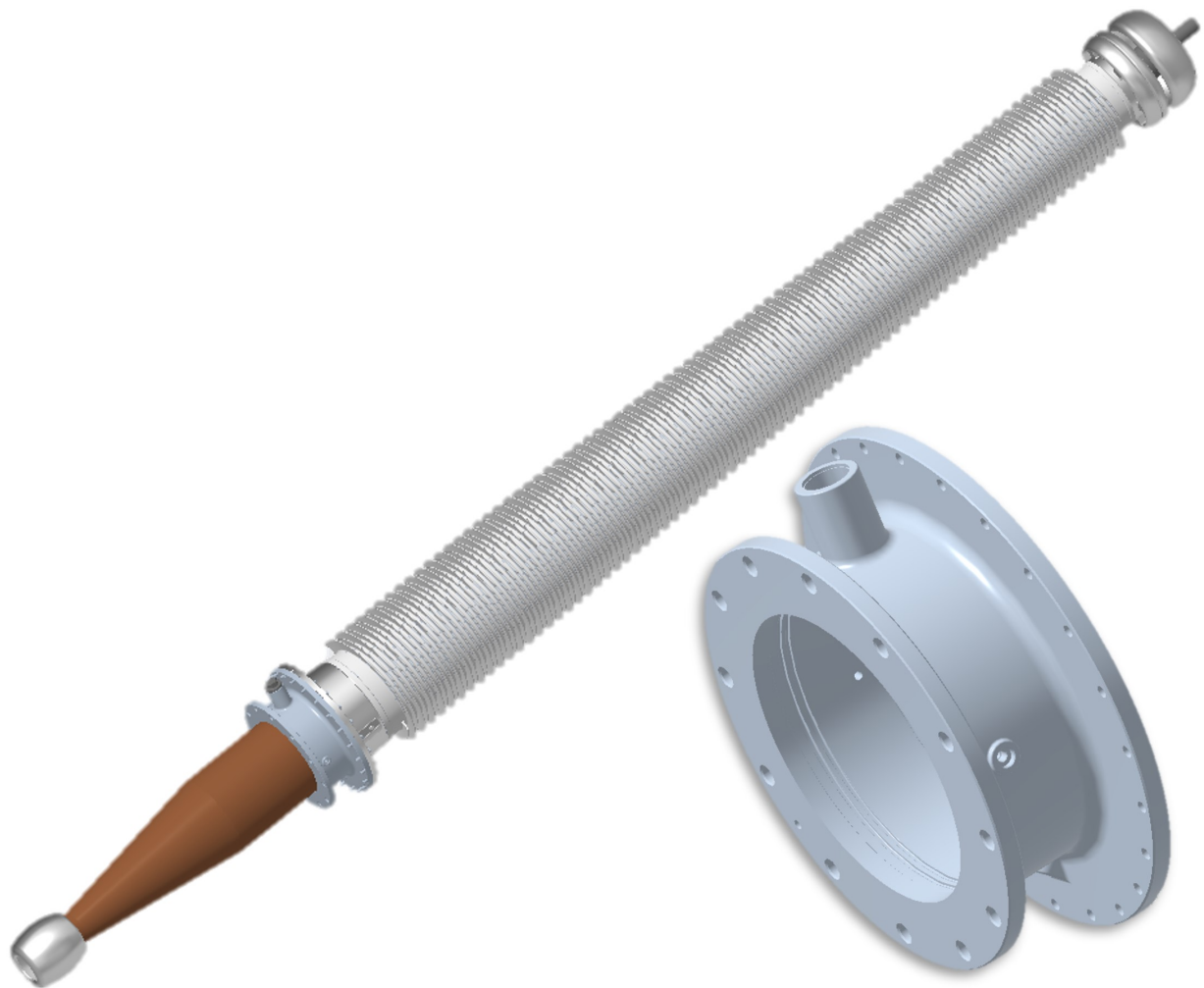




**CHALMERS**  
UNIVERSITY OF TECHNOLOGY



## **Dual Taps on Transformer Bushings**

Master's thesis in Product Development

**SIBI PRANAV RAJARAJAN**

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DEPARTMENT OF INDUSTRIAL & MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2025

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# Dual Taps on Transformer Bushings

SIBI PRANAV RAJARAJAN



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*Division of Product Development*  
CHALMERS UNIVERSITY OF TECHNOLOGY  
Gothenburg, Sweden 2025

