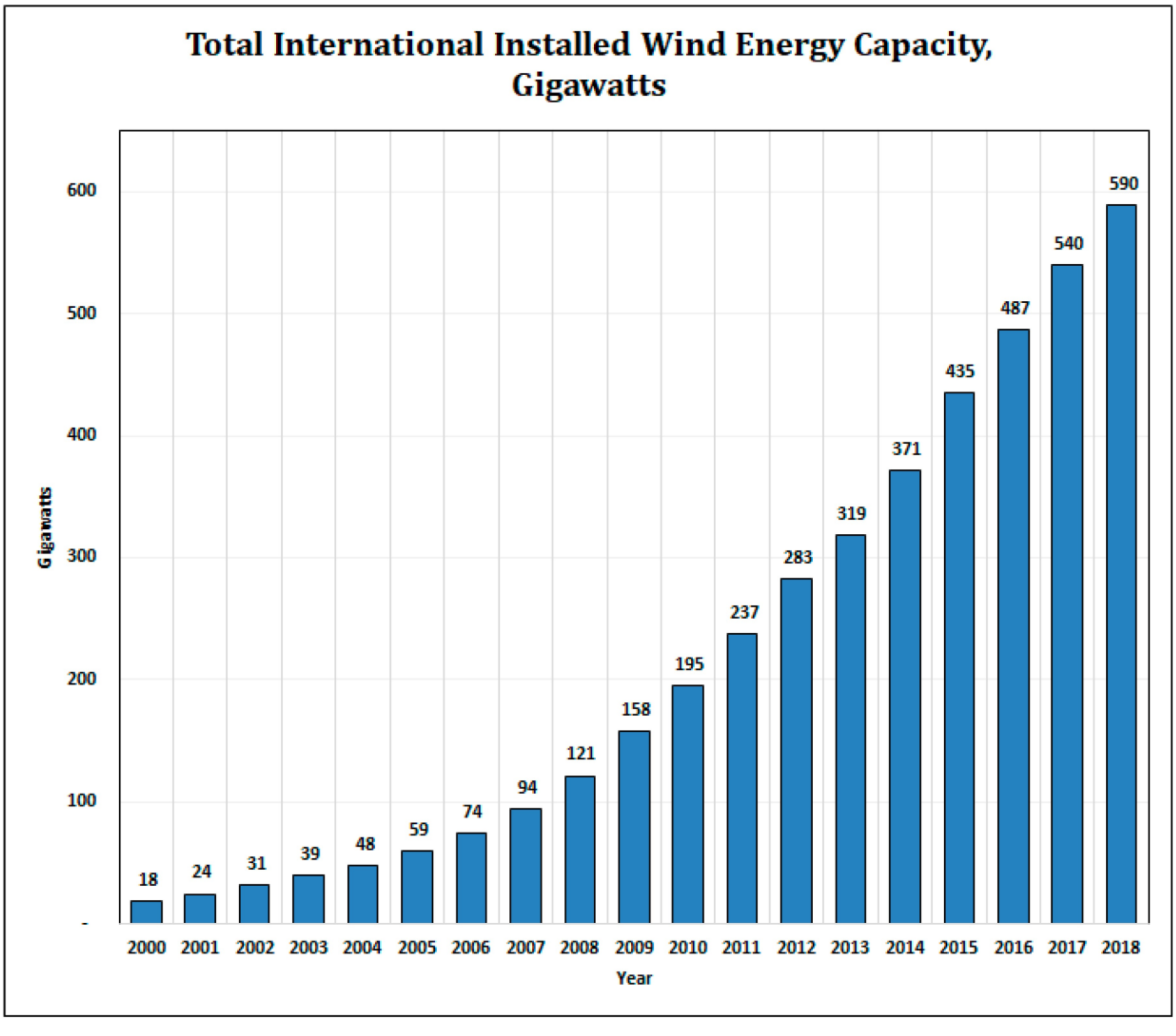


Figure 1.1 Exponential growth of Wind Power Capacity

As depicted in figure 1.2, a similar exponential growth trend is observed for solar power counterpart. Since 2000, it is estimated that the global cumulative solar photovoltaic capacity has been steadily increasing. Cumulative installed global solar PV capacity was 1,177 GW in 2022, with about 239 GW of additional PV capacity built in the same year [7].

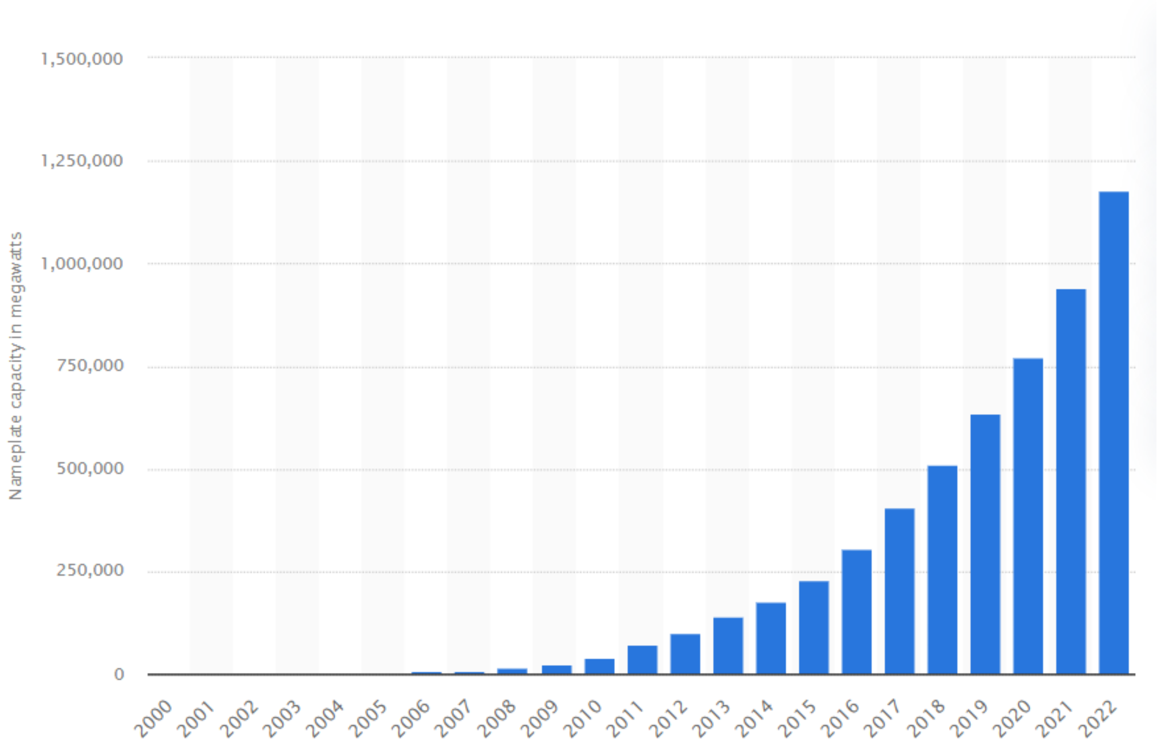


Figure 1.2 Exponential growth of Solar Power Capacity

What are the implications of such enormous growth of DC power systems in just two decades? Analysing this trend, it clear that the future will see even more rapid growth, and this will translate into severe disturbance of the transmission and distribution grid. With this anticipated growth of DC power networks, the importance of active research on measuring devices for protection and monitoring purpose is more important than before. In this thesis, focus will be placed on assessing the performance of Instrument transformers, specifically for DC power networks. The research will consider also the market outlook and projected future direction of these measuring instruments considering that DC power generation is steadily growing.

1.2 Problem Statement

The research horizon of instrument transformers is quite broad. However, a chunk of works presented in literature concerning instrument transformers are typically in relation to AC power networks. As such, several authors in literature have identified the major challenges confronting todays AC networks that calls for the swift and in-depth research on instrument transformers whose purpose is to measure the power system parameters for monitoring and protection in the mist of these challenges. For instance, the authors in [8] observed that the wide adoption of Renewable Energy Sources (RESs) across all voltage levels; the increasing emergence of electric vehicles in the low voltage (LV) level and the extensive installation of all types of energy meters are affecting network power quality, This has lead the massive revolution in the operation check of instrument transformers; both inductive type and the emerging Low-Power Instrument Transformers (LPITs) in the power network in recent years. Based on this observation, the authors assessed the accuracy of off-the-shelf inductive type current transformer under actual distorted conditions of the power network by collecting and injecting current from a power network into the IT for the analysis. The outcome revealed that despite its non-linear behaviour, the inductive instrument transformer showed satisfactory operation under the practical non-rated conditions of the network which the test subjected it to. Similarly, [6] investigated the combined effects of temperature and vibration on the accuracy and response of a voltage instrument transformer for medium voltage AC power network. Just like what [8]observed, the authors also noted the disturbance of the AC power network as a result of incorporating distributed renewable energy into the grid and the arrival of power electronic in the traditional equipment. Considering that the international standard on instrument transformers (EC 61869-X series) does not capture the effect of vibrations or combined effects of different factors on ITs performance, the authors developed and set-up a new methodology and test platform for the determining the frequency response and accuracy of medium voltage instrument transformer under the combined influence of vibrations and temperature. It was concluded from the test that the frequency response and accuracy of the voltage instrument transformer was greatly impacted by temperature than vibration at the fundamental 50Hz frequency.

It is evident that a lot of work has been done on the performance of instrument of instrument transformers especially the classical inductive type in relation to AC power networks as confirmed by [9]. Several other authors have investigated this topic while active research is still ongoing in the area. Despite the growing emergence of DC power networks, least research has been done to check the performance of instrument transformer in relation to them. Considering the high fatality of DC power and the fast growing of this technology, it has become paramount that the focus of research on instrument transformers for DC networks be given maximum attention. This research seeks to fill this gap in literature by assessing the performance of instrument transformers for DC power networks.

1.3 Aim and objectives.

The main aim of this this thesis is to effectively correlate the dynamics of instrument transformers for DC networks with the current market trends and future prospects of these measuring devices. This aim can be achieved with the following objectives.

I. To review in detail the all the available types of instrument transformers for DC networks and to present their working principle, topologies, drawbacks, current advances and recommended future research.
II. Assess the market trend of instrument transformers for DC networks and map the trends of the market dynamics of these measuring instruments with respective locations across the world.
III. To determine which DC network industry has the most potential to attract and dominate the use of instrument transformers for power quality measurement and metering.

1.4 Research Questions

In an attempt to determine suitable information for tackling the research and to achieve the goal and objectives of the research, several research questions are formulated, answers to whom are deemed to be the results of the study. These questions were formulated in relation to the goal of the thesis and expected outcomes. Below are the research questions for this research.

1. What are the different classifications of instrument transformers?
2. What are their working principles?
3. How are their circuit diagrams represented?
4. Which are the crucial performance parameters of instrument transformers and how does it influence choice?
5. How is the market of instrument transformers like? Who are the major players of the market? Is it competitive or dominated by few firms?
6. Where are they mostly used? Is it dominated in AC or DC networks?
7. Where does the future of Instrument transformers lie in term of DC networks? Will it be dominated in HVDC networks or LVDC systems.

1.5 Methodology Used

Selecting the best research technique is critical to the success of any research effort. Qualitative research, experimental research, survey-based research, quantitative research, and action research are all prevalent approaches. Because the focus in this study is not tied to a statistical examination of specific facts, a qualitative research technique appeared to be the most suitable method. The entire approach of the research revolves around an intensive literature review to find essential information to guide in making informed decision and predicting the future. This study is broadly divided into three main sections with each section featuring a unique approach to qualitative research. As shown in figure 1, a section will be dedicated to review of literature on instrument transformers. In this approach, the various types of DC instrument transformers and their circuitry representations will be presented. In addition, critical performance parameters are that crucial for the selection and use of any type of instrument transformer for measurement will be determined and collective called "Technological/Technical Requirements" of instrument transformers.

In the second section of the research, again through qualitative research approach, the market dynamics of instrument transformers will be examined. The scope of this research covers only DC networks hence the market analysis of these measuring instruments will be limited to the DC network industry. As part of this approach to understand the outlook of the market: evolution, trends and prospects, various companies in the manufacture and sale of instrument transformers will be contacted for information regarding the new developments in the market. Opinions of experienced personnel engaged in the sale of these equipment will be sought, analysed and correlated to data from literature to help map effectively the data from literature with what is happening exactly on the field for proper decision making. A group of matrixes describing the dynamics of the market of instrument transformers will be identified and collective called the "Economic Requirements".

In the third section of the thesis, all the major and growing DC power technologies is assessed through a thorough investigation of literature. The aim of this is to categorise the essential factors such as growth rate, regulation, levelized cost of energy, vulnerability to faults and other crucial aspects that may lead to steady increase in demand for measuring instruments such as instrument transformers within the industry. These factors will be collectively called "Network Requirements".

The three categories of requirements identified from each of the sections, that's: Technological/Technical Requirements, Economic requirements and Network requires will serve as an input into a decision-making framework called Quality Function Deployment (QFD)/Multi Criteria Decision Making techniques (MCDM). Owing to the fact that each parameter within the set of requirements identified has varied degree to which it influences the choice of instrument transformers, they need to be arranged in order of relevance. To assess the relative importance of each parameter within the Technological/Technical Requirements, the Analytical Hierarchy Process (AHP) tool will be used to assign weights to each of the parameters before it is used in the QFD/MCDM framework. Analysing these three set of data in the framework, a DC Network will be found to be base/ideal solution. This network then becomes the one with the most potential to attract most of instrument transformers use in the future considering all the requirements. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) will then be employed to arrange all the other considered DC networks in order of decreasing potential of being the future direction for instrument transformers. Considering that, changes in the industry, technologies, policies etc can influence the future direction of their measuring instruments, a sensitivity analysis will be performed taking into consideration crucial changes that could occur and factor it back into the framework to determine the ideal solution in the case of unforeseen changes in the industry.

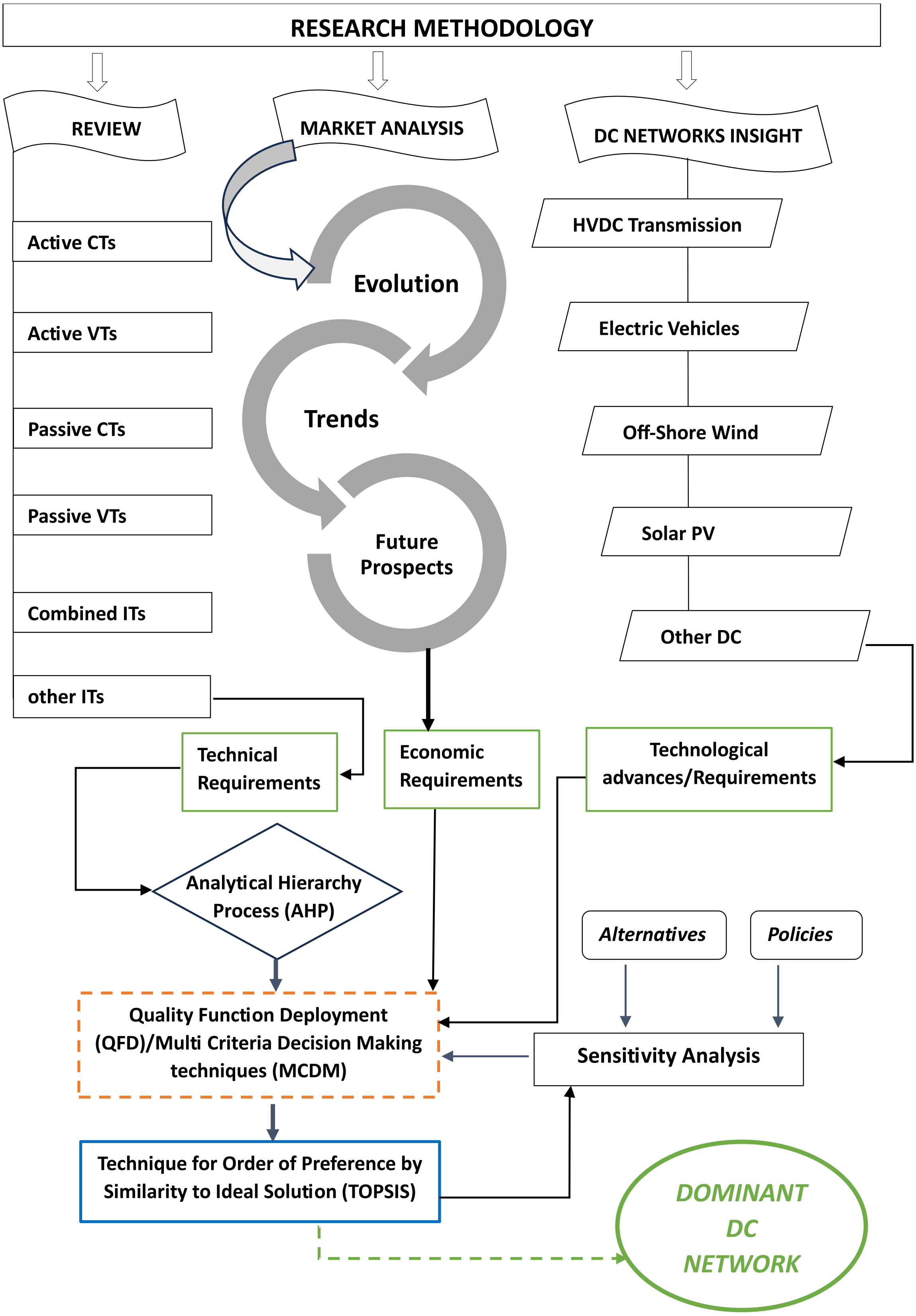


Figure 1.3 Research Methodology

1.6 Work organisation

This thesis is organised in four chapters. The first chapter is the introductory chapter which provides a general overview of the research. Details in this chapter includes the problem statement, research questions and methodology used. The second chapter of the study is deals with the technical aspects of instrument transformers. It consists of detailed analysis of the topologies, performance matrixes and advances in design. It also features as comprehensive comparison of various technologies among one another against critical performance indexes. The third chapter of the work involving market analysis of instrument transformers. While the second chapter is concerned technological and technical aspects of instrument transformers, this chapter focuses on the business aspect of these measuring devices. due to the dynamic nature of markets, financial tools will be used for the analysis. Following the market analysis, another chapter maybe included whose content will consist of analysis of DC power networks: HVDC transmission, offshore wind, solar PV, electric vehicles and others. In this chapter, a decision-making framework will be established to determine the direction of instrument transformers in DC networks. As explained in detailed above, the following tools will be used: Quality Function Deployment (QFD)/Multi Criteria Decision Making techniques (MCDM), Analytical Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). The final chapter is dedicated to the discussion of the obtained results, conclusions and recommendations for further research.

CHAPTER 2

CLASSIFICATION OF DC INSTRUMENT TRANSFORMERS: WORKING PRINCIPLES AND TOPOLOGIES

This chapter will be based on the different kinds of technologies and operation principles of instrument transformers, their topologies and/or circuit diagrams. It will be focused on an exhaustive discussion on both current and voltage transformers used in DC power networks placing also emphasis on the current state and advances of these technologies. Out of this review, the section will identify key performance parameters of instrument transformers in general. Next, all the available technologies will be compared against each identified key performance parameters.

2.1 Classification of DC Instrument Transformers

The classification of the types of instrument transformers varies quite significantly depending on the lens from which you are viewing from. Since there's no clear classification of DC instrument transformers in literature, this section of the thesis seeks to broadly categorize DC ITs based on different factors. In terms of the electrical quantity being measured, ITs can be broadly grouped into voltage transformers (CTs) and current transformers (VTs). Based on the operation range of voltages, they can be classified as low voltage ITs (LV ITs), medium voltage ITs (MV ITs) and high voltage ITs (HV ITs). Also, based on the need for external driving circuitry for operation, DC instrument transformers can be said to either passive or active.

When it comes to the technological principle based on which the transformation is done, instruments transformers are categorized herein as, Combined and Resistive voltage dividers instrument transformers fiber Optical current sensors (FOCS), Hall Effect Sensors, Pockels effect-based instrument transformer and shunt resistor current transformers. The list of classification based on technology is inexhaustive as several technologies are constantly emerging and researchers are combining multiple technologies. According to Lesniewska, (2022), aside the well-known inductive instrument transformers which is not covered in this thesis and those already mentioned here, several other designs have emerged such as instrument transformers that uses the Bluetooth technology and microwaves. These solutions are however not widely accepted and used because they are less reliable and accurate as compared to the inductive type of instrument transformers (out of scope for this thesis). Some authors simply classify the instrument transformers into conventional and non-conventional where the conventional ones are the inductive voltage and current transformers (VT and CT) while the non-conventional ones also referred to as low power instrument transformers (LPITs) [10] are the ones mostly used for DC networks. From the perspective of purpose of use, ITs are divided into protection or billing. In this section, a compressive classification of the IT types is provided considering a combination of all the various ways in which they are categorized in literature. Figure 2.1 below presents the flowchart of the classification.

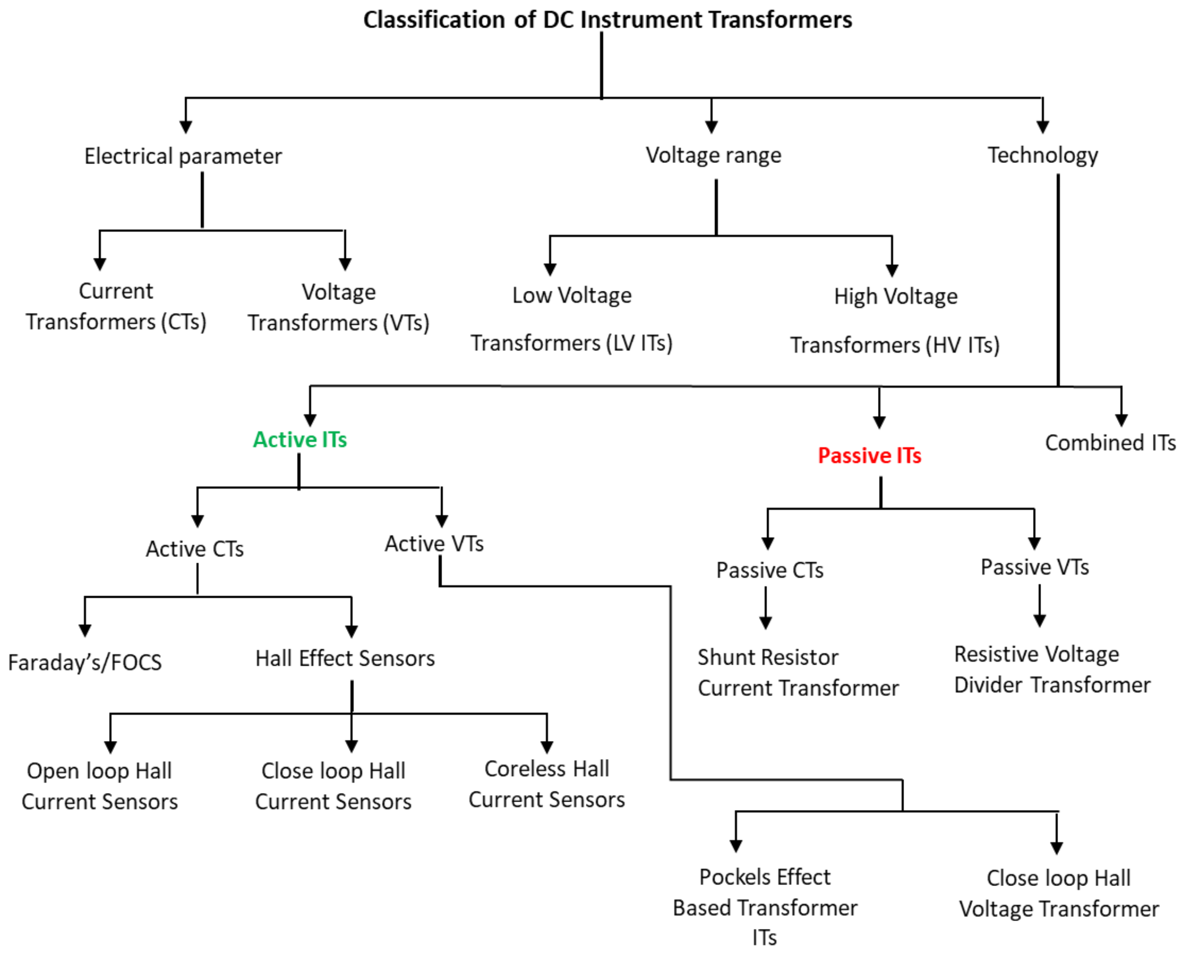


Figure 2.1 Classification of Instrument Transformers

2.2 Electronic Instrument Transformers

Unlike the analogue output produced in the case of conventional, electronic instrument transformer being a non-conventional one, a digital output representing the magnitude of the current or voltage being measured is provided. The realizing of electronic instrument transformers is due to the presence of electronic components in the measurement setup. Electronic instrument transformers are based on several principles including optical (Pockel and Faradays effect for voltage and current measurement respective) [11], Rogowski coil [12], Hall effect [13], and coaxial capacitors/capacitive dividers [14]. Based on the type of transducer used, the sensor measures either voltage or current by producing an output proportional to the quantity of interest. This quantity is then sent by a secondary converter (SC) to a device called merging unit (MU), whose output is digital and provides time coherent power to substation measurement and equipment providing protection functions [11]. According to [12], while electronic voltage transformers (EVTs) and electronic current transformers (ECTs) are small in size, they have attained remarkable performance. The ECTs and EVTs use digital capabilities to communicate with protection relays and bay control units via process level LAN. The current and voltage signals generated are delivered as digital signals. Due to their capabilities, electronic instrument transformers are the forefront of the digitalization process of substations of the electric grid. Over the past few years, they have been given attention based on the numerous other advantages they offer aside their digital operations. Electronic instrument transformers provide the following benefits over traditional instrument transformers: broad range of measurement, no core saturation, lower footprint, less weight and ease of digitalization [13], [15]. These advantages among other make the electronic instrument transformer a vital component in the development of smart grids and establishment of intelligent/digital substations.

2.3 Active Current Transformers (CTs)

From figure 2.1 the classification of instrument transformers under the category of Active CTs are fiber optic current sensors based on Faraday's principle, open loop hall current sensors, closed loop Hall current sensors, and coreless Hall current sensors. In this section, these instruments will be discussed.

2.3.1 Fiber Optic Current Sensor (FOCS)

Optical instrument transformers are realised using a combination of optical fibres in conjunction with other external circuitry to sense direct currents. It is known to provide a lot of advantages compared to other current sensing devices such the Rogowski coil. In this section, a dip dive into its structure, operation principle, representation, innovative redesigns by researchers, and the major advantages it offers will be discussed.

Description of optical fiber

An optical fiber is a circular dielectric waveguide with two primary components made of plastic or glass: the core and the cladding. It also contains surrounding coating that is utilized to safeguard the optical fiber and is often comprised of materials such as acrylate or polyimide [16]. In most cases, the core is constructed of glass. The core is characterized by an index of refraction is n_1 and radius a. The cladding surrounds the core, as seen in figure 2.2. Even while light will travel along the fiber core without the cladding layer, the cladding serves certain important roles. The cladding layer is comprised of a dielectric material with a refractive index of n_2. Cladding is commonly constructed of glass or plastic. The cladding serves numerous tasks, including reducing light loss from the core to air, scattering loss at the surface, and so on [17].

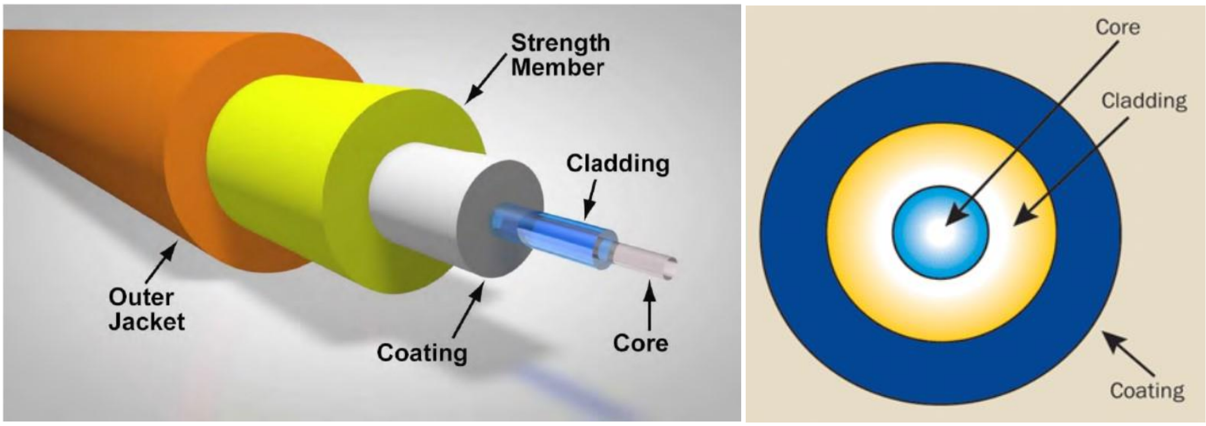


Figure 2.2 Structure of Optical Fiber

The optical sensing principle

Optical sensing is a method of measurement or acquiring information of a measurand by the analysis of the characteristics of light. Typically, fiber optic sensor obtains the value of a measurand by the transformation of a change in the magnitude of a physical parameter usually light waves into a corresponding change in the magnitude of second quantifiable parameter; the measurand. This type of sensing technology is noncontact technique that has long been used in the field of instrumentation and sensors. The measurements take advantage of light's wave nature, in which the qualities of wave amplitude, polarization, frequency, and phase are directly linked to the attribute desired to be measured. The detection of the energy produced by the light field as a result of the presence of the measurand is the first step in a measurement. The measured energy of the light field is then linked to the measurand through its physical attributes, by understanding how light interacts with the environment of the measurand and how the environment modifies the wave properties. The measurement is especially designed to have the light interact with the environment with a specified sensitivity[18], which means that a characteristic of the light, such as polarization or phase, will change in a predictable way as a result of the interaction in the environment. [19].

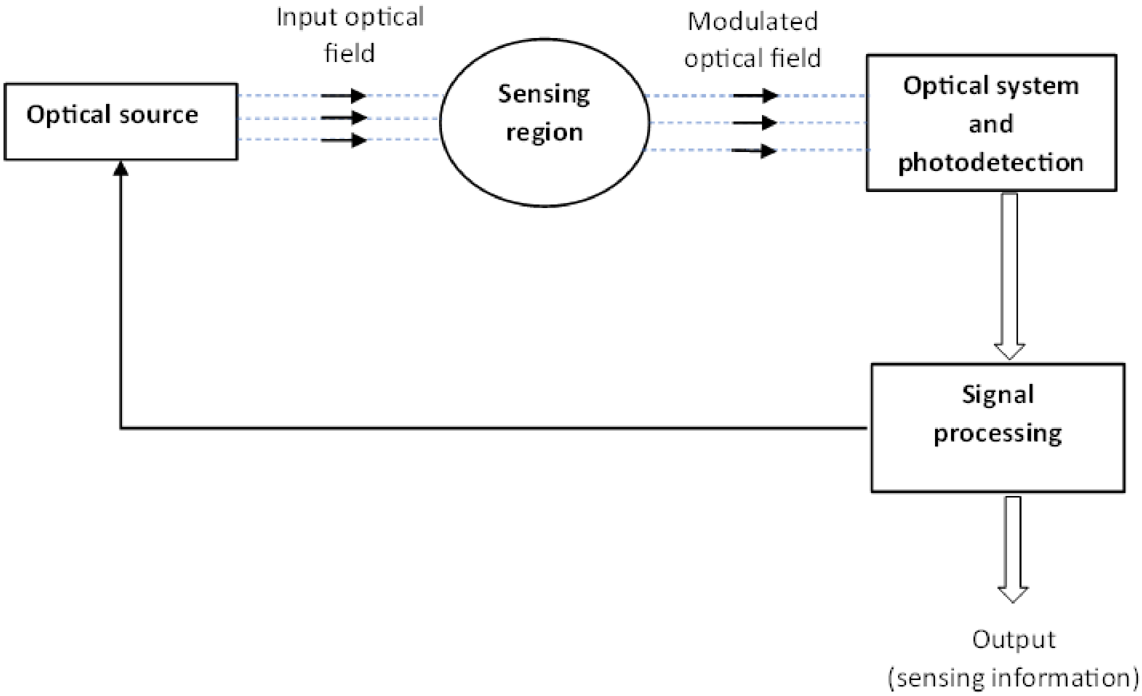


Figure 2.3 Optical Sensing Principle

As mentioned earlier, the measurement is possible by exploiting and modifying the various properties of light waves. Depending on the nature or properties of the measurand, one or more of the light wave properties is modified and correlated to the magnitude of the measurand. Intensity, phase, polarization, and wavelength of the light are typically the information being modified in the presence of the quantity to be measured. For the scope of this thesis, only the polarization and phase will be considered because these are the two parameters of the light wave that are utilized in the presence of electromagnetic field generated by current flowing through a conductor or a busbar to measure the current. Table 2.1 however highlights the various properties of light modified for different purposes.

Table 2.1 Light wave properties modified for different measurement purposes.

Types Information	Physical Mechanism	Detection Circuitry	Typical Examples
Intensity	Modulation of light by emission, absorption, or refractive index change	Analog/digital	Pressure, displacement, refractive index, temperature, liquid level
Phase	Interference between measurand-induced signal and reference in an interferometer	Fringe counting, intra-fringe detection	Hydrophone, gyroscope, magnetometer, pressure
Polarization	Change in gyratory optical tensor	Polarization analyser and amplitude comparison	Magnet field, large current measurement, e.g. in a busbar
Wavelength	Special dependent variation of absorption and emission	Amplitude comparison at two fixed wavelengths	Temperature measurement

FOCS Operation Principle

FOCS is a class of highly accurate fiber optical sensors for high current measurement, both alternating and direct currents (AC and DC) without encountering the problems of non-linearity and magnetic core saturation as experienced by current transformers employing iron for magnetic flux linkage in their operation. The Fiber-Optic Current Sensor (FOCS) which is a non-conventional instrument transformer (NCIT) is based on the Faraday's effect for its principle of operation[20].

As previously stated, the FOCS system designed for use in high-voltage substations uses the Faraday effect to measure current employing a closed loop optical system using an optical fiber, that which has been described in the preceding section. In place of the complex and large sensor head seen in traditional transducers, a simple loop of optical fiber is coiled once or multiple times around the busbar. When polarized light waves are subjected to a magnetic field produced by the current flowing in the conductor/busbar, the Faraday effect is observed. The waves therefore acquire a phase difference as a result of the field [21]. In the FOCS measurement system, both left and the right circularly polarized light waves propagates through the looped coil of the sensing fiber wound around the conductor. The differential magneto-optic phase shift between the two polarized light waves; left and right circularly polarized travelling through the optical fiber is introduced because of the magnetic field of the current carrying conductor. According to Zhang et al., (2015) the refractive index of a crystal (fiber optic) will change in the presence of an electric field or voltage, hence when two eigen light waves are emitted or propagates through the crystal, they will produce birefringent phase delay. They two waves are reflected with their polarization orientation is being switched at the fiber's end before retracing their optical journey to the sensor electronics. When a direct current flows, a phase difference accumulates that is proportional to the closed loop integral of the magnetic field over the length of the sensing fiber[23] (refer to equation 2.1 and 2.2). The gyroscopic function of the fiber-optic detects the magneto-optic phase shift. The differential phase shift is a direct and very accurate measure of current (ABB, 2023). The FOCS achieves its great performance by employing an interferometric approach based on non-reciprocal phase modulation to determine the precise values of the primary current. (Xu et al., 2019). As shown in figure 2.4 below, the FOCS consist of a birefringence modulator whose function is to introduce birefringence in the optical path (change in refractive index for light polarized in different directions) for closed loop detection. The formula for the current and resulting phase shift are presented below.

$$\Delta\emptyset_F = 4VI \tag{2.1}$$

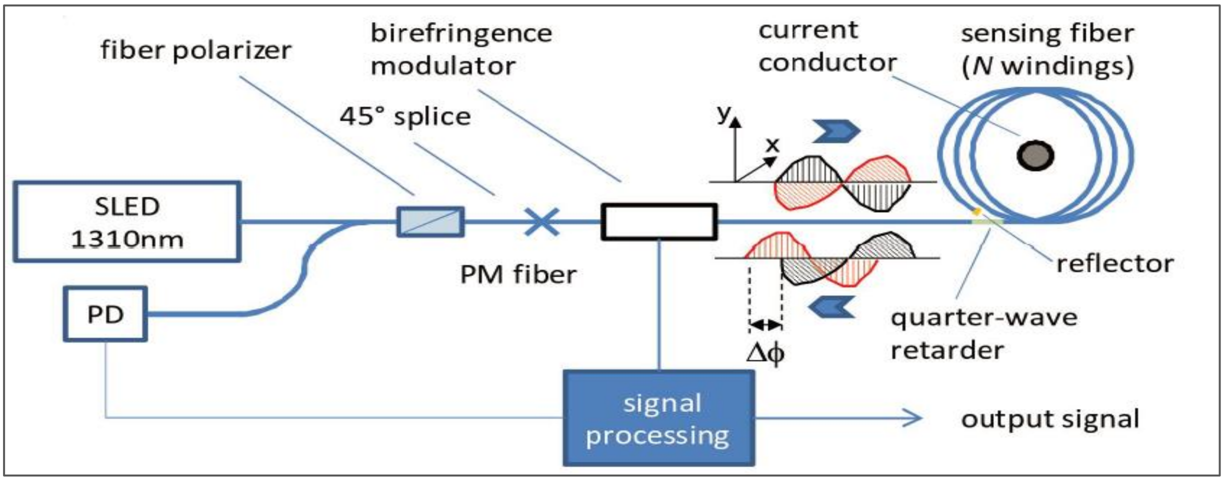
$$I = \oint \vec{H} d\vec{S} \tag{2.2}$$

Where V is the material constant (Verdot constant)

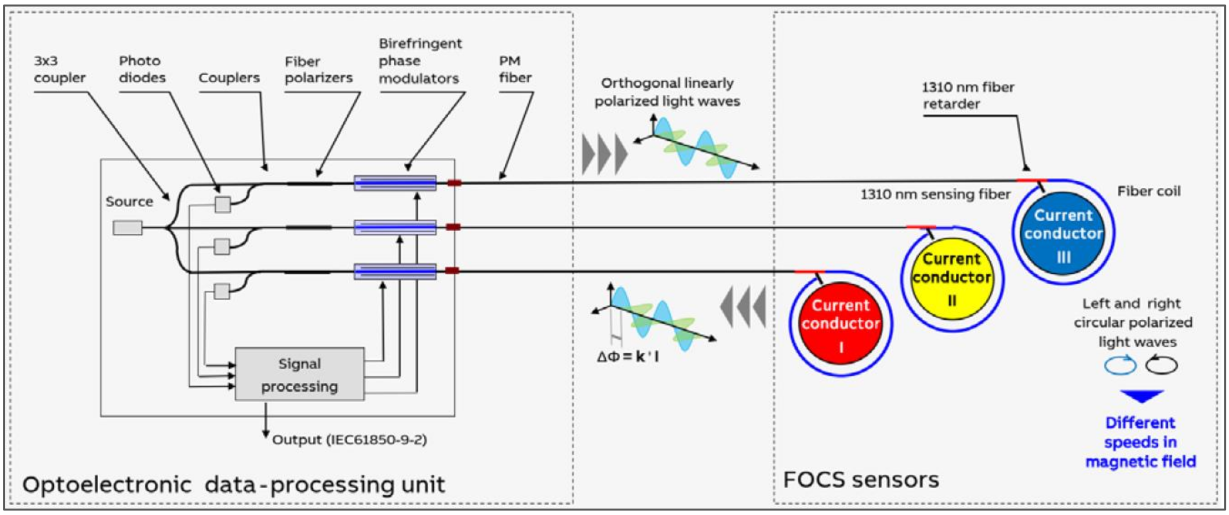
H is the magnetic field

S is the length of the sensing fiber.

$\Delta\emptyset_F$ is the magneto-optic phase shift.



(A)



(B)

Figure 2.4 Fiber optic current sensor scheme (a) Single phase representation (b) 3-phase representation

Researchers have it that Fiber-optic current sensors (FOCS) have matured to the point that they are being used in high-voltage substations for large current measurements and contribution towards the digitalization of substations[20]. The first FOCS configuration (reflective fiber coil) research was conducted in the early 1990s, and much work has been done since then on the introduction of improvements and distinctive modifications of this technology, such as. In 2005, DC FOCS for industrial current measuring was established. In the early 2010s, an AC FOCS pilot project was implemented, which included 3-phase AC FOCS incorporated into a 420kV Disconnecting Circuit Breaker (DCB). Also, in 2014, a standalone model of the system was introduced. It has been estimated that over 4000 of Fiber optical current sensors from various manufacturers have been installed and deployed in the industry globally [20], [23]. ABB, one of the leading manufacturers, installers and researchers of FOCS presents its recent model of a FOCS as depicted in figure 2.5.

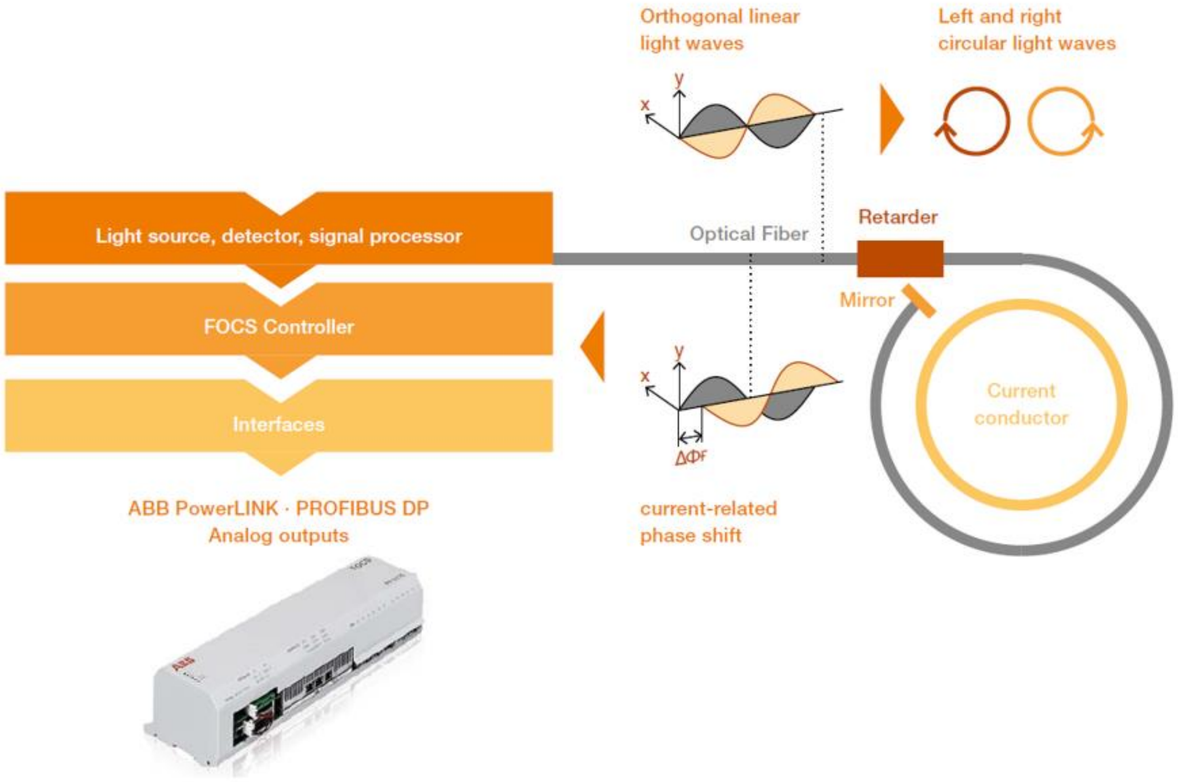


Figure 2.5 ABB Fiber Optic Current Sensor

The FOCS offers great precision, strong scale factor stability, and a linear response over a wide magneto optic phase shift range. Optionally, special connectors for fiber-optic can be used to enable the installation and interchange of optoelectronic data processing units. Furthermore, the sensor has an inherent capability for measuring DC offset current, is nonconductive and lightweight, covers a wide current range with only one sensing coil, environmentally friendly, and safe because there is no risk of shocks or explosion [23].

Hall Effect Instrument Transformer

The hall effect current transformer is an instrument transformer realized using the Hall effect principle which exploits the magnetic properties of a current carrying conductor to measure the voltage across the conductor or the current flowing through it. The general Hall effect principle, closed loop, open loop and coreless configuration of instrument transformers based on the Hall effect are discussed in this section.