Dual Taps on Transformer Bushings

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Dual Taps on Transformer Bushings  
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## **Abstract**

In power systems, High Voltage (HV) bushings play a major role in preventing major transformer failures or any unplanned outages in the network. It conducts current through a wall or a grounded steel tank of a transformer. According to the statistics, bushing failure is one of the major causes for the transformer failure, accounting for 15-30%. Therefore, it brings greater importance to monitor the condition of the bushing through an online monitoring system continuously. Also, the condition of the bushing is monitored periodically by manual testing after taking the bushing out of service. In Hitachi Energy Sweden AB, the bushings are provided with a single tap configuration, either a test tap or a voltage tap, to connect the online monitoring system or the offline equipment during manual testing. The customer needs to disconnect the online monitoring system to perform manual (offline) testing. The process of connecting and disconnecting the online measuring system is time-consuming and poses safety issues to the testing personnel. The goal of this thesis work is to develop a dual tap configuration that allows the customer to perform offline and online measurements in parallel.

To develop the intended dual tap configuration, the primary step was to analyze the feasibility of the possible configurations, followed by generating concepts that fulfill the desired functionality. Once the concepts were generated through functional analysis and morphological matrix, the next step was to screen the concepts through elimination matrix, Pugh matrix, and Kesselring matrix, resulting in finalizing the concept. Finally, the chosen concept was developed into a digital prototype that serves the intended functionality.

Keywords: Test Tap, Voltage Tap, Online Bushing Monitoring System, Capacitance



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Sibi Pranav Rajarajan , Gothenburg, September 2025



# List of Acronyms

Below is the list of acronyms that have been used throughout this thesis, listed in alphabetical order:

|         |  |
|---------|--|
| AC      | Alternating Current                                  |
| AI      | Artificial Intelligence                              |
| BIL     | Basic lightning-impulse Insulation Level             |
| BOM     | Bill of Materials                                    |
| BEP     | Break-even Point                                     |
| CAD     | Computer Aided Design                                |
| CAGR    | Compound Annual Growth Rate                          |
| CIGRE   | Conseil International des Grands Réseaux Électriques |
| DC      | Direct Current                                       |
| DF      | Dissipation Factor                                   |
| FMEA    | Failure Mode and Effects Analysis                    |
| GIS     | Gas-Insulated Switchgear                             |
| GST     | Grounded Specimen Test                               |
| HV      | High Voltage   |
| HVDC    | High Voltage Direct Current                          |
| LTspice | Linear Technologies SPICE                            |
| LV      | Low Voltage  |
| NPV     | Net Present Value                                    |
| OIP     | Oil Impregnated Paper Bushing                        |
| PD      | Partial Discharge                                    |
| PTC     | Parametric Technology Corporation                    |
| PEEK    | Polyetheretherketone                                 |
| PTFE    | Polytetrafluoroethylene                              |
| PF      | Power Factor   |
| PSU     | Public Sector Unit                                   |
| RBP     | Resin-Bonded Paper Bushing                           |
| RIP     | Resin-Impregnated Paper Bushing                      |
| RIS     | Resin-Impregnated Synthetics Bushing                 |
| OEM     | Original Equipment Manufacturer                      |
| UHV     | Ultra High Voltage                                   |
| US      | United States  |
| UST     | Ungrounded Specimen Test                             |



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# 1

## Introduction

This chapter describes the company background, the purpose and scope of the project, the limitations in the work, research questions, the report outline, and the competitor analysis.

### 1.1 Company Background

Hitachi Energy is a global technology leader in manufacturing transformers and HV equipment, and offers services related to developing renewable energy integration. They produce and supply all the integral devices in an electric power grid, ranging from power plants to consumers. It has its headquarters in Zurich, Switzerland, with 45,000 employees globally and operational branches in over 90 countries. In Sweden, Ludvika is considered to be one of the most crucial facility of the company. Here, the major products manufactured are power transformers, HV equipment, and building up the HVDC links. Hitachi Energy components come under the business unit of power transformers, wherein the components for transformers & HVDC stations are manufactured. The main products that are being delivered from components are bushings and tap changers. The thesis work focuses on transformer bushings.