The Hall Effect

Edwin Hall, a scientist, invented the Hall-effect concept. In 1879, he found that by introducing a conductor or semiconductor with current flowing in one direction in a straight line and perpendicular to a magnetic field, a voltage at right angles to the current channel could be detected. Hall's hypothesis related magnetic force acting on the current (flowing charges) to the accumulation of charged particles at one side of the wire[24]. When an external electric current travels through a conductor in a magnetic field produced by either permanent magnet or current carrying conductor, the magnetic field applies a transverse force to the moving charge carriers, pushing them to one side of the conductor. This is especially noticeable in conductors that are thin and flat. At equilibrium, charge accumulation on the conductor's sides will balance this magnetic force, resulting in a detectable voltage between the two sides of the conductor. The Hall effect is the existence of this detectable transverse voltage[25]. Figure 2.6 below is the illustration of the hall effect principle.

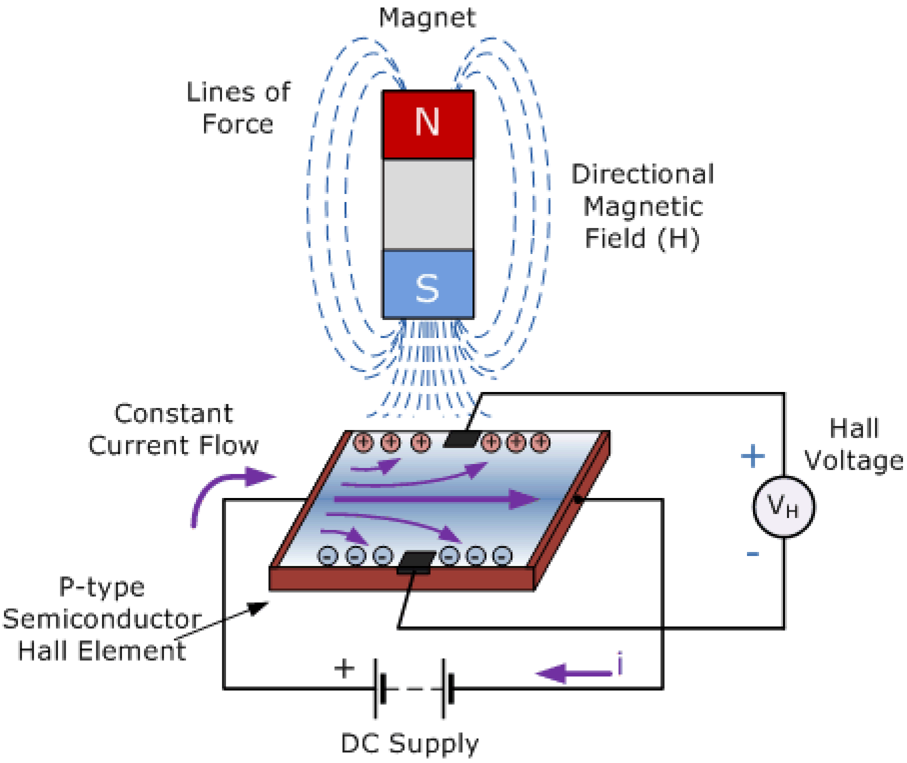


Figure 2.6: Hall Effect Principle

It is the Lorentz force causes the accumulation of charges on the surface of the plate (positive charge on one face and negative charges on the opposite side of the plate). The charge accumulation will continue until the electric field of charges, arising from the magnetic field counterbalance with the magnetic component of the Lorentz force [26]. The transverse voltage (Hall voltage) originates from the moving charge carrier’s magnetic force.

The magnetic force is given as

$$F_m = eV_dB \tag{2.3}$$

Where V_d is the drift velocity of the charge carriers as shown in figure 2.7.

The current when expressed in terms of the drift velocity is given as

$$I = neAV_d \tag{2.4}$$

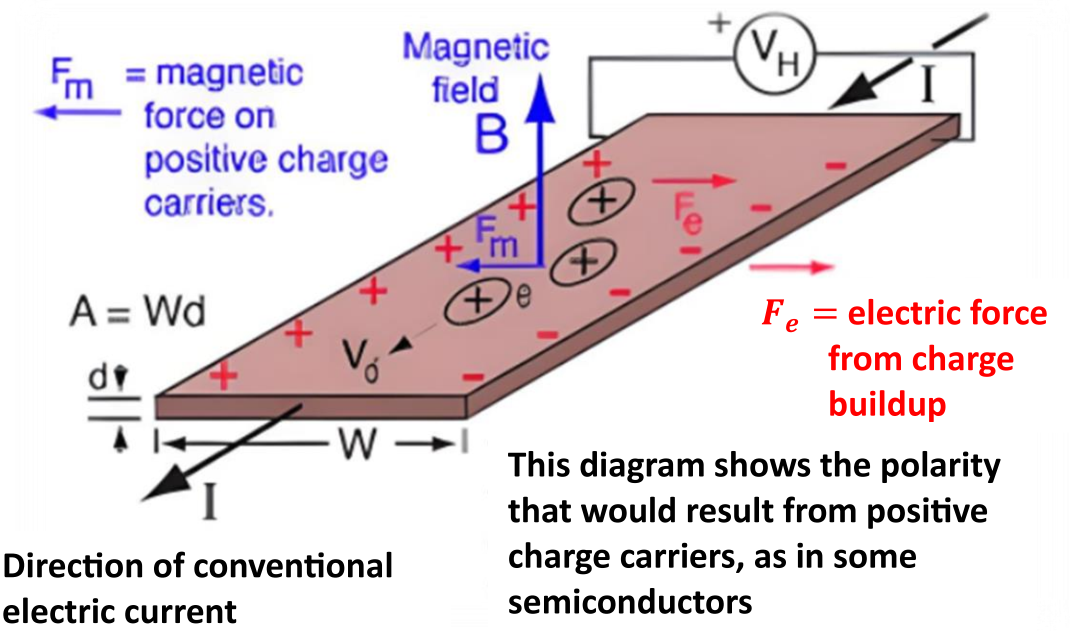
Where n is the density of charge carriers

$A = Wd$ is the area of thin flat conductor.

e is the electron charge.

From eq. 2.4 the drift velocity of the electrons in the conductor is computed as;

$$V_d = \frac{I}{neA} \tag{2.5}$$



Direction of conventional electric current

This diagram shows the polarity that would result from positive charge carriers, as in some semiconductors

Figure 2.7 Detailed Hall Effect Principle

As shown in figure 2.7, at equilibrium, the magnetic force on positive charge carries F_m is equal to the electric force from the charge buildup and its expressed as.

$$F_m = F_e = V_He/W \tag{2.6}$$

By substitution,

$$\frac{eIB}{neWd} = \frac{V_He}{W} \tag{2.7}$$

By definition, the hall voltage V_H which is directly proportional to the magnetic field and current is.

$$V_H = \frac{IB}{ned} \tag{2.8}$$

From the equation above, the Hall voltage is directly dependent on the magnetic field. It also inversely proportional to the thickness of the conductor. Therefore, to have a higher value of the Hall voltage, the hall element must be as small as possible. Similarly, the concentration of charged carriers n in the material should be kept minimal to ensure a higher Hall voltage. For this reason, the material used for the manufacture of Hall elements are carefully selected giving priority to factors including those mentioned above. Research in this area is quite matured and the materials used have undergone significant modification over the past decades. In the realm of commercial Hall sensors, the predominant sensing materials encompass a variety of elements, with notable examples being Indium Antimonide (InSb), Indium Arsenide (InAs), Gallium Arsenide (GaAs), Germanium (Ge), and Silicon (Si). Among these, InSb and GaAs stand out for exhibiting the most optimal performance characteristics[27], [28], [29].

Hall-Based Current Transformers

The electronic current transformer based on the Hall effect is composed of three main parts: the current carrying conductor whose voltage or current is to be transformed, a hall probe whose operation principle has been elaborated above and an analogue front-end (AFE) composed of electronic devices for further signal processing[29], [30]. Figure 2.8 is the generic schematic of hall based electronic transformer.

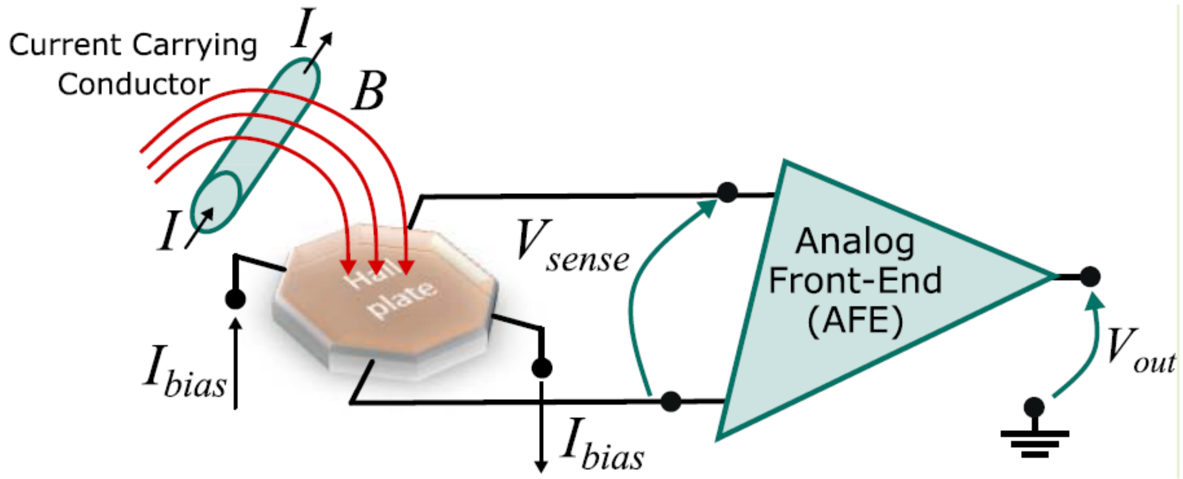
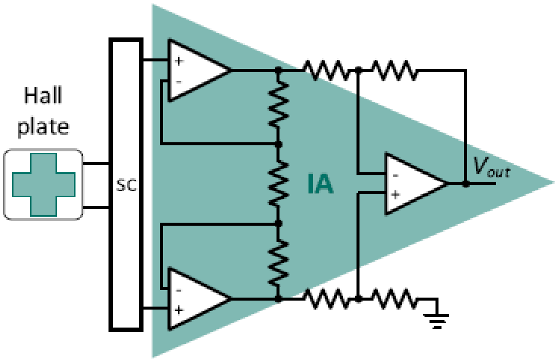
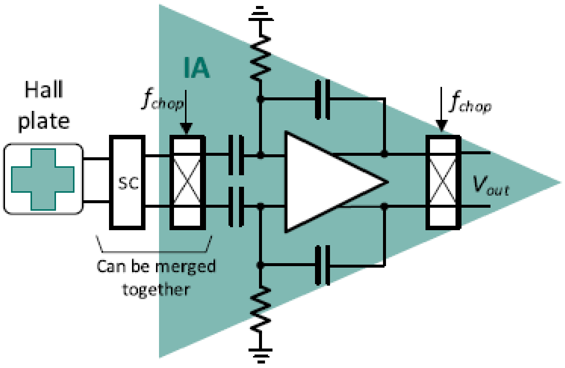


Figure 2.8 Generic schematic of a Hall-based current transformer.

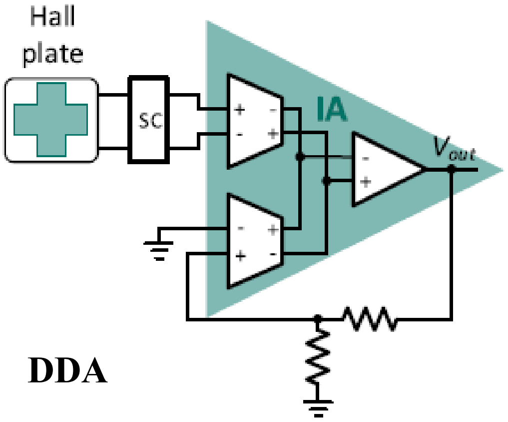
As reported in [29], the pivotal significance of the analogue front-end (AFE) in the scheme of the electronic current transformer arises from its direct influence on the sensor's performance, hence the need to adapt to the distinctive characteristics of the Hall plate. Generally, the AFE is composed of circuitry for detecting the Hall voltage and biasing the Hall plate. The AFE is mandated to meet various criteria. These include the imperative need for a high differential gain, typically exceeding ×100, contingent upon the specific application and technological context; a high input impedance to prevent current draining from the sense contacts and an insignificant offset in relation to the inherent one displayed by the Hall plate. By the adoption instrumentation amplifier (IA), the initial two requirements can be fulfilled. The common configuration of the IA implemented in this type of electronic transformer include the three operational amplifiers (thee-op amp) topology, the differential-difference amplifier (DDA) or the capacitively-coupled instrumentation amplifier (CCIA). Figure 2.9 presents the outline of these architectures. However, detailed presentation of the configurations can be found at [30], [31], [32], [33], [34]



3 op-amp



CCIA



DDA

Figure 2.9 Different instrumentation amplifier architecture for Hall-based electronic instrument transformer

Based on the design circuitry architecture, hall effect current transformers can be realized as either open loop, closed loop or coreless. While they both operate on the hall effect principle, there can be quite significant differences between the two configurations in terms of their performance and application.

2.3.2 Open Loop Hall Current Transformer

A current sensor based on the Open Loop Hall Effect comprises three key elements: a toroid shaped iron core with high permeability, a Hall sensing element, and electronics for signal processing. The structure of this sensor is illustrated in Figure 2.10. The toroid core, equipped with effective permeability (μ_r), enhances the magnetic flux generated by the primary current-carrying conductor. Positioned in the core's air gap, the Hall element detects the flux. To ensure a reliable output signal, amplification is essential for effective signal processing [35], [36].

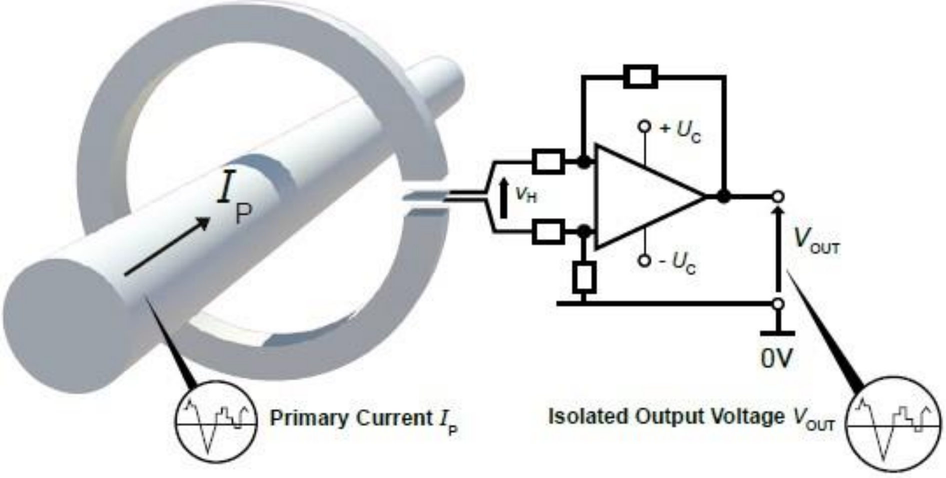


Figure 2.10 Configuration of open loop Hall effect current transformer

When a current-carrying conductor is considered for current measurement, it produces magnetic flux which are concentric in nature. If we assume that the primary current conductor is infinitely long, then the strength of the magnetic field can be approximated as follows.

$$B = \frac{\mu_0 I}{2\pi r} \tag{2.9}$$

where μ_0 represents vacuum permeability, I is the current and r is the radius of the current conductor.

Using the Biot-Savart Law for a long straight cable presented in eq. 2.9 above, the measured current can be calculated accurately. Usually, the magnitude of the voltage signal detected by the Hall sensor is very small. To enhance the signal from the Hall element, the current conductor can be wound around the ferrous core N times. This increases the magnetic field produced by the primary current and hence the current measured. In an open-loop configuration, the Hall element output is straightforwardly amplified, and the resulting voltage represents the measured current, scaled accordingly[37]. This modifies the Biot-Savart Law as:

$$B = \frac{\mu_0 N I}{2\pi r} \tag{2.10}$$

2.3.3 Closed Loop Hall Current Transformer

This transformation is achieved through a transistor circuit, and the resulting current is directed into a secondary winding. The main objective of the closed-loop hall effect current transformer is to compensate for the magnetic flux generated by the primary winding. By converting the Hall voltage to a current and introducing it into the secondary winding, the closed-loop system effectively compensates the flux. In a typical closed-loop Hall effect current transformer, the fundamental components include a Hall effect sensor coupled with an amplifier[38]. This amplifier is responsible for driving a transistor, which acts as the switch for controlling the flow of secondary current from the power supply. The secondary current pass-through wire turns coiled around a magnetic concentrator, also known as the core. In contrast to an open-loop configuration, where there is no secondary winding, the closed-loop system transforms the Hall voltage into a current. resets the magnetization state in the core. This reset is crucial for mitigating the impact of the primary measured current on the concentrator material. As a result, this process helps reduce the offset of the Hall voltage, enhancing the accuracy and reliability of the current measurement in the transformer system [39]. The block diagram representation of this type of transformer is presented in figure 2.11.

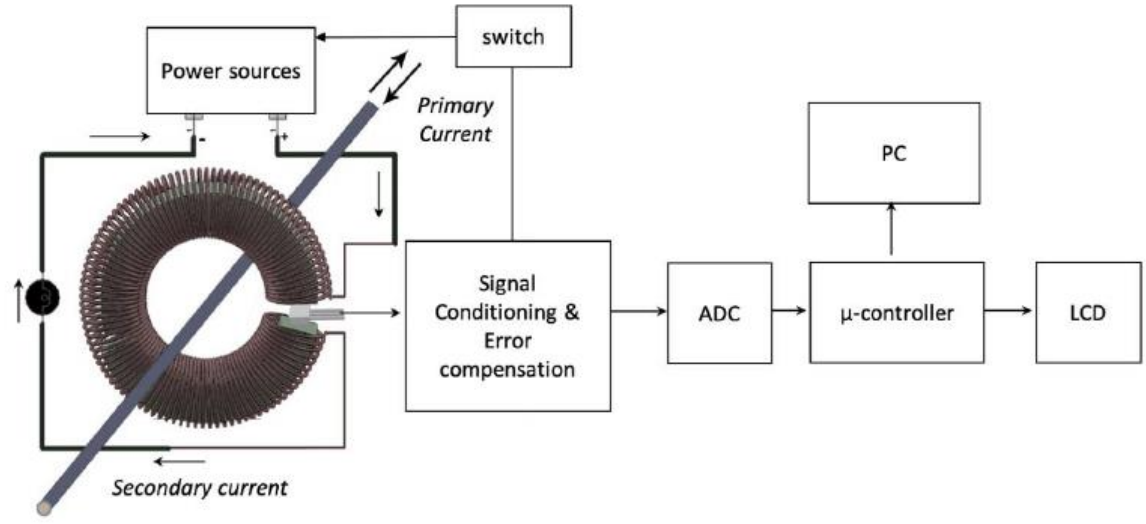


__Figure 2.11 Block diagram of closed loop hall effect current transfer__

The voltage generated by the Hall sensor is directly proportional to both the magnetic flux and the primary current. The output voltage undergoes amplification through an operational amplifier and is then fed into a push-pull transistor circuit, where it is transformed into a secondary current. This process is intended to introduce a second magnetic flux to effectively counteract the primary magnetic flux within the core. For this reason, this configuration is usually called the Hall effect compensated transducers or zero flux sensors [38]. The secondary current produced is symmetric to the primary current. Typically, the secondary winding consists of approximately 1000 turns at minimum [37], [40]. To measure the compensation current accurately, a measuring resistor (also known as the load or burden resistor), denoted as R_M, is connected in series with the secondary coil. As a result, the voltage waveform across this measuring resistor serves as a true representation of the primary current. This arrangement allows for precise measurement of the compensation current, contributing to the overall accuracy and reliability of the transducer or sensor system [41].

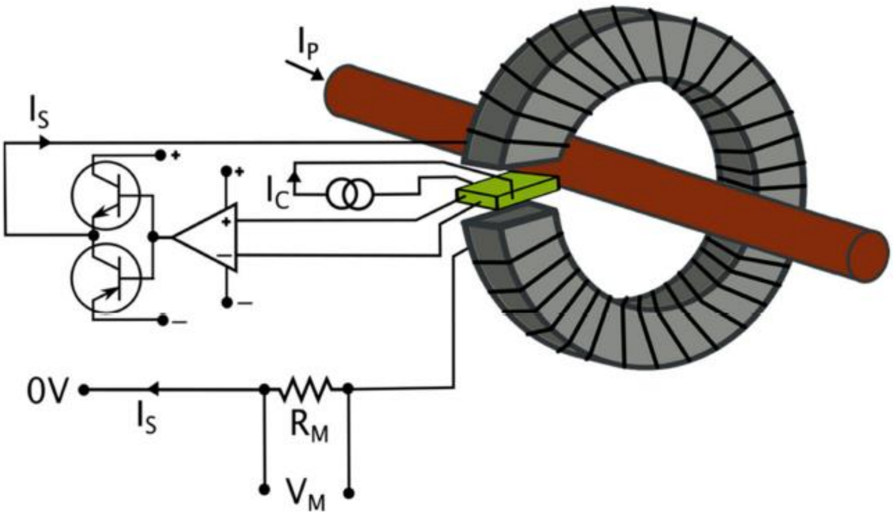


Figure 2.12 Circuit diagram of closed loop hall effect current transformer

The compensation of the magnetic flux generated by the primary current is possible because the magnetic flux produced by the secondary winding (compensation coil) is opposite to the magnetic flux generated by the primary current, hence the magnetic flux of the primary is compensated while at the same time the output of the hall voltage being reduced gradually. When magnetic flux of both the secondary and primary are balanced, the compensation current no longer increases. This phenomenon is called the principle of magnetic balance detection. It is expressed mathematically as[26], [40]:

$$N_p \times I_p = N_s \times I_s \tag{2.11}$$

According to [40], the air gap's magnetic flux density should not exceed the maximum flux density detectable by the sensor. The calculation of magnetic flux density is determined by the following expression:

$$B = \frac{4.\pi.10^{-7}.\mu_i.N_p I_p}{I_m + I_g.\mu_i} \tag{2.12}$$

where B is the magnetic flux density in tesla (T); $N_p I_p$ is the primary circuit mmf; $\mu_i$is the initial permeability of the core;); I_g is the length of air gap (m); I_m is the mean length of core in meters (m)

However, the core's effective permeability can be calculated as:

$$\mu_e = \frac{B.I_m}{N_p I_p} \tag{2.13}$$

For calculating the magnitude of the secondary current supplied to the compensator winding, the following formular is used.

$$I_S = \frac{V_H.G}{R_M.Z_S} \tag{2.14}$$

Where I_S is the secondary current, V_H is the Hall voltage, G is the gain of the operational amplifier, R_M is the measuring resistance and Z_S is the secondary windings' impedance.