Hitachi Energy has been a demanding supplier in bushing technology for over 100 years, with customers globally. They have the most reliable and wide portfolio of bushings for various applications. Also, they have had their global footprint in delivering dry bushing technologies for over six decades. Hitachi Energy Sweden AB is one of the bushing manufacturing factories located in Ludvika, Sweden. Bushings that are manufactured at Ludvika can withstand the harsh environmental conditions and also meet the international standard requirements for safety and reliability. Additionally, they offer other services to prevent any foreseeable failure by early identification of defects, such as diagnostic tools and monitoring devices. They provide the greatest benefits to the customers, which include minimizing downtime, seamless upgrades, offering replacements, transparency in cost, fast and reliable deliveries.

### 1.2 Project Background

In High Voltage (HV) transformers, the bushing is a vital component, as it conducts current through a wall or grounded steel tank without causing flashover or short circuit. According to [13], bushing failure is one of the major causes of transformer

failures. IEEE, IEC, and CIGRE statistics show that around 15-30% of transformer failures are due to the failures in the installed bushings, and specifically, more than 40% of those failure events of bushings resulted in disastrous consequences such as explosion, fire, tank rupture, etc. In the case of generator step-up transformers, the major failures are caused by the bushing malfunction, which causes 30%. Therefore, it is of great importance to continuously monitor the bushing condition by using online monitoring systems. In addition, the standard capacitance or power factor test is performed at power frequency 50 Hz/60 Hz to evaluate the bushing condition periodically, which is usually an offline testing procedure. However, the main purpose of online monitoring systems is to provide the real-time evaluation of bushings when in service. This enables the early detection of any fault or the signs that may cause potential defects, and this, in turn, improves the longevity of bushings. [13].

In line with the above context, the conventional technique allows the customer to use the single tap configuration, either the voltage tap or the test tap, and perform an offline test by disconnecting the online monitoring system and reconnecting the online system to resume the measurement of capacitance and loss factor after the offline measurement. The significance of capacitance and dissipation factor will be discussed in the upcoming chapter. This process of disconnecting and connecting the online system is time-consuming and involves safety complications for the personnel handling the online equipment. The project focuses on addressing the specialized customer request to bring up the solution for the development of a dual tap to conduct periodical offline testing and perform the online and offline measurements in parallel without compromising the safety and reliability in measurement.

### 1.3 Objective of the Thesis

The thesis aims to develop a dual tap design for transformer bushings to facilitate online and offline measurements in parallel. The customer expects one of the taps, particularly the *voltage tap*, to be equipped with the online monitoring system, while the *test tap* to conduct offline testing. They must be consistent with one another, ensuring reliability. The design prototype must also consider the implications in bushing manufacturing, assembly, cost, and compliance with relevant standards.

### 1.4 Limitations

The limitations in this project are listed as follows,

- The primary outcome of the project is limited to developing only the digital prototype design of a dual-tap configuration for transformer bushings.
- Due to time limitations, the final production and implementation of the design is not carried out in this project work.
- The market study of the developed design is not performed as the main goal is to investigate the technical feasibility, estimation of cost, and impact analysis in product assembly.

## 1.5 Research Questions

The project presented in this report will bring solutions to the following questions through the thorough analysis and brainstorming sessions.

1. What are the current challenges faced by customers in using single tap for both online and offline testing?
2. How do the competitors address the requirement of two taps on bushings?
3. How will the new design impact the existing bushing assembly process?
4. What is the cost implication associated with the new design?

## 1.6 Outline of the Report

The documentation of the work is presented in such a way that it gives the reader a clear understanding of its purpose, the analysis performed to validate the requirement, and the detailed process flow in bringing up the solution for the stated problem. The structure of the report is formulated as follows:

- Chapter 1: Introduction, which explains the background, purpose, and limitations of the project.
- Chapter 2: Theory, that describes bushing and its types, offline testing, and online monitoring system in a detailed manner.
- Chapter 3: Competitor analysis and benchmarking, explains the detailed analysis of bushing manufacturers in the market and benchmarking solutions for the problem stated above.
- Chapter 4: Methods, that presents an overview of procedures, required to arrive at the final solution.
- Chapter 5: Results, that comprehensively explain the circuit configuration, concept generation, concept screening, and the development of the final prototype.
- Chapter 6: Commercial assessment, that explains the product structure, Bill of Materials (BOM), and the market competitiveness of the designed final prototype.
- Chapter 7: Conclusion, that presents a brief discussion of the overall project and future work.



# 2

## Theory

### 2.1 High Voltage Bushing

The standard IEC 60137 that gives the characteristics and guidelines for testing of bushings, defines HV bushing as "device that enables one or several conductors to pass through a partition such as a wall or a tank, and insulates the conductors from it; the means of attachment (flange or fixing device) to the partition forms part of the bushing" [16]. The standard C57.19.00 elaborates IEEE guidelines of testing procedure for bushings, and it defines the bushing as "an insulating structure, including a through conductor or providing a central passage for such a conductor, with provision for mounting a barrier, conducting or otherwise, for the purpose of insulating the conductor from the barrier and conducting current from one side of the barrier to the other" [4]. In simpler terms, the bushing comprises current-carrying HV conductors that travel through the grounded barrier such as wall or transformer tank [2]. The bushing provides the insulation support to the wall of the buildings or equipment, such as transformers, generators, both mechanically and electrically [1]. The main function of the bushing is to offer insulation support to the device during its normal operation or when overvoltages occur due to lightning, switching events in the power system network. Additionally, the line conductors and external connections are mechanically supported by the installed bushings [7][2]. The bushing insulation system must be designed in such a way that it is capable of withstanding the operating voltage and overvoltages [1]. In case of the conductor design, it must be capable to carry the rated current so that it does not overheat the surrounding insulation [3].

#### 2.1.1 Types of Bushings

Bushings are classified in many ways, according to their rated voltage, their application of end usage, and the materials used for the insulation [3]. Based on their real time usage, the bushing are classified as follows

1. Based on the insulation media on the ends
2. Based on the core construction type

##### 2.1.1.1 Based on the insulation media on the ends

The following sections explain the different types of bushings based on their end application, which determines the insulation medium on both ends.

### 2.1.1.2 Air to oil type



**Figure 2.1:** Air to oil - Transformer bushing [8]

Air to oil bushing type has two different insulation media on its upper and lower ends. The upper end of the bushing has air insulation medium, and the lower end of the bushing contains oil as insulation medium. The insulation strength of the oil is higher than that of air at atmospheric pressure, so the oil side length is shorter than the air side length. These type of bushings are generally installed in transformers i.e., between air and oil-filled apparatus [3]. The bushing of air to oil application is shown in the Figure 2.1 [8].

### 2.1.1.3 Air to air type



**Figure 2.2:** Air to air - Wall bushing [9]

Air to air bushing type has the same insulation medium on its upper and lower ends. Both the upper and lower ends of the bushing has air insulation medium. The outdoor air side insulation part has higher creepage length as it must have higher withstanding capability for harsh pollutants, depending on the site. On the other side, the indoor air side insulation part has comparatively lesser creepage length. Also, the outdoor insulation has higher flashover distance to endure overvoltages during natural phenomenon. These types of bushings are generally installed in buildings [3]. The wall bushing of air to air application is shown in the Figure 2.2 [9].

#### 2.1.1.4 Special type of bushings



**Figure 2.3:** Air to SF<sub>6</sub> bushing [10]

There are other type of bushings that are manufactured for special types of applications. They are air to SF<sub>6</sub> type, Oil to oil type, and Oil to SF<sub>6</sub> type. SF<sub>6</sub> circuit breakers require SF<sub>6</sub> type of bushing, also called gas bushing, oil to oil type is found between oil-filled device and oil bus ducts, and the oil to SF<sub>6</sub> type is found between oil-filled device and SF<sub>6</sub> bus ducts [3]. An example of gas bushing - air to SF<sub>6</sub> type is shown in the Figure 2.3 [10].