Finally, the voltage measured by the closed loop hall effect current transformer can be computed as follows:

$$V_L = I_S \times R_M = \frac{V_H.G}{R_L.Z_S}.R_M \tag{2.15}$$

A closed-loop configuration of Hall effect sensor is an optimization of the signal conditioning to enhance the capability of the Hall effect sensor in handling the deviation error appears in the electrical current measurement.

2.3.4 Coreless Hall Current Transformer

As the name suggests, the coreless Hall effect current transformer is a type of transformer based on the hall effect principle whose configurations does not include a magnetic iron core. The main disadvantage of the open and closed loop hall based current transformer is the saturation of the core as emphasised by several authors in literature[42], [43]. To attain substantial current measurements without using an iron core structure, hall sensors are usually organized into a circular array when developing this novel electronic current transformer (ECT). Nevertheless, this ECT, equipped with a circular array of hall sensors, typically faces challenges in striking a balance between the accuracy of the measurement and the number of hall sensors used. Works has been in presented in literature with 3 hall sensors, 4 hall sensors[44], [45], [46], 6 hall sensors [47] and even 8 hall sensors [48]. Figure 2.13 shows some configurations of coreless hall.

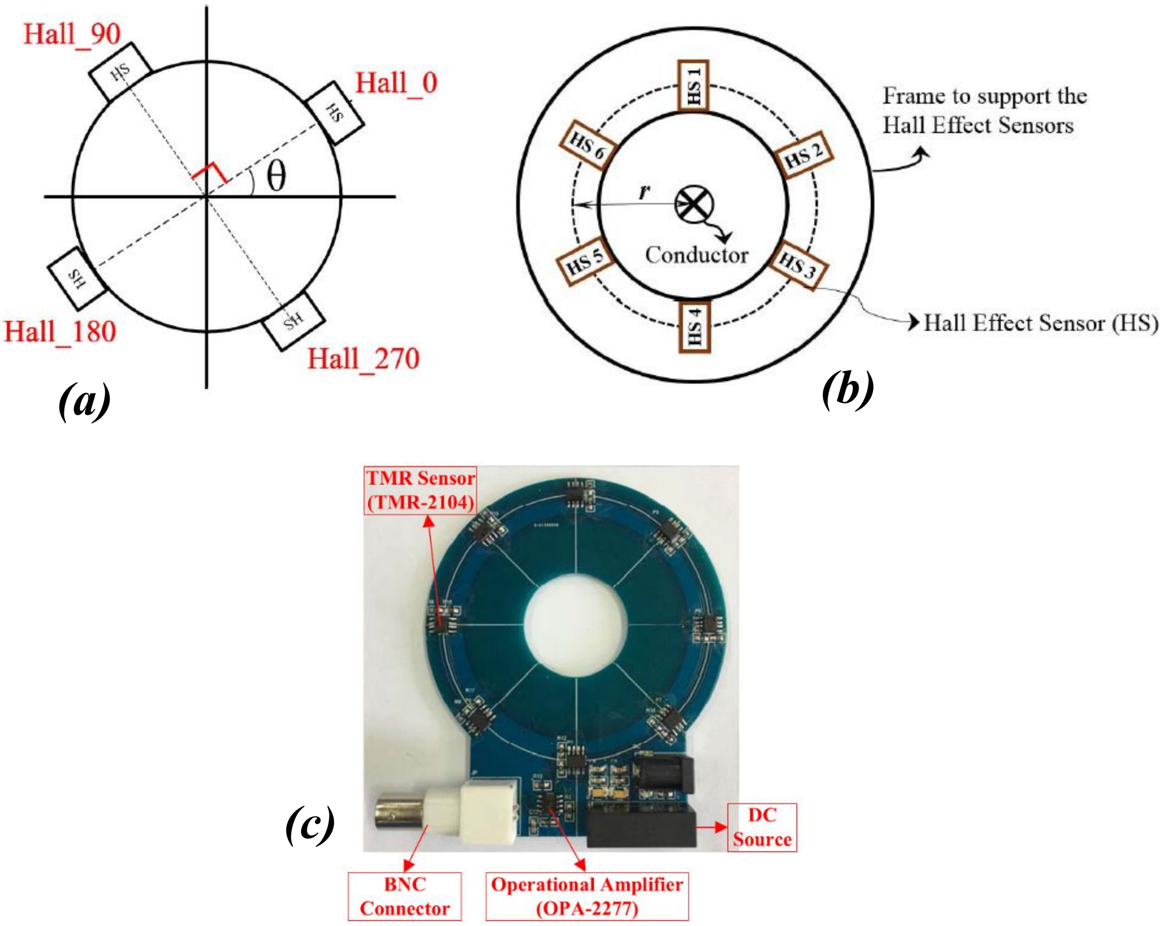


Figure 2.13 Coreless Hall effect current transformer. (a) 4 sensors (b) 6 sensors (c) 8 sensors

The positioning of the hall sensors in a circular array around the current carrying conductor is critical to achieving reliable measurements. The spacing between adjacent sensors should be equal[49]. The simple formula adopted for the spacing between sensors is given as follows/

$$spacing\ (^\circ) = \frac{2\pi}{N} \tag{2.16}$$

Where N is the number of hall sensors used. While this number is not fixed, it is known that increasing it will increase the precision of the measurement. On the contrary, the more sensors used, the costlier and complicated the system will be.

Operating principle of coreless HCT

The configuration and sensing mechanism of the coreless HCT is similar to the open and closed loop configurations. The coreless design of HCTs incorporates N number of Hall sensors positioned symmetrically around a power cable. Each of these Hall sensors detects the magnetic fields produced by the current in the power cable and then generate a corresponding Hall voltage. As seen in figure 2.14 a weighted adder circuit is linked to the rear end of the Hall sensors to collect all N Hall voltages and compute their average. By taking into account the sensitivity of all the Hall sensors and applying the Biot-Savart law for an infinite straight line as presented in equation 2.9, it becomes possible to estimate the actual current flowing through the cable[28], [46].

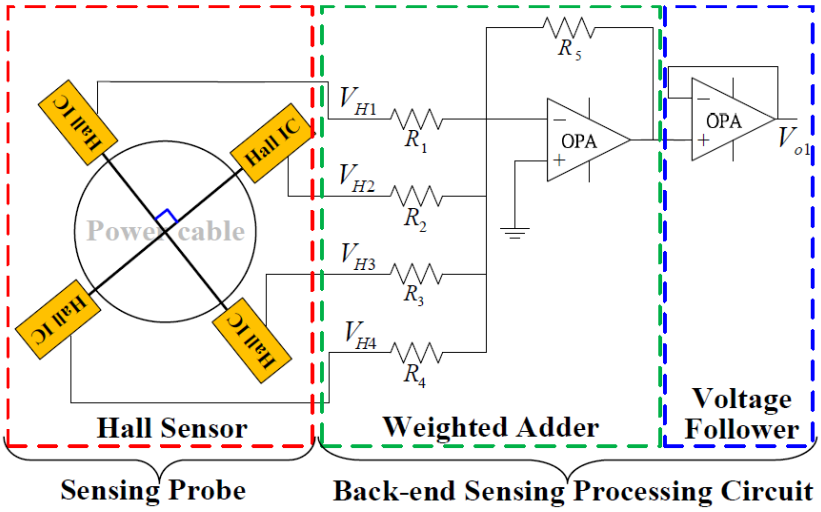


Figure 2.14 Configuration of coreless Hall current transformer

2.4 Active Voltage Transformers (VTs)

In this section, the discussion will be based on active CTs. To reiterate from figure 2.1, active VTs are grouped into Pockels optical voltage Transformers and closed loop Hall voltage transformers.

2.4.1 Pockels Optical voltage Sensors

Similar to the discussion for the FOCS based on the Faraday's principle in section 2.3 above concerning active current transformers, the Pockels optical voltage sensors (OVS) also uses the principle of modification of polarized light properties for measuring the magnitude of a voltage source.

Principle of Pockels Effect

The Pockels effect is a phenomenon observed in certain crystal materials. These crystals exhibit a unique behaviour where their refractive index can be altered by an external electric field[50].

When these crystals are in their natural state without any electric field, they appear optically uniform (isotropic). However, upon the application of a voltage, they transform into anisotropic structures, meaning that their refractive index undergoes changes in response to the electric field. This intriguing phenomenon is commonly referred to as the electro-optic effect [51]. In simpler terms, the application of an electric field induces alterations in the crystal's refractive index, influencing its optical properties. The refractive index is mathematically represented through a power series in relation to the applied electric field E, expressed as

$$n = n_0 + aE + bE^2 \tag{2.17}$$

$$\Delta n = aE + bE^2 \tag{2.18}$$

Where n_0 is an ordinary refractive index of the crystal when no electric field is applied.

Δn is change in refractive index due to the applied electric field or the birefringence.

$a \text{ and } b$ are the coefficients for the electro-optic effect.

E is the electric field.

The change in the refractive index has a term linearly depending on the electric field and another contribution having a square dependence. The linear dependence corresponds to the Pockels effect while the square dependence is related to Kerr's effect. Also depending on the direction of the applied electrical field with respect to the light beam in optical modulators, the effect can either be longitudinal or transverse. In the in the case of parallel configuration, the opto-electric effect is longitudinal and transverse when they are perpendicular to each other.

Longitudinal Pockels effect

The longitudinal Pockels effect is realized when the configuration of the Pockels cell is such that the electrical field applied is parallel to the propagation direction of the light beam. For the longitudinal configuration of Pockels cells, the electric field, $V = E * l$ [52]. Where V is the applied voltage and l is the length of the crystal.

The phase retardation in this case is given by.

$$\delta = \frac{2\pi}{\lambda_0} n_0^3 rEl = \frac{2\pi}{\lambda_0} n_0^3 rV \tag{2.19}$$

Where δ is the phase retardation.

λ_0 is the wavelength of the light source.

r is the electro-optic permittivity

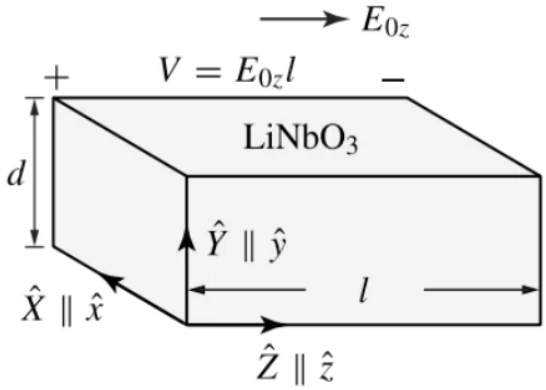


Figure 2.15 Longitudinal Pockels effect

Due to considerations of crystal symmetry and the aim to prevent birefringence when no electric field is present, the majority of Pockels cells are designed to operate with a longitudinal field[53].

Transverse Pockels effect

For the transverse configuration where the direction of the light beam and that of the applied electric field are perpendicular to each other, the electric field $V = E * d$, where V is the applied voltage and d is the electrode separation (two electrodes servers as the entry point of the voltage into the Pockels crystal, the distance between the two electrodes is define by the dimensions, d of the crystal[54]).

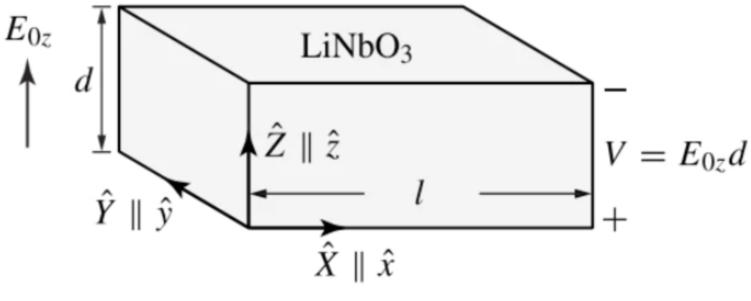


Figure 2.16 Transverse Pockels effect

The phase retardation in this case is given by.

$$\delta = \frac{2\pi}{\lambda_0} n_0^3 r E l = \frac{2\pi}{\lambda_0} n_0^3 r \frac{l}{d} V \tag{2.20}$$

It can be observed from equations (2.19) and (2.20) that, for a given applied voltage, the resulting phase retardation is independent on the physical dimensions of the crystal in the case of longitudinal configuration while it is directly proportional to l/d in the case of transverse configuration.

Pockels Electro-Optic Phase Modulation

As discussed above, when voltage is applied to an electro-optic crystal, it becomes optically anisotropic thus, introducing a birefringence effect. The difference in refractive index of the crystal creates a fast and slow axis for the orthogonally polarized light. The difference in velocity for beams with polarization components travelling along these two axes or direction causes a retardation of the phase of one polarization component relative to the other thereby changing the emerging beam's polarization state. Similar to the FOCS, the magnitude of the applied voltage to crystal is proportional to phase retardation introduced. The detection of the voltage magnitude is carried out by a detection system composed of an amplifier and other electronic components.

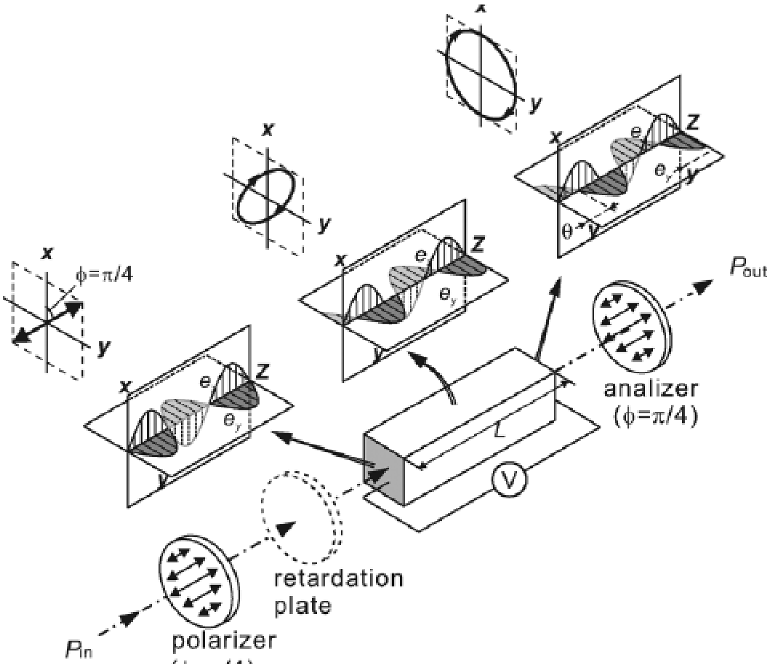


Figure 2.17 Pockels effect opto-electric phase modulation.

Consider a longitudinal arrangement of a phase modulator based on the Pockels effect shown in figure 2.17 above. For voltage measurements, longitudinal configuration of the Pockels cells is used. The reason is to prevent birefringence in the absence of applied voltage. In this configuration, the phase retardation is given by equation (2.19). however, there is an additional

δ_0 is introduced by the retardation plate or due natural birefringence of the optical components present in the arrangement. Equation (2.19) can be rewritten as

$$\delta = \frac{2\pi}{\lambda} n_0^3 r_{41} V = \pi \frac{V}{V_\pi} \tag{2.21}$$

Where V_π is known as the half-wave voltage of the crystal. It is the value of V at which the phase retardation caused by the Pockels effect reaches π. Is it defined as.

$$V_\pi = \frac{\lambda}{2 n_0^3 r_{41}} \tag{2.22}$$

Where r_{41} is the Pockels constant. V_π is the characteristic of the crystal and its independent of the dimensions of the crystal[55].

From the configuration in figure the intensity of the transmitted light with retarded phase is detected by the analyzer. The direction of the analyzer is parallel to that of the polarizer. The intensity of the output light is expresses mathematically as.

$$P_{out} = \frac{P_{in}}{2}\{1 + cos(\delta + \delta_0)\} = \frac{P_{in}}{2}\left\{1 + cos\left(\pi \frac{V}{V_\pi} + \delta_0\right)\right\} \tag{2.23}$$

The main problem for measuring high voltage (HV) directly using Pockels sensors arises when an applied voltage surpasses the half-wave voltage V_π. In such cases, accurately estimating the applied voltage becomes challenging through the analysis of the detected light intensity, which changes sinusoidally with the applied voltage, as expressed in equation (2.23). This difficulty complicates the direct measurement of HV using Pockels sensors[56].

2.4.2 Closed Loop Hall Voltage Sensor

The operating principle of closed loop Hall voltage sensor is very similar to the closed loop Hall current sensor described in section 2.3.3 above. However, there is a slight modification in the configuration of the of the circuit. The primary distinction from a typical current sensor lies in the incorporation of an internal primary winding that comprises a significant number of turns. This enables the sensor to generate the required ampere-turns for measuring the small primary current.

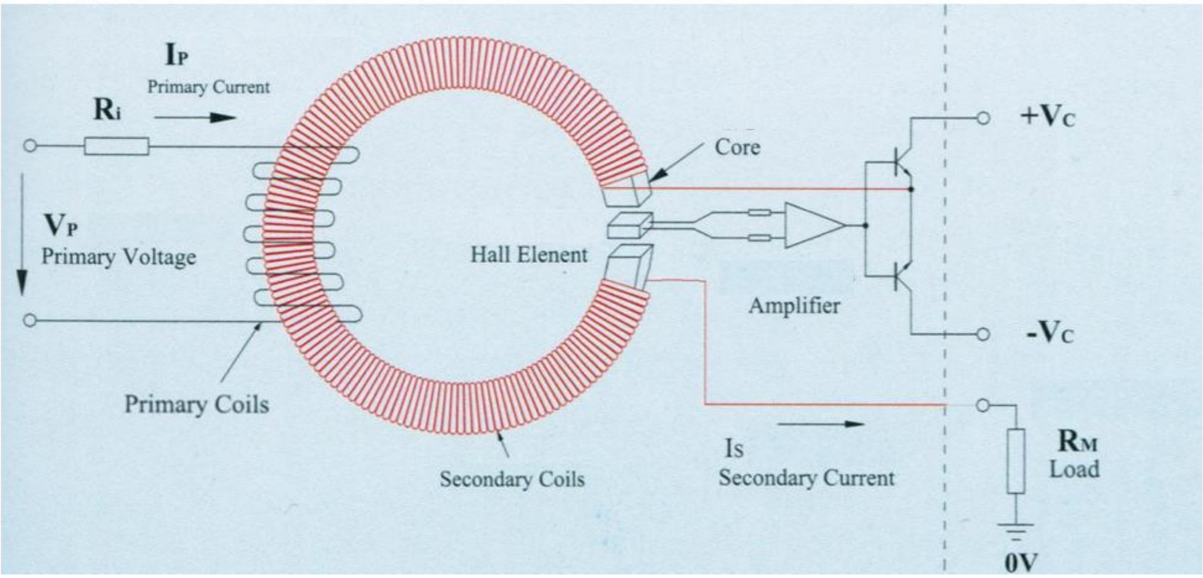


Figure 2.18 Closed Loop Hall Voltage Sensor

As seen in figure 2.18 above, the voltage to be measured is denoted as V_p. Out of this voltage to be measured, a very small current in mA range is taken by incorporation of a limiting resistor. This current circulates through the internal primary winding creating a magnetic flux linked with the iron core. Similar to the case of closed loop hall current sensor, the flux generated is compensated or balanced by the flux generated by the current supplied to the secondary winding (compensating winding). The current supplied to the secondary winding is generated by the hall element together with the electronic circuitry. This current serves as the true primary voltage representation. The inclusion of the primary resistor (R_i) in the voltage sensor configuration is optional, offering flexibility in the design [57], [58]. The magnitude of the primary current produced is expressed as.

$$I_p = \frac{V_p}{2R_i} \tag{2.24}$$

Since $I_s \times N_s = I_p \times N_p$

Then the primary voltage is given as

$$V_p = 2R_i I_p = 2R_i \frac{I_s \times N_s}{N_p} \tag{2.25}$$

2.5 Passive Current Transformers

From the classification of instrument transformers formulated in this thesis and presented in figure 2.1 above, Passive current transformers form a broad category. Unlike the active current transformer counterpart, which require an external power source for its operation, passive CTs operate without an independent power supply. The sensing element of this kind of transformers are usually in direct contact with the current carrying conductor or busbar. In the next sections, the available types of passive current transformers will be discussed.

2.5.1 Shunt Resistor Current Transformer

In high voltage direct current (HVDC) applications, a resistive shunt is commonly utilized as a sensor[59], [60]. This kind of sensor in the DC measuring system is a low value resistive shunt, which is employed to measure high-magnitude direct current flowing through the high-voltage bus bar[59]. A shunt, an electrical component characterized by low resistance, serves the purpose of measuring high currents. The prevalent form of shunt is the DC current shunt, which consists of a resistor with a predetermined calibrated resistance. Positioned in series with a load, as illustrated in Figure 2.19, the DC current shunt enables the measurement of current passing through the load. The voltage drop across the shunt resistor is directly proportional to the current through the load. Employing Ohm's Law, the current through the load can be calculated by dividing the voltage drop across the shunt resistor by the known resistance of the shunt resistor [61]. In certain cases, the voltage drop across the shunt is transformed into a light signal and transmitted to the control room through fiber optics. Some authors have also presented designs in which USB cables are used as the medium of communication between a data acquisition board and computer for real-time correction of the temperature of the shunt resistors[62].

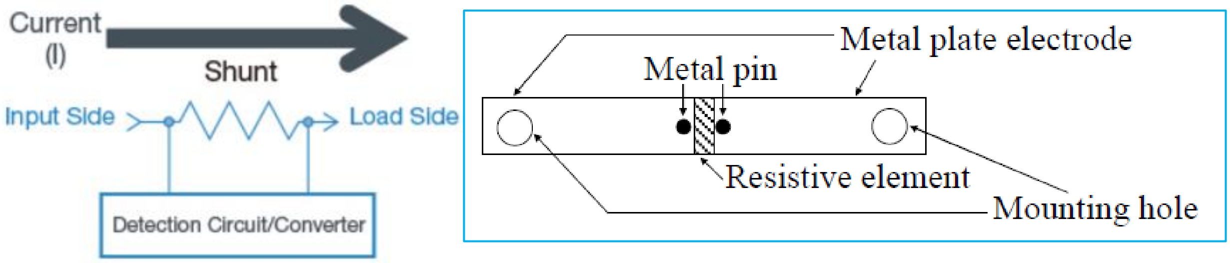


Figure 2.19 Shunt resistor in series with load on busbar

Various types of shunts are available, including bifilar strip shunts, coaxial tubular shunts, and squirrel cage shunts. Among these, coaxial current shunts[63], [64] are currently considered the most precise instruments for measuring AC-DC transfer difference and AC current within a frequency range extending up to several hundred kilohertz (usually 100kHz[60]). Typically shaped like a cylindrical cage, coaxial current shunts facilitate the flow of current from the input plate over the bars to the resistors connected in parallel on the output plate. The return path of the current occurs over the other side of the bars. At the coaxial terminal on the output plate, the voltage drop is measured using a thermal converter, an AC voltmeter (when measuring AC currents), or a sampling voltmeter[65]. In specific applications, particularly those involving high current measurements, the need arises for shunts capable of dissipating substantial amounts of energy. Bifilar strip shunts and coaxial tubular shunts may not be suitable in such instances due to limitations in their heat dissipation capabilities. In these cases, squirrel cage shunts are often preferred. Squirrel cage shunts typically comprise numerous parallel copper-manganese conductors, and their structural design resembles that of a double squirrel cage. Figure 2.20 below shows a shunt bar configuration consisting of 8 bars (4 on top, 4 below) each of rated value 600A. Designed by [62], this sensor is capable of measuring current direct current (DC) of up to 1000A as opposed to the numerous designs reported in literature with maximum rating typically limited to 100A.

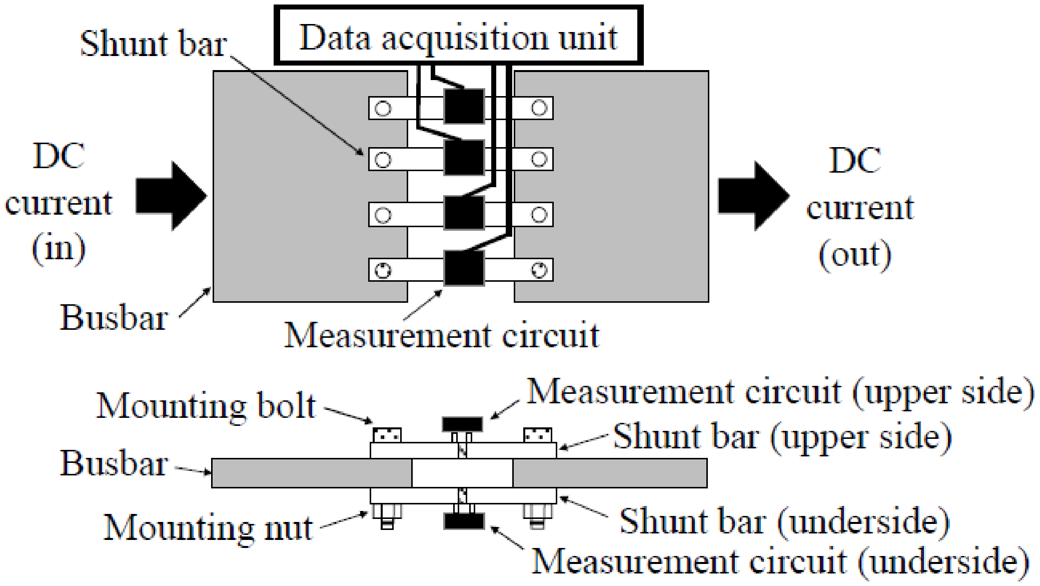


Figure 2.20 Shunt bar configuration for measuring DC current.

The resistance of a shunt resistor typically falls within the range of 0.01 ohms to 0.0001 ohms, with the most employed values ranging from several milliohms to several hundred milliohms. At the rated amperage, the voltage drop across the shunt resistor typically ranges between 50 millivolts and 100 millivolts. While it is ideal to use a shunt resistor with the lowest possible resistance, practical considerations necessitate selecting it based on factors such as the amplification factor of the operational amplifier and the specific current value intended for detection. Because of the low magnitude of the voltage drop across the shunt, a differential operational amplifier is usually employed to magnify the signal for further processing and transmission for use by digital systems. The configuration of the shunt for current measurement coupled with a differential op-amp is presented in figure 2.21 below.

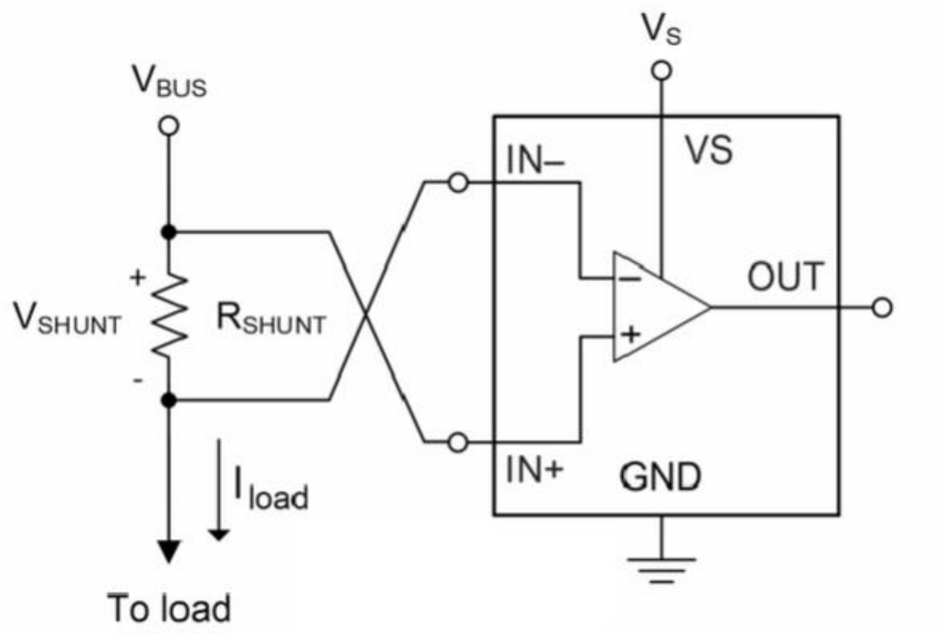


Figure 2.21 Shunt resistor with differential op-amp

According to a presentation by Rajani Machukonda[66], the product marketing engineer for Texas Instrument Current Sense amplifiers, the size or value of a shunt resistor is determined based on two main considerations, that's, the required accuracy of the sensor at minimum load current and the power dissipation at maximum load current. At low current the amplifiers input offset error is said to be the dominant source of error of the measurement while at high load currents, the power dissipation become problematic due to its square dependence of the current. The maximum value of the shunt resistor is limited by the maximum load current, gain and full-scale value of the amplifier (V_{out}).

$$R_{Shunt\_max} = \frac{V_{out} \div Gain}{I_{load\_max}} \tag{2.26}$$

$$offset\ erro = \frac{V_{OS}}{R_{shunt} * I_{load\_min}} \tag{2.27}$$

$$power\ dessipated = R_{shunt} * I_{load}^{2} \tag{2.28}$$

Where V_{OS} is the amplifiers input offset voltage.

R_{shunt} is the shunt resistance.

V_{out} full scale value of the amplifier
I_{load_max} maximum load current

At low load currents, the magnitude of the voltage drop across the shunt is lower. Considering also that the amplifiers offset error is dominate at low load currents, the magnitude of the voltage drop becomes more smaller resulting in uncertainties and large errors in the measurements. However, as the voltage drop increases, the offset error decreases hence more accurate measurement result can be realized. At higher currents, the voltage drop increases which is good in other to reduce the offset error for better accuracy. On the contrary, larger power dissipation becomes predominant at high current. This contradiction presents a complex task and therefore trade-offs must be made in the selection process of shunt resistor values for any application. Higher values of shunt resistor will lead to a reduction in the measurement error but results in larger power dissipation according equations 2.27 and 2.28 respectively. These trades-offs are visualized by the plots in figure 2.22, a graph comparing the value of shunt resistance and the magnitude of offset error at low current (in this scenario 1A) and power dissipation at high current (10A in this demonstration).

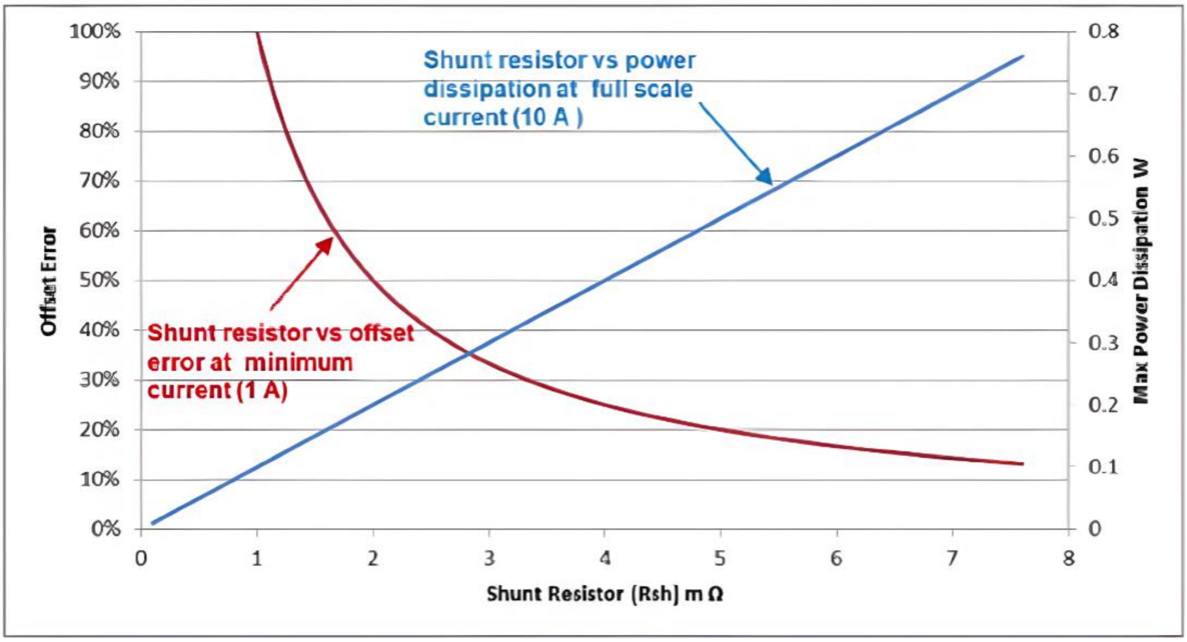


Figure 2.22 Shunt resistor vs Offset error vs Maximum power dissipation

The accuracy of current sensing is predominantly influenced by the parameters of the shunt resistor, playing a crucial role in overall performance. Two key parameters defining the precision of shunt resistors are tolerance and temperature coefficient. These factors impact the accuracy of current sensing. In scenarios involving high currents, where the dissipated power is substantial, the rise in internal temperature of shunt resistors can be notable, leading to variations in shunt resistance. The temperature coefficient is contingent on the material constituting the active part of the shunt resistor, and efforts are made to keep it as low as possible within the specified range of operational temperatures. Minimizing the temperature coefficient is essential for maintaining accurate and reliable current sensing, especially in applications where variations in temperature can significantly affect performance [59], [60], [67]. Most shunts are manufactured using manganin, an alloy composed of 84% copper, 12% magnesium, and 4% nickel. This material exhibits an exceptionally low temperature coefficient of resistance, measuring only 0.0015% per degree Celsius (15 ppm/°C). To provide a basis for comparison, copper has a temperature coefficient of resistance of 0.4% per degree Celsius. Shunts are typically specified for a 50mV, 75mV, or 100mV drop at full-scale current. Among these, 50mV shunts are often preferred due to their lower power dissipation, resulting in less self-heating. For continuous operation, manufacturers generally recommend limiting shunts to less than 2/3 of their rated current [68].

The biggest problem of shunt resistor current transformer is the heating of the current shunts when rated currents are applied [64], [65]. The authors of [65] proposed an innovative solution to reduce the heating of the resistors by employing forced air cooling in a coaxial shunt arrangement. Achieving a uniform and reduced temperature of the shunt bars, their design as show in figure 2.23 had a 100A current rating.

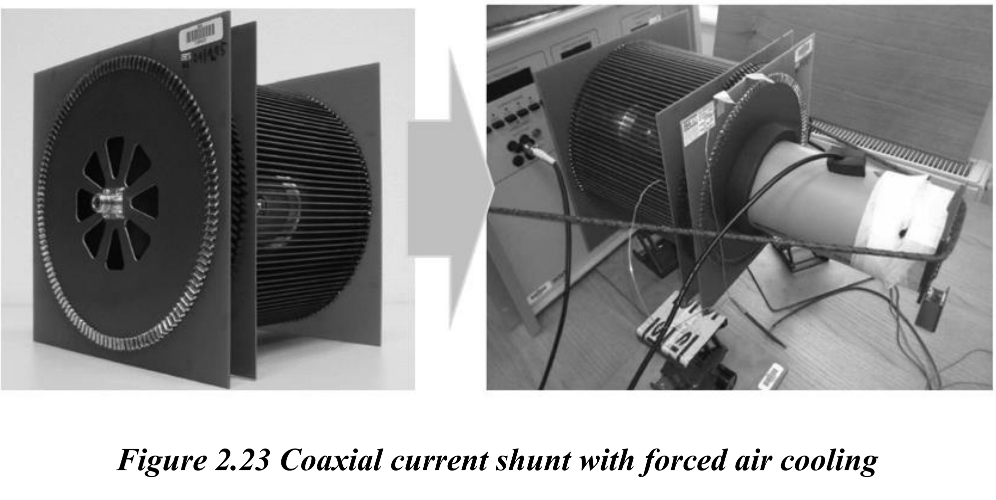


Figure 2.23 Coaxial current shunt with forced air cooling

2.6 Passive Voltage Transformers

Like the passive current transformer's counterpart, the passive voltage transformers category of instrument transformers also operates without an independent power supply. Similarly, the sensing element of this kind of transformers are usually in direct contact with the current carrying conductor or busbar. In the next section, resistive voltage divider will be discussed.

2.6.1 Resistive Voltage Divider Voltage Transformer

Transformers based on High-voltage resistive dividers is the one of the principal equipment for measuring DC high voltage. It is connected to the current carrying conductor in series by a high-voltage arm and a low-voltage arm. The high-voltage arm typically consists of many high-voltage resistors in series, with resistor values usually ranging from $10^6\Omega$ to $10^9\Omega$, and insulation resistance values ranging from $10^{12}\Omega$ to $10^{15}\Omega$ [69]. Several researchers have presented works in which Mega-ohm and kilo-ohm sized resistors were used for the high voltage and low voltage arm respectively [70], [71]. While the transformation ratio of the divider is the most important parameter for the voltage transformation, it is paramount to take into consideration the power dissipation by the resistors at rated voltage. It is desirable that resistor values be selected appropriately to ensure large volage transformation ratio while minimizing power losses in the form of heat dissipation. In its basic form, the passive voltage divider transformer is a series connection network of two resistors. This connection makes it possible to use the voltage divider rule to calculate the voltage drop across each series connected resistor [72].

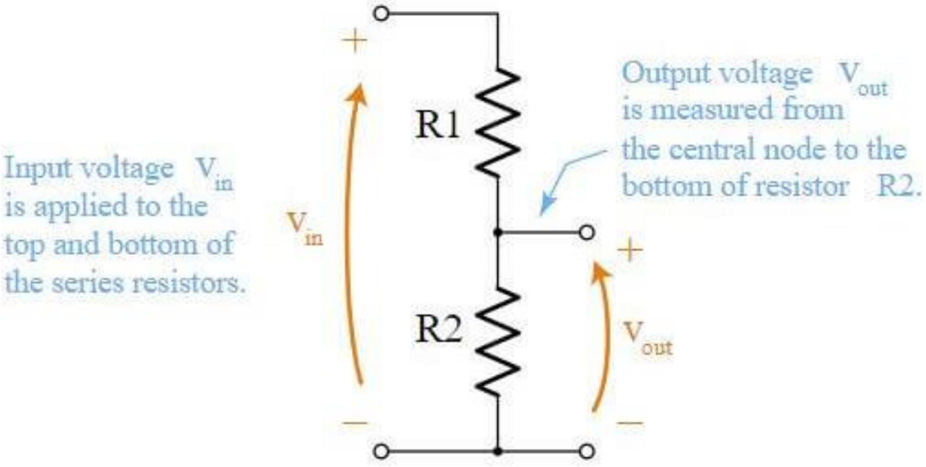


Figure 2.24 Resistive Voltage Divider Circuit

From the above figure [73], R1 and R2 represent the high and low voltage series connected resistors respectively. The output voltage which is measured between the central node ground (low voltage arm) and the voltage transformation ratio is given as.

$$V_{out} = V_{in} \frac{R_2}{R_1+R_2} \tag{2.29}$$

$$K = \frac{R_1+R_2}{R_2} \tag{2.30}$$

Voltage Coefficient of Resistance (VCR)

As mentioned before, the proper selection of the resistors is critical to the accurate operation of the voltage divider transformer. Certain resistor types exhibit variations in resistance corresponding to an increase in the voltage applied across their terminals. This undesirable characteristic, termed the Voltage Coefficient of Resistance (VCR), results in a modification of the effective ratio within the high-voltage (HV) divider as the applied voltage intensifies. Consequently, this phenomenon can substantially compromise the accuracy of the voltage divider. To mitigate this issue, it is imperative to employ HV resistors with a minimal VCR. Optimal resolution can be achieved by opting for high voltage resistor technologies characterized by low VCR values, with metal oxide resistors being a prevalent choice for precision dividers[74]. The Voltage Coefficient of Resistance is precisely defined as the alteration in resistance per unit change in voltage, expressed as a percentage of the resistance at 10% of the rated voltage[70]. This metric is mathematically represented as:

$$VCR = \frac{R_1-R_2}{R_2} \times \frac{1}{V_1-V_2} \times 100 \tag{2.31}$$

Where

R_1 is the resistance at the rated voltage V_1 and R_2 is the resistance at 10% of the rated voltage V_2.

Heating of resistive elements due to inaccurate selection of resistance values or higher VCR can induce alterations in their active resistance, consequently diminishing the accuracy of voltage measurements conducted through a resistive divider transformer. Increased resistance leads to less self-heating of resistive parts, resulting in lesser errors. However, increasing resistance lowers the total current that flows through the voltage divider. However, with substantial resistance, measurement precision becomes vulnerable to leakage current within the insulation. [75].

Leakage Current

Leakage current has been identified as one of the important sources of the voltage variation of DC high-voltage resistive dividers. According to [76] leakage currents are caused by the stray conductance to ground and distributed along the resistance R (see figure 2.26). Where R is the sum of the high and low voltage arm resistances. Under the influence of factors such as surface aging, humidity, dust pollution, as well as the specific structure and manufacturing technology employed in the divider circuit elements, the application of high voltage to a high-voltage resistor divider transformer induces the generation of leakage current[69]. To analyse the error in the measured voltage $V_{measured}$ introduced by the leakage current, we simplify the circuit by introducing an equivalent resistance for all the conductance as depicted in figure 2.27.

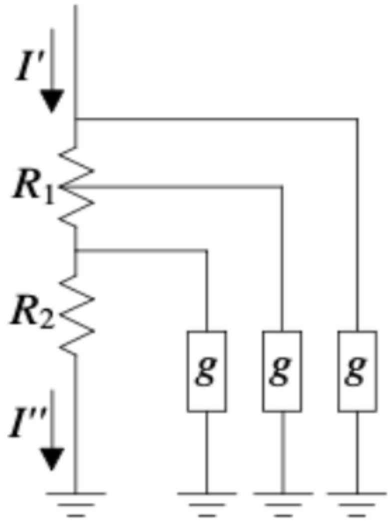


Figure 2.26 Resistive Voltage Divider Circuit with Stray Conductance

From figure 2.26 above, a larger portion of the injected current flows primarily through resistors within the high-voltage arm (I') while a smaller fraction of it exit through the low-voltage arm. This difference is said to be accounted for by the presence of the stray conductance. This disparity, termed as the leakage current, constitutes the principal factor contributing to voltage fluctuations in DC high-voltage resistive dividers. Due to the leakage current in the stray conductance, the measured voltage $V_{measured}$ will be different from the actual voltage V_{real}[69], [76]. Let's consider the equivalent circuit of figure 2.26 below for the numerical analysis of the error generated.

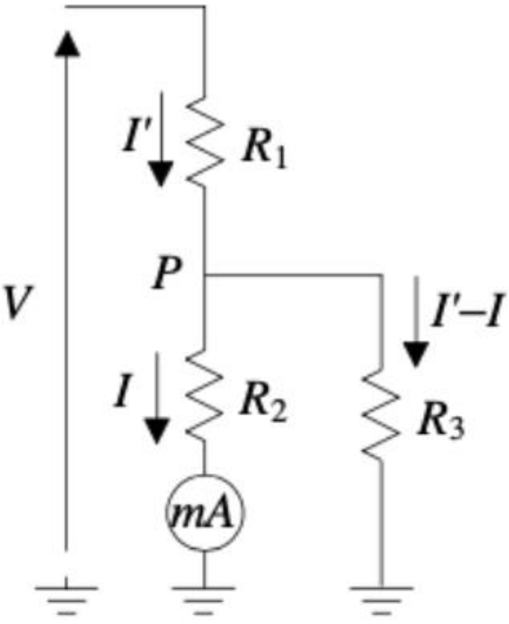


Figure 2.27 Resistive Voltage Divider Circuit with Equivalent Stray Conductance

From the equivalent circuit above, 3 currents are realized, I' flowing through the high voltage arm, I through the low-voltage arm and the leakage current $I' - I$ through the equivalent representation of the conductances. The expressions for the real and measured voltage considering the above equivalent circuit are given as.

$$V_{real} = R_1 I + R_2 I' \tag{2.32}$$

$$V_{measured} = (R_1 + R_2) I \tag{2.32}$$

We can rewrite V_{real} in such a way that it will be related to $V_{measured}$. this done to help us understand the magnitude of the error and parameters within the circuit that influences it. Knowing this, we can optimise the design or certain parameters to help reduce the error due to leakage current.

$$V_{real} = R_1 I + R_2 I' + R_1 I - R_1 I = V_{measured} + R_1 (I' - I) \tag{2.33}$$

From 2.27 above, R_2 and R_3 are parallel hence the voltage drop across two branches are equal. Therefore, it holds that.

$$R_2 I = R_3(I' - I) \tag{2.34}$$

The expression of the leakage current which is the difference between the high and low voltage arm currents is given as.

$$I' - I = \frac{R_2}{R_3} I \tag{2.35}$$

By substitution, the expression of the real voltage with respect to the measure is given as.

$$V_{real} = V_{measured} + \frac{R_1 R_2}{R_3} I \tag{3.36}$$

By analysing the above equation, the best way you can minimize the measurement error is by the realization of a higher of the resistance R_3. This can be achieved by proper manufacturing of the resistors. In [71] the authors got the best performance by setting R_3 to 1 Mega-ohm (1M Ω). Lower values led to significant changes in the voltage transformation ratio. According to [76], the error can me reduced also by reducing the product between R_1 and R_2. However, it is desired to reduce R_2 and keep $R_2 \ll R_3$ so that the leakage current $I' - I$ on R_3 will be negligible. This approach is similar to the first, in either way R_3 is still kept high.

Design Considerations

The configuration of the voltage divider necessitates the implementation of effective electric field control techniques to mitigate corona discharge and uphold measurement accuracy. Adequate resistor voltage ratings and clearances in the design must be ensured to eliminate the possibility of flashovers. Furthermore, the design of the high-voltage (HV) divider should impose constraints on the surface electric field at all junctures within the voltage divider, thereby averting partial breakdown and corona discharges. The corona discharges give rise to accompanying leakage currents that propagate into the surrounding air. These currents induce alterations in the effective divider ratio, consequently diminishing accuracy, especially at elevated voltage levels. Moreover, such discharges pose a substantial risk of causing enduring damage to the insulating materials incorporated in the divider and may result in catastrophic breakdowns along the high voltage resistor chain[74].

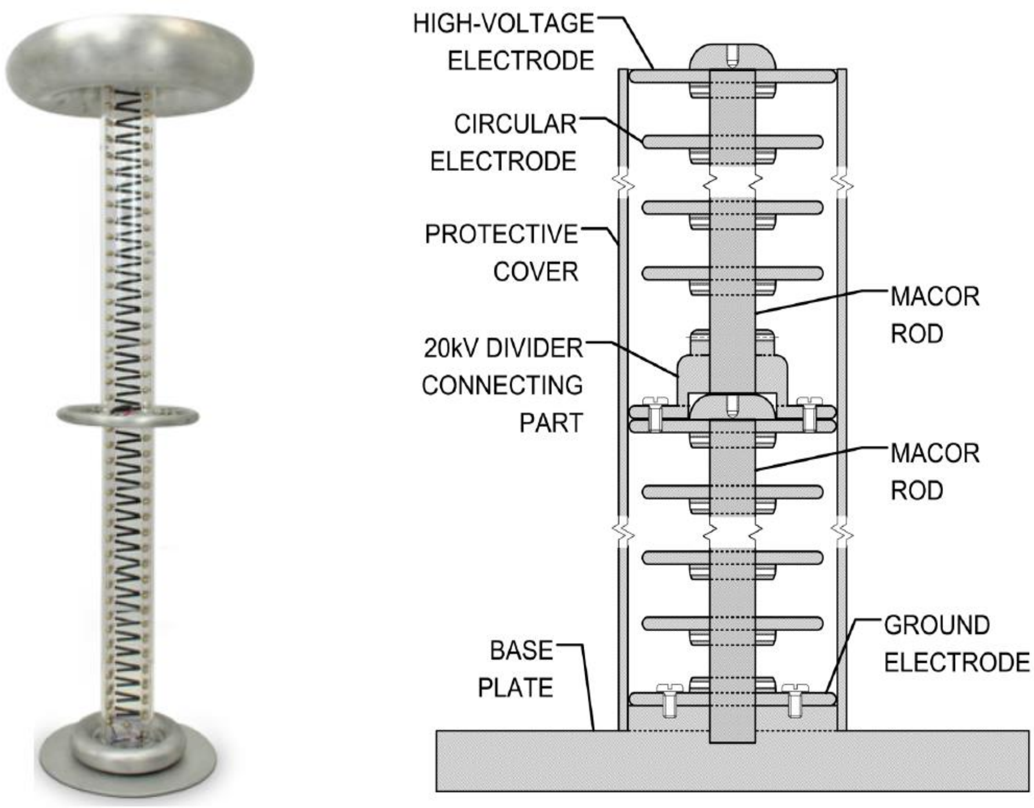


Figure 2.25 Structure of Resistive Voltage Divider Transformer

As depicted in figure 2.25 above[77], in addition to the measures, a sizeable anti-corona terminal, typically adopting a hemispherical or toroidal configuration, is commonly integrated at the uppermost section of the divider[78]. Supplementary anti-corona components, along with voltage equalizing shields, are occasionally incorporated at the base and midpoint of the divider chain[79]. These additions serve the dual purpose of balancing electric field stresses along the divider chain and averting undesired corona discharges. Such measures contribute to the overall balance and integrity of the high-voltage divider system, ensuring optimal performance and mitigating the risk of corona-induced issues.

2.7 Performance Requirements

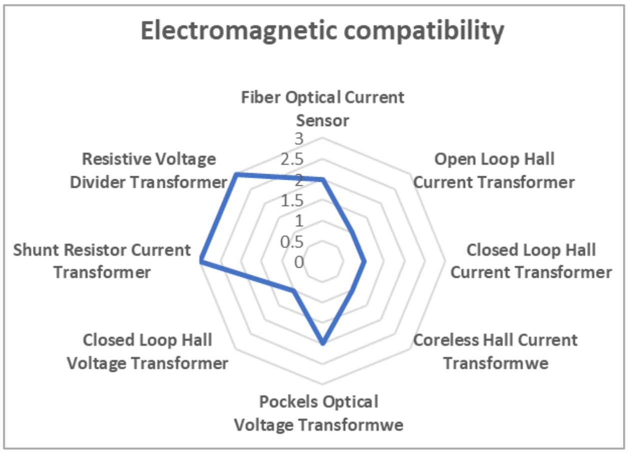
As mentioned already in the methodology of the research, the performance requirements are a group of indices that influences the choice of instrument transformer. These parameters are the ideal requirements for any kind of instrument transformer. From the above review of the various kinds of instrument transformers for DC power networks, table 2.2 below presents the main performance requirements for DC ITs. These critical performance indicators were carefully selected from the above literature review and Specific Requirements for DC Current and voltage Transformers specified in the IEC 61869-14 standard for instrument transformer-part 14. Being the ideal requirements, not all the covered DC instrument transformers have the capability of satisfying these requirements perfectly, hence the degree of satisfaction of the requirement by each transformer is assessed using the traffic light approach. In this approach, RED light signals a low satisfaction or bad response against a certain requirement, while YELLOW means an intermediate satisfaction and GREEN depicts a great or excellent performance. The assigned level of satisfaction for each of the instrument transformer is based on the results and opinions of authors in literature and not experimental approach or experience with the device.

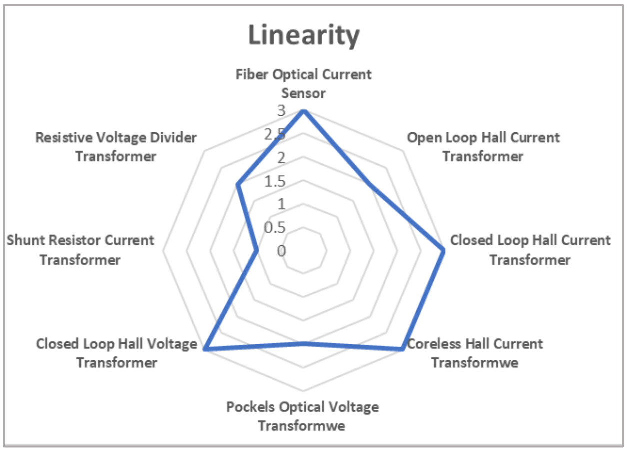
Table 2.2 Comparison of the performance of DC instrument transformers

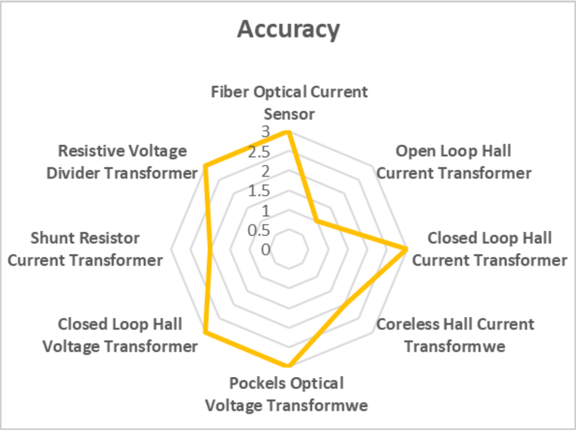
	ACTIVE CTs				ACTIVE VTs		PASSIVE CTs	PASSIVE VTs
PARAMETER	*Fiber Optical Current Sensor*	*Open Loop Hall Current Transformer*	*Closed Loop Hall Current Transformer*	*Coreless Hall Current Transformwe*	*Pockels Optical Voltage Transformwe*	*Closed Loop Hall Voltage Transformer*	*Shunt Resistor Current Transformer*	*Resistive Voltage Divider Transformer*
Temperature Withstand	**EXCELLENT** Polarzied light confined in the fiber is less affected by temperature variation	**EXCELLENT** Commercial devices has maximum operating temperature limited to abour **125 °C**	**INTERMEDIATE** Commercial devices has maximum operating temperature limited to abour **85 °C**	**INTERMEDIATE** Overall performance maybe susceptible to temperature variation due its less robustness	**FAIR** Temperature variation changes the refractive index of pockel crystals and influences measurements	**INTERMEDIATE** Commercial devices has maximum operating temperature limited to abour **85 °C**	FAIR Temperature rise changes the resistance of shun and influence accuracy. Max Tepm. Around **70 °C**	**FAIR** Measurememt is greatly impacted by the temperature and voltage coefficient of the resistors**. Max Tepm. Around 75 °C**
Linearity	**EXCELLENT**	**INTERMEDIATE** around 0.3-0.1 of fullscae	**EXCELLENT** <0.1% of fullscale	**EXCELLENT**	**INTERMEDIATE**	**EXCELLENT**	**FAIR**	**INTERMEDIATE**
Electromagnetic compatibility	**INTERMEDIATE** Stray electromagnic fields can inflence the magnitude of phase delay	**FAIR** Stray electromagnetic fields can influence measurements by affecting the Hall voltage generated	**FAIR** Stray electromagnetic fields can influence measurements by affecting the Hall voltage generated or lead to overcompensation of the electromagnetic field	**FAIR** Stray electromagnetic fields can influence measurements by affecting the Hall voltage generated	**INTERMEDIATE** Polarized light can be affected by stray electromagnetic fields	**FAIR** The iron core is suspectible to electromagnetic interference and can influence measurement	**EXCELLENT** Shunt resistors have no compnents susceptible to electromagntic interference	**EXCELLENT** Shunt resistors have no compnents susceptible to electromagntic interference
Footprint/size	**EXCELLENT** The sensing unit which is a simple coiled loop of optical fiber of small size	**EXCELLENT**	**FAIR**	**EXCELLENT**	**INTERMEDIATE**	**FAIR** The presence of an iron core, primary and secondary windings makes it bulky	**FAIR** Bulky due to large size of resistors and their distribution for cooling	**FAIR** Bulky due to large number of resistorts connected in series
Accuracy	**EXCELLENT** **<0.1%**	**FAIR** **1% -4%**	**EXCELLENT** **0.001% - 0.9%**	**INTERMEDIATE** Accuracy of measurement depends on the number of hall sednsors used	**EXCELLENT**	**EXCELLENT** **0.01% - 0.6%**	**INTERMEDIATE** + **0.5% -1 %** Accuracy is dependent on current magnitude. Accuracy is lowest at low current and highest at rated current	**EXCELLENT** **0.01% - 0.5%**
Range	**EXCELLENT** **A - MA** Measurement range extends to mega amperes:	**INTERMEDIATE** **mA - several kA**	**INTERMEDIATE** **mA - several kA**		**INTERMEDIATE** the measurement range is limited by the half-wave voltage V_π of the pockels crys tal	**INTERMEDIATE** **V - several kV**	**FAIR** **A - few kA** The range of current measurement is limited due to larger power dissipation at higher currents and heating.	**EXCELLENT** **A - MV** Measurement range extends to mega volts:
Vibration Withstand	**FAIR**	**INTERMEDIATE**	**EXCELLENT**	**FAIR**	**INTERMEDIATE**	**EXCELLENT**	**EXCELLENT**	**EXCELLENT**
Reliability	**EXCELLENT**	**INTERMEDIATE**	**EXCELLENT**	**INTERMEDIATE**	**INTERMEDIATE**	**EXCELLENT**	**INTERMEDIATE**	**EXCELLENT**
Stability (long ans short)								0.01-0.025%/8hrs (Short) 0.002 % / Year (Long)
Robustness	**INTERMEDIATE** Sensing unit is a flexible fiber cable which is less robust	**EXCELLENT** Physicall compact and more robust	**EXCELLENT** Physicall compact and more robust	**FAIR** The construction is less robust. Considered to be under research and developemnt		**EXCELLENT** Physicall compact and more robust	**EXCELLENT** The construction of current shunts are compact and robust	**EXCELLENT** Physicall compact and more robust
Saturation	**EXCELLENT** Absence of iron core elimates the problem of saturation. Magnitude of achievable phase delay is endless	**FAIR** Experiences core saturation due to absence of compensation winding	**EXCELLENT** The presense of compensation winding elimates core saturation problem	**EXCELLENT** Being coreless, it expereinces no saturation	**EXCELLENT** NO core, NO saturation	**EXCELLENT** The presense of compensation winding elimates core saturation problem	**EXCELLENT** The absence of an iron core eleminated the problem of core saturation	**EXCELLENT** NO core, NO saturation
Sensitivity	**EXCELLENT** **µV/A**	**INTERMEDIATE** **mV/A**	**EXCELLENT** **µV/A**		**EXCELLENT**	**EXCELLENT** **µA/V**	**INTERMEDIATE** **mA/V**	
Response time	**EXCELLENT** Time to reach 90% of primary current is in the order of **microseconds (µs)**	**INTERMEDIATE** Time to reach 90% of primary current is in the order of **milliseconds (ms)**	**EXCELLENT** Time to reach 90% of primary current is in the order of **microseconds (µs)**	**INTERMEDIATE** Time to reach 90% of primary current is in the order of **milliseconds (ms)**	**EXCELLENT** Time to reach 90% of primary current is in the order of **microseconds (µs)**	**EXCELLENT** Time to reach 90% of primary voltage is in the order of **microseconds (µs)**	**EXCELLENT** Time to reach 90% of primary voltage is in the order of **microseconds (µs)**	**EXCELLENT** Time to reach 90% of primary voltage is in the order of **microseconds (µs)**
Power consumption	**FAIR** Auxiliaries such as polarizers and other components require significant power for operation	**EXCELLENT** No compensation winding so external Power is not required in the sensing process	**FAIR** Generation of secondary electromagnetic field requires significant power	**EXCELLENT** Only a few electonics require low power supply	**INTERMEDIATE**	**FAIR** High power consumption to produce both primaty and secondary fluxes	**EXCELLENT** External power source is not required for measuremes. However electronics for futher processing may require low power	**EXCELLENT** External power source is not required for measuremes. However electronics for futher processing may require low power
Galvanic isolation	**EXCELLENT** The measurement circuit is physically isolated from the busbar/conductor	**EXCELLENT** The measurement circuit is physically isolated from the busbar/conductor	**EXCELLENT** The measurement circuit is physically isolated from the busbar/conductor	**EXCELLENT** The measurement circuit is physically isolated from the busbar/conductor	**FAIR** There is no galvanic isolation. Voltage is applied directly to the pockels crystal.	**EXCELLENT** The measurement circuit is physically isolated from the busbar/conductor	**FAIR** There is no galvanic isolation because the measuring circuit(shunts) is in direct contact with the busbar/conductor	**FAIR** There is no galvanic isolation because the measuring circuit is in direct contact with the busbar/conductor

2.8 Comparative Analysis

A comparison of the performance of each of all the 8 DC instrument transformers against each performance requirement is carried out. Using the traffic light approach as specified in section 2.7 above, a value of 3 is assigned to green, 2 to yellow and 1 to red. Using these indicators, a radar plot for each performance requirement is drawn and presented in figure 2.26 below. From the graphs, the more circular the plot is, the better the performance of all the instrument transformers against the performance parameter. This is evident in the plot of saturation: aside open loop hall current transformer, all other DC ITs do not have the problem of iron core saturation. Similarly for response time, all the instruments have a relative fast response time implying that they are suitable for not only measurements purposes but also protection purposes which usually require faster response time for quick isolation. On the other hand, the more deformed the curve is the worse is the performance of all the transformers against that performance requirement. For instance, the plot of power consumption and electromagnetic compatibility exhibit quite a significant degree of deformation indicating a poor correlation between the degree of satisfaction. Generally, passive transformer has good electromagnetic compatibility while consuming little or power. On the second hand, active transformers are more likely to be susceptible to electromagnetic interferences and has the worse power consumption because they are electronic/digital devices. other observations from the analysis are poor temperature withstand and large footprint of passive transformers. Figure 2.26 presents all the plots from the comparative analysis.






Accuracy
Fiber Optical Current Sensor
Open Loop Hall Current Transformer
Closed Loop Hall Current Transformer
Coreless Hall Current Transformwe
Pockels Optical Voltage Transformwe
Closed Loop Hall Voltage Transformer
Shunt Resistor Current Transformer
Resistive Voltage Divider Transformer
3
2.5
2
1.5
1
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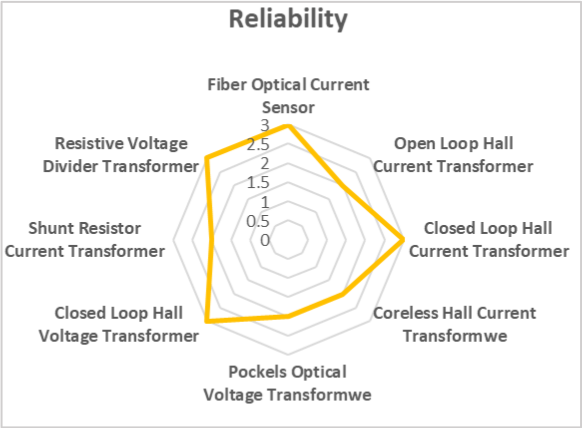
Reliability
Fiber Optical Current Sensor
Open Loop Hall Current Transformer
Closed Loop Hall Current Transformer
Coreless Hall Current Transformwe
Pockels Optical Voltage Transformwe
Closed Loop Hall Voltage Transformer
Shunt Resistor Current Transformer
Resistive Voltage Divider Transformer
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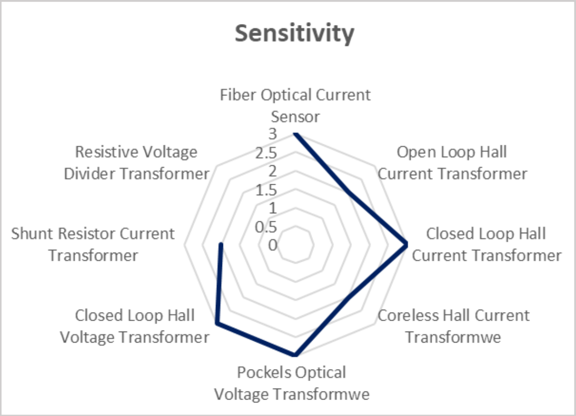
Sensitivity
Fiber Optical Current Sensor
Open Loop Hall Current Transformer
Closed Loop Hall Current Transformer
Coreless Hall Current Transformwe
Pockels Optical Voltage Transformwe
Closed Loop Hall Voltage Transformer
Shunt Resistor Current Transformer
Resistive Voltage Divider Transformer
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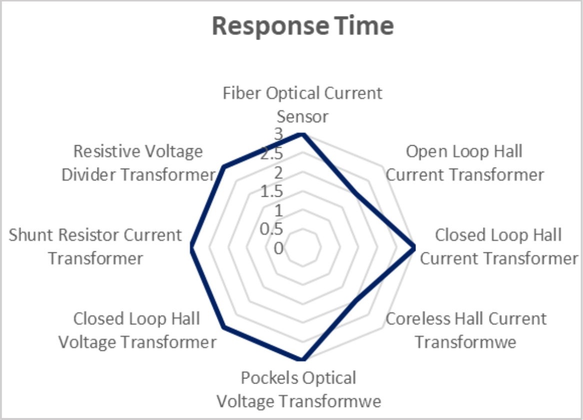
Response Time
Fiber Optical Current Sensor
Open Loop Hall Current Transformer
Closed Loop Hall Current Transformer
Coreless Hall Current Transformwe
Pockels Optical Voltage Transformwe
Closed Loop Hall Voltage Transformer
Shunt Resistor Current Transformer
Resistive Voltage Divider Transformer
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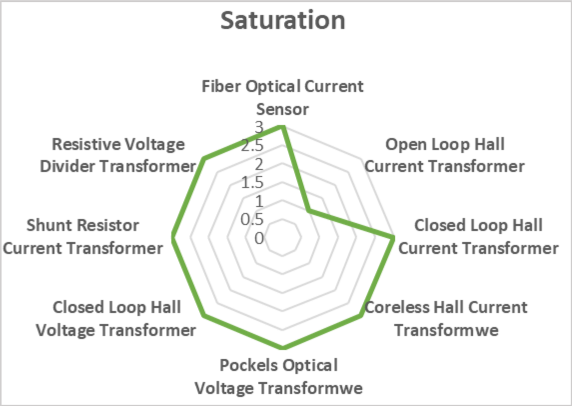
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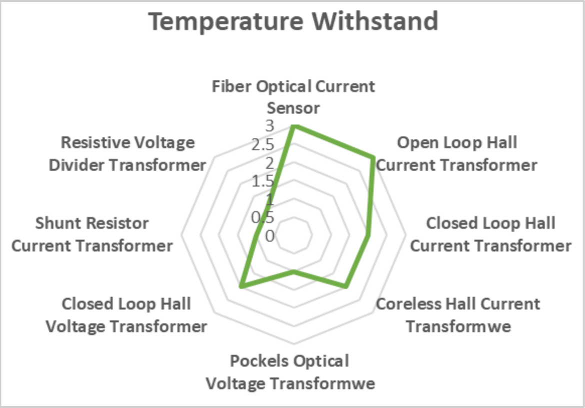
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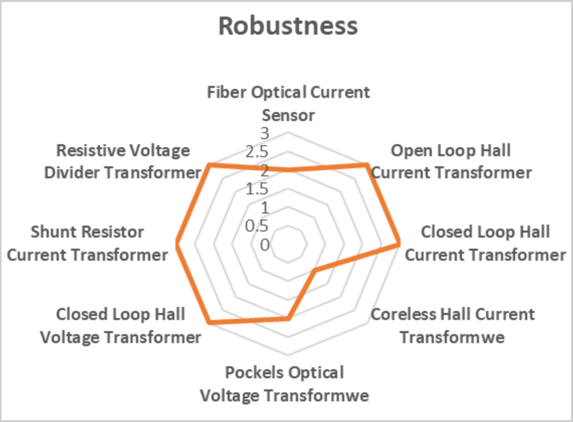
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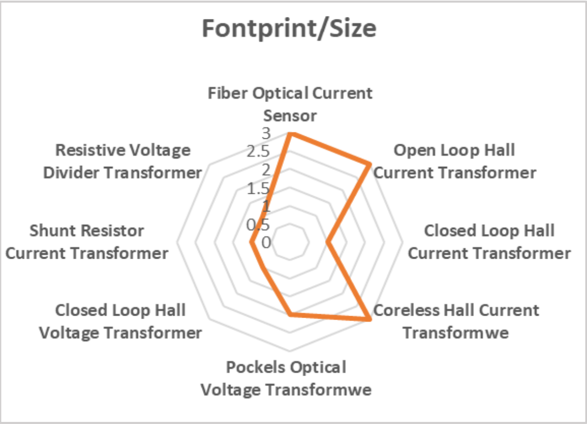
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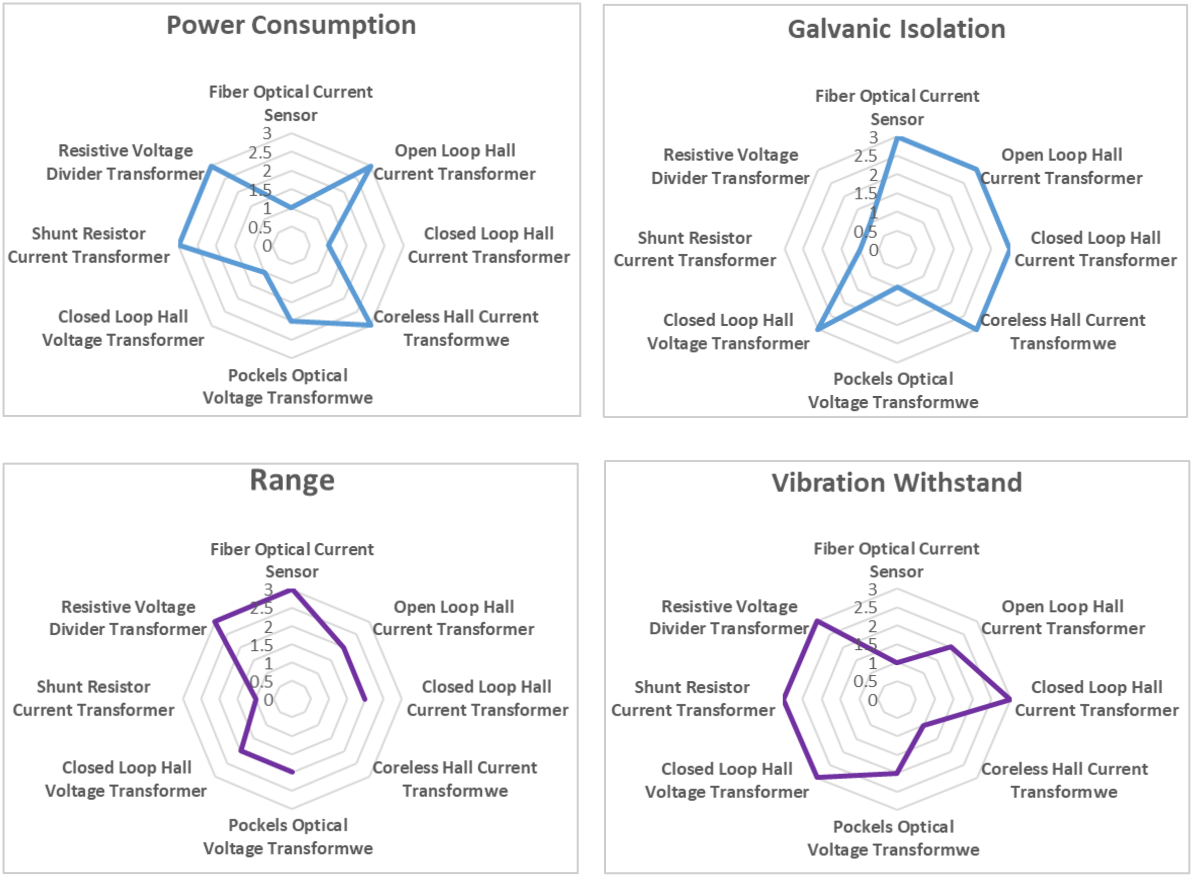


Figure 2.26 Comparative Analysis

CHAPTER 3

MARKET DYNAMICS OF INSTRUMENT TRANSFORMERS FOR DC NETWORKS

The section of the thesis is organised to be solely dedicated to the market dynamics of instrument transformers for DC applications. The assessment takes into account the evolution, trends and future perspective of the markets involving DC networks instrument transformers. The scope of the analysis cuts across the entire world where data is available, however, prominence is placed in specific geographical areas. Being a market investigation, several financial tools and matrixes will be presented in this chapter for the investigation.

3.1 Scope of The Market Analysis

Owing to the fact that data available for instrument transformers covers all kinds of instrument transformers, this section of the thesis won't be limited to only DC instruments transformers, instead the data and analysis presented herein are valid and covers both AC and DC instruments transformers. In relation to the geographical coverage of the analysis, all regions of the world will be touched on. However, emphasis will be placed on the hotspots of the market and also growing markets. Specifically, the markets of instrument transformers in Asia Pacific, Europe, MEA, North and Latin America will be analysed.

3.2 Market Overview

The market trends and forecast of instrument transformers have been extensively analysed by several research institutions. However, the market value is quite unclear as significant variations are presents in the estimated current and projected market value in the reports by these institutions. According to Straits Research report on instrument transformers market, globally, the market size of instrument transformers was valued at USD 7.45 billion in the year 2021 and based on their projections, it is expected to reach about USD 13.02 billion by the end of 2030[80]. At this growth rate, the compounded annual growth rate (CAGR) was calculated to be 6.4% from 2021–2030. Similar results and forecast have been presented by Allied Research Institute. According to their report, in 2020, the worldwide market for instrument transformers reached a valuation of $6.97 billion. It is anticipated to achieve a total of $13.01 billion by 2030, exhibiting a compound annual growth rate (CAGR) of 6.5% from 2021 to 2030. In an updated version of this report using 2022 as the base year, Allied Research Institute estimated that the market was valued at $9.6 billion in 2022 and predicted to reach a value of $17.2 billion by 2023 giving rise to a CAGR of 6.1% with analysis duration of 2023-2032[81].

Uncorrelated results have been presented by other research institutions. Morodor Intelligence reports that the global instrument transformers market is currently (2024) valued at $4.95 billion[82]. This finding is in strong disagreement with the figures reported by the other institutions as discussed above. Although the analysis period for this study is shorter (2024-2029) compared the previous ones, the CAGR which is gauged at 5.1% is somewhat in correlation with the other reports presented. Also, Transparent Market Research believes that the global instrument transformers industry was valued at $4.7 billion in 2022 and will experience a CAGR of 7.7% between 2023-2031 reaching a value of $8.9 billion by the end of 2031[83]. According to MARKETSandMARKETS [84], a research institution that claims 8 out of top 10 instrument transformers companies depend on their analysis for growth, in 2023, the global market of instrument transformers was worth $7.1 billion and is projected to grow up to $10.6 billion by 2030 with a CAGR of 5.8%. Although appreciable variations are observed in the past, present and forecasted market value of instrument transformers which may be due to due different methodologies or assumptions used during the analysis, one can notice one thing among the all the findings. That's in the next decade, the market of instrument transformers is not expected to grow to reach a CAGR up to 10%. Based on the data analysed in this section, the minimum and maximum CAGR reported in literature for the market are 5.1% and 7.7% respectively. Figure 3.1 is the graphical representation of the market outlook by Straits Research

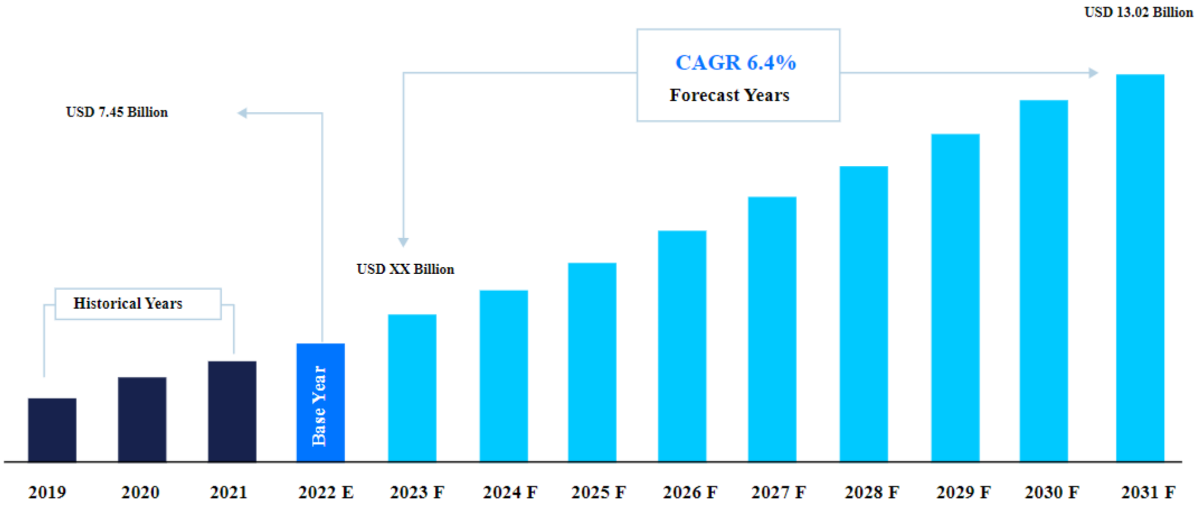


Figure 3.1. Instrument Transformers Market Outlook.

In table 3.1, the summary of the market outlook presented by the various research institutions is presented.

Table 3.1 Summary of Instrument Transformers Market Outlook

Research Institution	Analysis period	Base year mark value	Final year market value	Compounded Annual growth rate (CAGR)
Straits Research	2021-2030	$7.45 billion	$13.02 billion	6.4%
Allied Research Institute	2021-2030	$6.97 billion	$13.01 billion	6.5%
Allied Research Institute	2023-2032	$9.60 billion	$17.20 billion	6.1%
Morodor Intelligence	2024-2019	$4.95 billion	-	5.1%
Transparent Market Research	2023-2031	$4.70 billion	$8.90 billion	7.7%
MARKETandMARKETS	2023-2030	$7.10 billion	$10.60 billion	5.8%
Expert Market Research	2024-2032	-	$14.80 billion	7.1%
Research Nester	2023-2035	$3.00 billion	$7.00 billion	7.0%
OpenPR	2023-2030	$9.19 billion	$15.10 billion	7.34%
Fact.MR	2022-2032	$3.18 billion	$5.69 billion	6.0%

3.2 Market Segmentations

The market of instrument transformers is very broad and exhibits different dynamics based on the segments. To better understand and analyse the market, it has been fragmented into several segments each of which is affected by different conditions and displays different trends and forecast. The various segments of the instrument transformer market are categorised by voltage level, type, geographical location, installation type, end-users, phase, and cooling[85]. With respect to the voltage level segment, we have markets for low, medium, high, extra-high and ulta-high voltage markets. In terms of type, markets are available for Current, potential, and combined instrument transformers. The markets based on geographical location is broadly classified into regions where Asia Pacific, Europe, Latin America, North America and the MEA regions are the major markets for instrument transformers. With regards to installation type, market is available for either outdoor or indoor installation. The end-user's market is composed of power utilities, industries and OEMs, transportation sector (railways, electric vehicles etc) and others.

Although there are several segments of the instrument transformers market, focus will be placed on the voltage level, geographical location and the end-users markets. This scope narrowing is for alignment with the aim and objectives of this the thesis. In figure 3.2, the various market segments are presented.

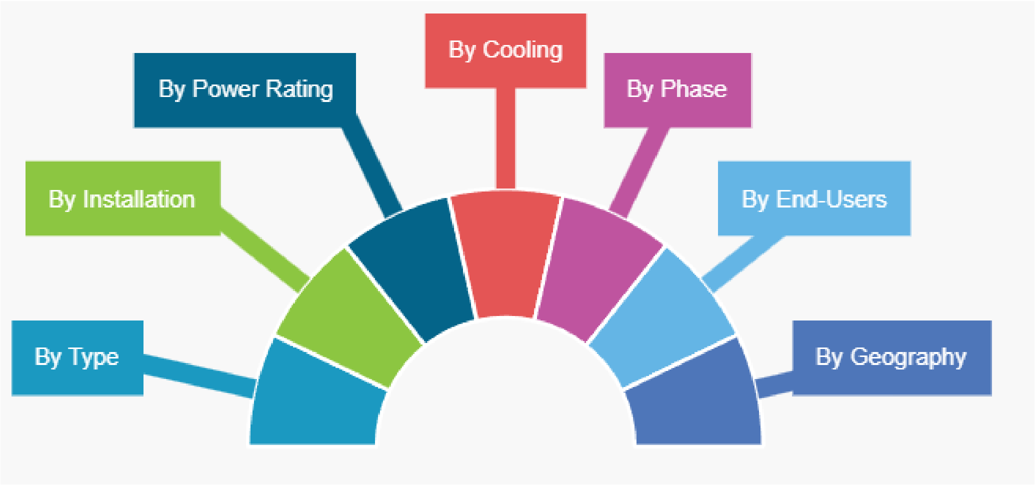


Figure 3.2 Instrument Transformers Market Segmentation

3.3 Instrument Transformers Market Dynamics

The market of instrument transformers is accelerated and at the same time retarded by several factors. The dynamic nature of the market will be assessed in this section of the thesis. In particular, the main drivers of the market, opportunities and the challenges of the market will be discussed.

3.3.1 Market Drivers

Several factors are driving the growth of the instrument transformer market. Some of the main drivers are modernization and refurbishment of the existing power grid, rising investment in infrastructure, growing deployment of renewable energy, increasing demand for electricity, expansion of the distribution network, smart grids and digitalization of substations[86]. The increasing demand for electricity globally is said to be primary driver of the instrument transformer market[85]. This demand surge is fuelled by urbanization, industrialization and technological advancements. The role is instrument transformers becomes paramount for the generation, transmission and distribution of electricity to meet this demand, hence the boom of the instrument transformer market. In the geographical regions where the instrument transformers market is really booming is driven excessive demand for electricity. Although the major drivers as listed above accelerate the markets in all regions, the degree of influence is significantly different across each geographical location. The market in some locations are more influenced by certain drivers than others. The major drivers in different regions are summarized below.

Asia Pacific

- Increasing demand for electricity
- Large scale renewable energy integration

Norh America

- Demand for refurbishment of existing grid infrastructure.
- Rising investment in infrastructure

Europe

- Upgradation of exiting grid infrastructure
- Growing deployment of renewable energy

Middle East and Africa

- Increasing demand for electricity
- Growing investment for expansion of distribution networks

3.3.3 Market Opportunities

Amidst the global shift towards renewable energy sources like solar and wind power, the instrument transformer assumes a pivotal role in effectively integrating these intermittent energy sources into the grid. Furthermore, the focus on modernizing grids and implementing smart grid initiatives enhances the demand for instrument transformers with advanced technologies, facilitating precise monitoring, control, and protection of electrical infrastructure, thereby boosting the global instrument transformers market. The incorporation of digital technologies such as IoT (Internet of Things) and AI (Artificial Intelligence) into power systems is poised to generate opportunities for smart instrument transformers, offering capabilities for real-time data analysis and remote monitoring. This transition towards more intelligent and efficient transformers aligns with the broader trend of digital transformation in the energy sector, providing companies with prospects to innovate and develop state-of-the-art products. Additionally, the surge in investments in transmission and distribution infrastructure is anticipated to create growth avenues for the instrument transformers market[81], [84].

3.3.3 Market Challenges

While the market of instrument transformers is forecasted to growth steadily, it is not without challenges. The instrument transformer market is anticipated to face growth challenges due to heightened competition from unorganized firms [81]. The instrument transformer market is not concentrated; hence several unorganized companies have found their way into the market with products that does not strictly adhere to international standards such as the IEC 61869 series stipulated for instrument transformer. Such companies do not only impede the growth of the market but pose a risk to several end-users who might have purchased products from them. Considering the delicate application of instrument transformers, any inaccurate device will serve as a threat to the network or user.

3.4 Ecosystem of Instrument Transformers Market

The market system of instrument transformers is a complex web of different players in various market segments. The ecosystem of instrument transformers is composed of various components such technologies, stakeholders, manufacturers and suppliers, utilities and power system operators, market demarcations and regulatory bodies such as the International Electrotechnical Commission (IEC) for ensuring quality, reliability, and safety of instrument transformers. The instrument transformers market is dominated by major companies that are well-established, financially stable, and have extensive experience producing instrument transformers. These firms have a substantial market presence and provide a wide range of products. They use innovative technology and have significant international sales and marketing networks[84]. In no order, some notable market players are ABB, Siemens, General Electric, Hitachi, Ltd, Schneider Electric, Mitsubishi Electric, Nissin Electric Co., Ltd., Instrument Transformer Equipment Corporation, Inc etc. Although the instrument transformers market is very big, is dominated by only a few notable well organised firms. Various reports have it that, the market of instrument transformers is less concentrated however, several other unorganized firms have a significant influence on distorting the market. All the components of the ecosystem interact to ensure the smooth running of the market. In figure 3.3, the complex ecosystem of instrument transformers showing how the components interact with one another is presented.

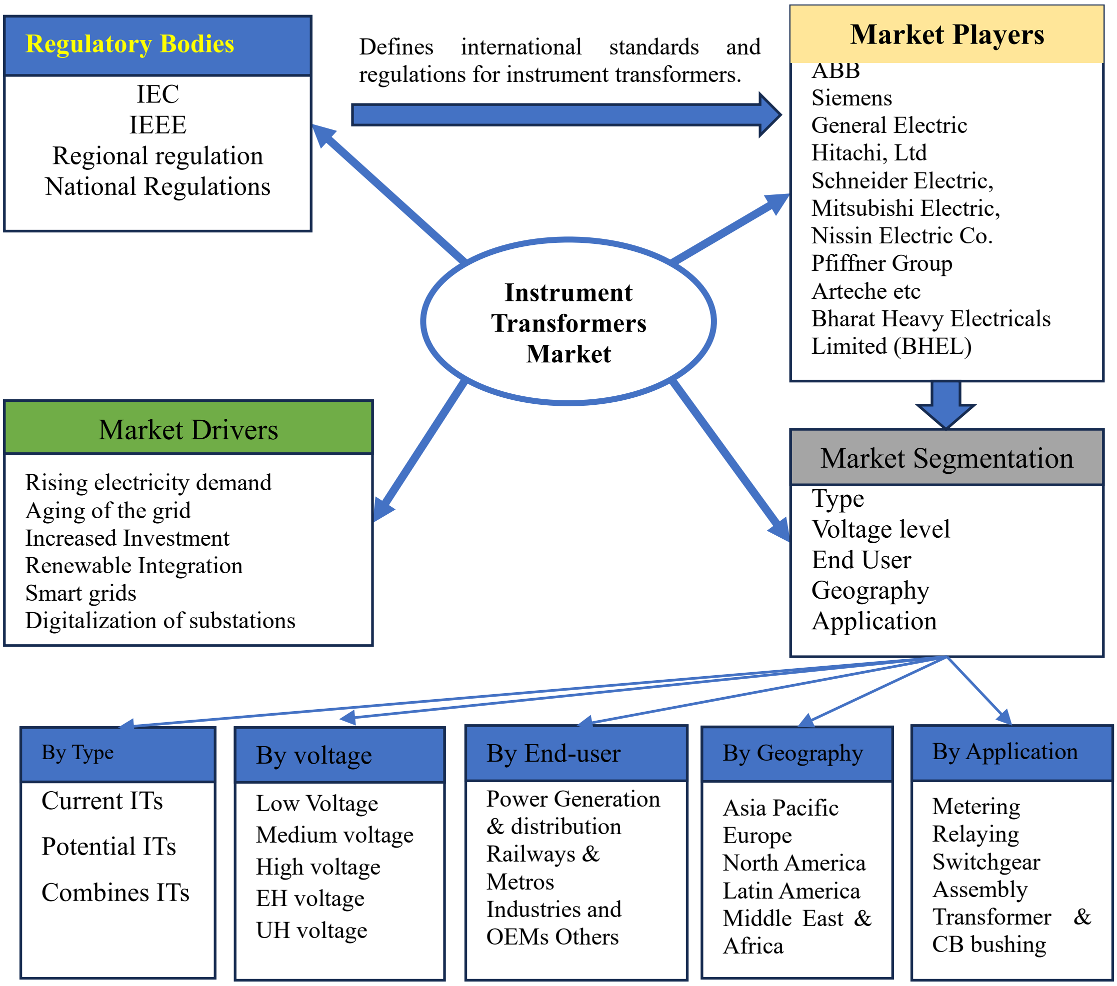


Figure 3.3 Ecosystem of Instrument Transformers Market

3.5 Regional Instrument Transformer Market Analysis

As stated previously and depicted in figure 3.3 above, by geography, the market of instrument transformers has been divided into regions. Asia Pacific, Europe, North America, Latin America and Middle East and Asia (MEA) are the main regions. Asia Pacific region is constituted by China, Japan, South Korea, India and Australia while Europe is made up of France, Italy, Russia, Spain, Netherlands, UK, Germany, the rest of Europe. USA and Canada make up the North America region. Latin America is composed Mexico, Brazil, Peru, Argentina etc. The countries constituting the MEA region are Saudi Arabia, UAE, Qatar, South Africa, Nigeria, Egypt and other African counties. The market exhibits different trends and driven by different factors in each of these regions.

Figure 3.4 Geographical Market Segmentation

The market and its drivers for instrument transformers varies significantly in each of the regions listed above. Generally, the market within any geographical location is assessed based on the growth and advancements of the power grid and other end user of instrument transformers. Analysis and forecast by various research institutions assume a linear trend between the growth or decline of the market with respect to all applications. For instance, a high investment for construction of new high voltage DC networks in any region simply implies that the market for DC instruments is will witness the steady growth or boom in that regions. This assumption is true for other applications such as the transportation section, industries, and others. In the next sections, the market dynamics for instrument transformers in each of the regions will be analysed.

3.5.1 Asia Pacific Market

According to the projections of all the 10 instruments transformers market reports reviewed in this section, Asia Pacif is the region with a flourishing market and also forecasted to have the highest compounded annual growth rate (CAGR) in the next decade. This makes Asia Pacific region dominant in the market. Several factors and drivers account for this results. The primary factors propelling the market in this area include rising power demand, governmental efforts to boost power generation through renewable sources, and the modernization and expansion of aging grid systems. The region comprises significant economies such as China, India, Japan, Australia, and the wider Asia Pacific region, including South Korea. Rapid advancements, especially in major economies, drive growth across various sectors, including power transmission, distribution, industrial, commercial, residential applications, and transportation. Urbanization and industrialization are swiftly progressing in the Asia-Pacific region, leading to heightened power requirements. Moreover, ongoing infrastructure endeavours, notably in growing Asian-Pacific economies, necessitate robust electrical systems. Instrument transformers play a crucial role in ensuring the effectiveness and resilience of electrical infrastructure, thereby fuelling market expansion. For example, in 2020, China allocated approximately USD 26.8 billion towards 14 Ultra-High Voltage (UHV) projects, comprising six Ultra-High Voltage Direct Current (UHVDC) transmission line projects, a back-to-back converter station, and seven Ultra-High Voltage Alternating Current (UHVAC) transmission projects, aiming to augment its UHV infrastructure. These initiatives are projected to boost the demand for instrument transformers across the region. Also in India, South Korea, Japan, and Indonesia, there is a notable surge in power consumption. These patterns are amplifying the demand for effective electrical infrastructure solutions throughout the Asia-Pacific region hence an anticipated growth in the instrument transformer market. In the Asia-Pacific region, major markets consist of China, India, Japan, Indonesia, and Australia. China holds the largest market share in the Asia-Pacific region, driven by rapid urbanization and industrial growth.

3.5.2 North America Market

The North American market is expected to experience substantial growth, driven by changes in the power sector structure in developed nations like the U.S. and the increasing adoption of smart grid technologies in the region. While some reports indicate that North America's instrument transformer market holds the second-largest share globally, others suggest that Europe occupies this position. Nevertheless, the rising investment in the power sector is anticipated to propel market expansion. Increased investments in power plants, electricity generators, and storage power stations are also expected to contribute positively to market growth. The automation and modernization of electrical infrastructure in North America are expected to stimulate demand for instrument transformers. In the Americas, the United States and Canada are significant markets for instrument transformers due to their robust technological architecture and highly developed energy infrastructure. The demand in this region is primarily fuelled by the need for grid modernization and the integration of renewable energy sources. The United States, as a mature market, has witnessed steady adoption of advanced technologies like smart grids, which require sophisticated instrument transformers for precise measurement and control.

3.5.3 Europe Market

The European region is poised for market growth fuelled by increasing electrification and expanding electrical grids. European Union (EU) countries are leading the way in adopting renewable energy sources, which in turn is driving demand for advanced instrument transformers capable of managing the intricacies of renewable energy systems. Energy efficiency and sustainability are top priorities, prompting substantial investments in research and development. Strict regulations governing the quality, performance, and construction of electrical equipment have established a highly standardized framework, encouraging the development of innovative and advanced instrument transformers. The instrument transformer market in Europe is experiencing several notable trends, including a rise in industry consolidation. Factors such as the pursuit of economies of scale, the desire to explore new markets, and the necessity to invest in new technologies are driving this consolidation. An example of a recent consolidation in the European instrumental transformation market is the establishment of a new joint venture firm in Spain called Arteche Hitachi Energy Instrument Transformers S.L. This collaboration was announced by Hitachi Energy and the Arteche Group. With the combined expertise of Arteche Hitachi Energy Instrument Transformers S.L. and Hitachi Energy, the partnership brings together a strong legacy of innovation and excellence in instrument transformer production[87].Additionally, the increasing importance of technology is evident in the European instrumental transformation market. The push to penetrate new markets and enhance productivity and efficiency is propelling the market forward. However, the European instrumental transformation market faces challenges as well. One significant hurdle is the need to comply with various regulations (mentioned earlier as a pro), which can vary from country to country, posing a considerable challenge for market players[88].

3.5.4 Latin America Market

Latin America: Although the instrument transformer market in Latin America is comparatively smaller than in other regions, it offers substantial growth prospects. Countries such as Brazil and Mexico are experiencing heightened investments in power infrastructure projects and initiatives aimed at modernizing the grid, which in turn is fueling the demand for instrument transformer solutions. According to credence research, Latin America currently holds approximately 8% of the market share, with potential for further expansion as the region continues to advance its power sector. Factors such as the region's expanding metropolitan areas, increasing population, rising power consumption, and the imperative to renovate existing power grid networks will contribute to the growing demand for transformers in the foreseeable future. Key players operating in this region include ABB, Siemens, and Trench Group, among others.

3.5.5 Middle East and Africa (MEA) Market

The electrification of the African continent in the coming decades is expected to significantly increase demand for instrument transformers[85]. There is a growing focus on extending the power grid to include rural areas in many developing and underdeveloped countries worldwide, including Africa. Regions such as Africa, which have limited electricity connectivity, have introduced various initiatives to extend the grid to remote locations. For example, Power Africa, a project led by the United States, aims to provide 30 GW of power by 2030, benefiting around 60 million households in remote areas of the continent. This presents an opportunity for the expansion of operations in the region. Europe, Middle East, and Africa (EMEA) region offer a diverse market landscape for instrument transformers. Africa's increasing need for electrification and the expansion of its power infrastructure are driving demand for both conventional and smart instrument transformers[90]. The expansion or construction of new distribution and transmission networks ensures that instrument transformers can be deployed in greater detail, further contributing to market growth [91]

3.6 Voltage Level Market Analysis: Towards HVDC or LVDC?

To reiterate, the voltage level market is segmented into low, medium, high, extra-high and ulta-high voltage markets. Although many reports provide wholistic analysis and projects which voltage level is likely to dominate the market, this approach suffers from overgeneralization. The direction of the voltage level is seen to be heading towards different directions in different geographical regions due mostly to the market drivers elaborated above. For better assessment, the routes in each of the regions will be considered separately.

3.6.1 Asia Pacific

Beginning with the Asia Pacific region, several notable projects on ultra-high voltage DC and AC justifies that in this region the trend for instrument transformer market is moving towards the UHVDC voltage level. An illustrative instance is the successful implementation of the +800kV, 6000 MW ultra-high voltage direct current (UHVDC) link connecting the Western (Chhattisgarh) and Southern (Tamil Nadu) grids in India. This achievement was announced by Bharat Heavy Electricals Limited (BHEL) in September 2021. As per BHEL's statement, the company contributed to the project by supplying instrument transformers, converter transformers, filter bank capacitors, shunt reactors etc from its Bhopal facility[88]. Similarly in China the State Grid Corporation of China (SGCC) in 2023 commenced the construction of an ultra-high voltage transmission network with a rated voltage of ±800 kV, with a total investment of 28.6 billion yuan (about $3.97 billion)[92]. The necessity for grid expansion to connect sparely located power stations and satisfy the growing demand for electricity is the primary driver for UHV systems in this region. Also, in 2020, China allocated approximately USD 26.8 billion towards 14 Ultra-High Voltage (UHV) projects. These projects included six ultra-HVDC transmission line projects, a back-to-back converter station, and seven ultra-HVAC transmission projects, aimed at expanding its UHV infrastructure[88]. Several other countries in this region are following same trend. The Australia-Asia PowerLink project, which is a significant solar link between Australia and Singapore, was approved by Indonesia in September 2021. This massive USD 22 billion project utilizes high-voltage undersea cables to transport solar-generated electricity over 5000 km through Indonesian waters to Singapore. The project includes an 800 km, 3 GW high voltage direct current (HVDC) overhead transmission line stretching from the Solar Precinct to a location near Darwin. The Central Luzon Link Expressway (CLLEX) Transmission Line in the Philippines, a 500 kV transmission line, is anticipated to be finalized by 2023. Similarly, the Java-Bali Transmission Line in Indonesia, scheduled for completion by 2025, will be a 500 kV transmission line connecting the Java and Bali islands. This connection aims to improve the reliability and stability of the power supply in both regions. In October 2021, the government of Pakistan received recognition for the successful implementation of the newly established ±660kV Matiari-Lahore high-voltage direct current (HVDC) transmission link, which operates under the China-Pakistan Economic Corridor (CPEC) initiative[82]. Many other industrialized countries in this region are following same trend and this clearly depicts and confirms that instrument transformers market is toward UHVDC.

3.6.2 North America

With regards to North America the dynamics of the voltage segment market for instrument transformers is quite undulating. This region being comprised of federal states, the need for ultra-high voltage transmission is less vivid. The voltage segment market in this region is leaning towards high voltage level. The need to increase the current power generating and transmission capacity in this region is said to be a result of the rising demand for electricity brought on by the expanding population and industries. North America is also known to account for a large number of industries and original equipment manufacturers (OEMs). In addition to that, The US government has implemented rules and incentive programs to better conventional electrical networks in rural areas and integrate sustainable resources. According to FactsMR [88] In 2021, the instrument transformers market in North American made a revenue of over USD 420 million primarily due to increased funding for the construction of long-distance power networks. These instances confirm that the market in this region is trending towards high voltage level. Although there are notable extra and ultra-high voltage projects in the regions such as the Atlantic Wind Connect, the market is not expected it trend towards that voltage level.

3.6.3 Europe

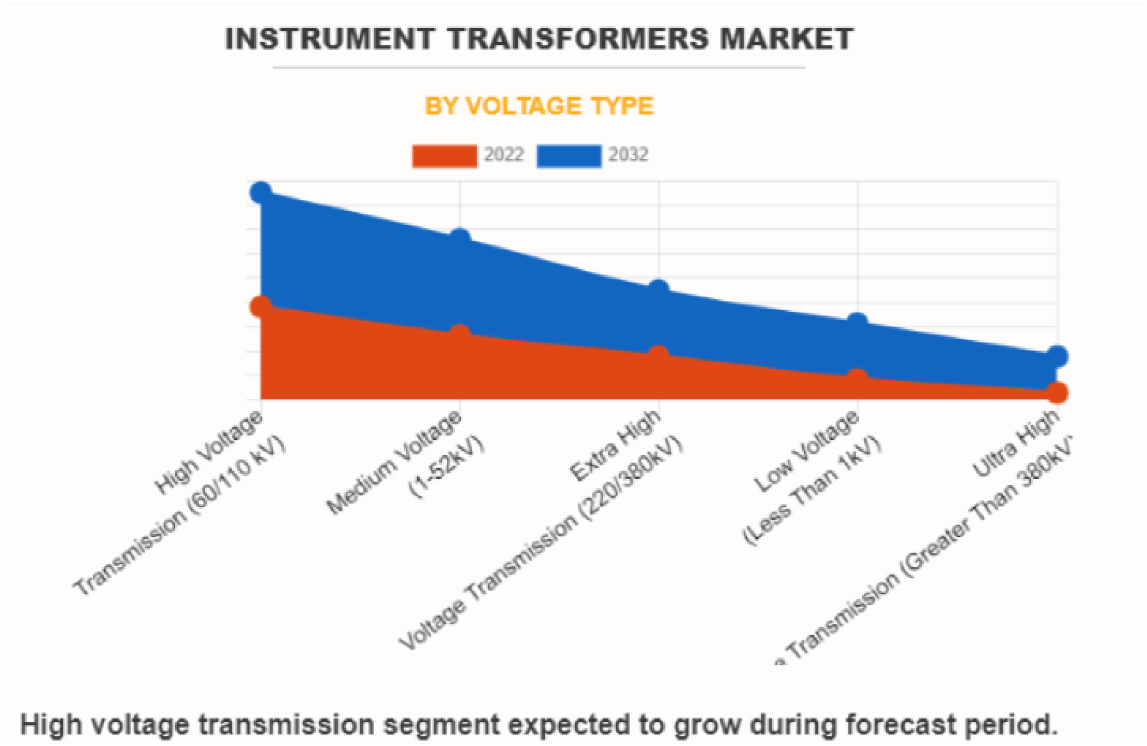
In the European region the instrument transformer market is leaning towards the high voltage levels. Europe is known for leading the way in adopting renewable energies and this is one of the drivers of the instrument transformer market in this region. Offshore wind, large scale solar PV and other renewable power sources are usually far away from the transmission grid and hence power generated from these sources needs to be transported to the grid. Considering that the future grid is going green, one can say with a satisfactory confidence level that future of instrument transformers in Europe lies in the hands of High voltage (HV). Europe's bigger ambition to incorporate large scale renewable energy requires expansion of the high voltage transmission network. In addition, Europe is also known to be actively working on improving cross-border electricity interconnections to enhance energy security, promote market integration, and facilitate the exchange of renewable energy. High voltage DC (HVDC) transmission being the effective technology for both long distance transmission and renewable energy integration, the demand for DC instrument transformers is mostly like to surge in Europe. This further strengthens the argument that in Europe, instrument transformers are leaning towards HVDC. For instance, 10 European countries forming the North Sea Countries joined hands in a Memorandum of Understanding (MoU) to implement the "Offshore Grid" Initiative. This project seeks to develop an offshore electricity grid in the North Sea to harness offshore wind power and connect it to onshore grids using HVDC technology. These projects among others in the European region drives the marker towards HVDC.

3.6.5 Middle East and Africa (MEA)

The MEA region which is dominated by developing economies is expected to experience a market trend leaning towards medium voltage. Most countries in this region are experiencing a rapid industrialization which is poised to surge demand for electricity. This the lack of universal access to electricity further propels the demand for electricity. According to African Energy outlook 2022 by the International Energy Agency (IEA) about 600 million people which is approximately 43% of the total population Africa, lack access to electricity [93]. A trend towards universal access fuelled by national contributions is observable. Nations like Ghana, Kenya, and Rwanda are making significant progress toward achieving full access by

2030, providing inspiring examples for other countries to emulate. How does this trend influence the instrument transformers market in this region? The ambition to reach universal electricity access calls for the construction and expansion of more distribution networks. As stated earlier, instrument transformer market is deemed to have to linear correlation with growth electrical infrastructure. Distribution of power to rural African communities to achieve universal access to electricity will accelerate the medium voltage instrument transformers market in the region. Generally, the growing demand for electricity in the middle east countries and Africa drives the market in the MEA region towards medium voltage applications.

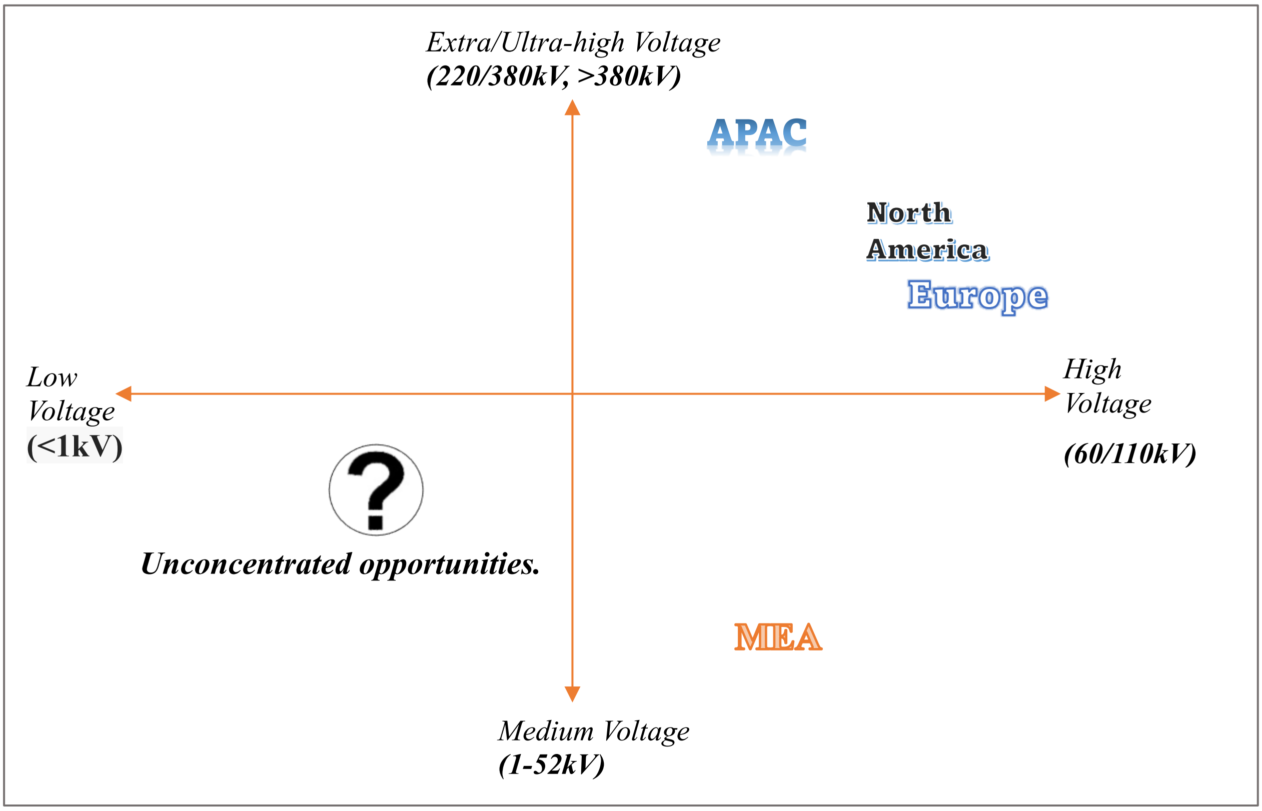
According the report by Allied Marker Research, globally the instrument transformer market by voltage level is currently dominate by high voltage and it’s expected to retain this spot for the next decade. The order of the trend follows: $high\ voltage \leftarrow medium\ voltage \leftarrow extra\ high\ voltage \leftarrow low\ voltage \leftarrow utra - high\ voltage$. Figure 3.5 below for the plot of the global trend.



High voltage transmission segment expected to grow during forecast period.

Figure 3.5 Voltage Market Segment Forecast

While this graph provides a wholistic understanding of which voltage level has the most potential in the market, it lacks in depth regional breakdown. Although this is true for at a global level, at the regional level differences exit. Following the regional analysis for voltage level market, figure 3.6 below gives further details on the trends at regional level.



3.7 Instrument Transformer Market Trends

Based on the review of the reports on instrument transformers published by various research institutions and the analysis carried out in this research, the major market trends and projections are listed below.

I. Asia Pacific (APAC) Dominates the Market. Very Lucrative Region of Instrument Transformers Marke
II. By ender user, Power Utility Sector likely to dominate the market.
III. China instrument transformer market share likely to increase due to new initiatives

CHAPTER 4

CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

This thesis has provided a comprehensive analysis of DC instrument transformers, addressing the challenges arising from the increasing demand for accurate measurement of DC signals in electrical power systems. By examining various types of DC instrument transformers and evaluating their performance characteristics, this research has contributed to the understanding of their operational principles and capabilities. From the comprehensive examination, a table has been developed consisting of 15 key performance indicators and 8 DC instrument transformers forming a *15x8* comparison matrix. From the comparative analysis, Fiber Optic Current Sensor (FOCS) dominated the DC instrument transformers. Furthermore, the investigation into market dynamics and regional trends has shed light on the evolving landscape of the instrument transformer market, highlighting opportunities for growth and expansion, particularly in the emerging markets. Overall, the insights gained from this study can inform decision-making processes in the power industry, guiding stakeholders in selecting and deploying efficient measurement solutions to meet the growing demands of modern electrical power systems.

4.2 Recommendations

Following the intensive technical and economic analysis of instrument transformers for DC power networks, the following recommendations are proposed for any company/player seeking to enter the market for instrument transformers.

1. Fiber optic current sensor is the best instrument transformer to manufacture and distribute because it satisfies most of the requirements by customers. This instrument is expected to penetrate deep in the market because of several satisfactory performance. In quest to transition to digital substations, this instrument presents a huge opportunity in the market for instrument transformers.
2. The instrument transformer market in emerging economies such as Africa, Asia and Latin America is ripe and ready for exploitation. These regions are investing heavily to expand its electricity infrastructure. Incoming market players can target these regions seeking to cater for their unique needs while establishing partnerships with local players to expand their reach and increase their market influence.

3. In the next few decades, the electrical infrastructure of Africa will begin aging propelling the need for replacement. This will boom the market of instrument transformers in the regions. For long term investment, this is the right time for an incoming market player to establish a base and build strong connections ahead of the anticipated flourishing market. To maximize opportunities, the player should concentrate on rapidly expanding regions while also preserving their position in slower-growing markets.
4. Prevailing strategies used by notable players of the market to dominate the market are Collaboration and Agreement, consolidation, product release and Acquisition. By emulating these tried and tested market strategies, an incoming company can break through the market. Typical examples are Siemens acquiring C&S Electric Limited in India to expand its low voltage manufacturing in India and also in Europe where Hitachi Energy and the Arteche Group join hands to form Arteche Hitachi Energy Instrument.
5. Although electric vehicles are growing rapidly, most regions are not leaning towards low voltage applications. Focusing on low voltage instrument transformers can be a lucrative venture in the near future. Hall based current and voltage sensors are recommended in this regard.

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APPENDIX A: SUMMARY OF DATA SOURCES

	DATA SOURCES			
Section	*Journal/Conference papers*	*Reports*	*Webpages*	*Total*
General Introduction	15	0	0	15
Fiber optic current sensor (FOCS)	6	1	1	8
Hall Transformers-GENERAL	9	0	2	11
Open Loop Hall Current Transformer	3	0	0	3
Closed Loop Hall Current Transformer	4	0	0	4
Coreless Hall Current Transformer	8	0	0	8
Pockels Optical Voltage Sensor	5	0	2	7
Closed Loop Hall Voltage Transformer	3	0	1	4
Shunt Resistor current Transformer	7	0	3	10
Resistive Voltage Divider	5	2	3	10
Market Analysis	0	11	2	**13**
TOTAL				**93**