#### 2.1.1.5 Based on the core construction type

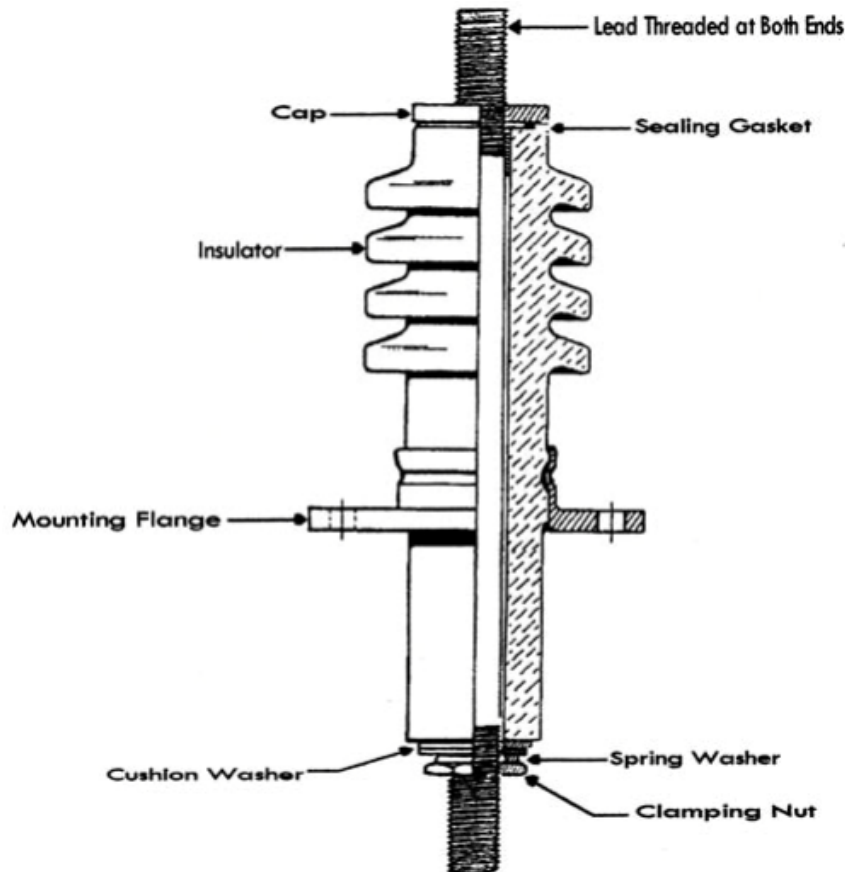
The bushings are classified into two types based on the construction of the core, namely

1. Solid or Non Condenser Bushing
2. Condenser or Capacitance Graded Bushing

#### 2.1.1.6 Solid or Non-condenser bushing

The construction of solid bushing is simpler than the condenser type as it comprises of single current carrying conductor housed in the cylindrical shaped insulation. The

insulation is generally made of paper, porcelain, epoxy, glass, resin, etc. Solid-type bushings are installed in lower kV transformers, which are used in the distribution system, in power generators, and in circuits for switching in generator step-up transformers.

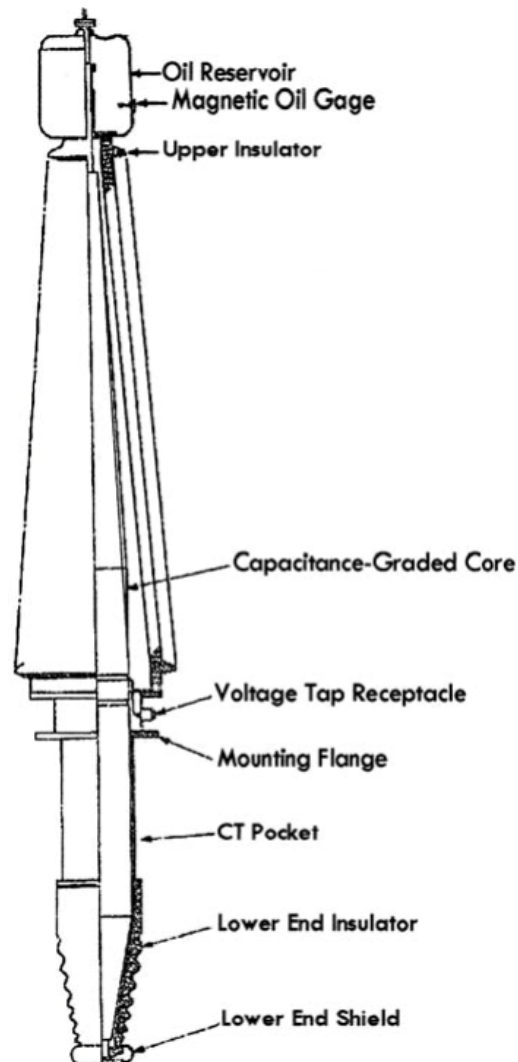


**Figure 2.4:** Solid bushing [3]

In the case of lower kV bushings, air is filled in the space between the central conductor and the outer insulation. On the other hand, for higher kV types, the space is filled with mineral oil of electrically graded type, and in some cases, the space is filled with a special compound. If it contains oil, it might be encompassed inside the bushing itself or in the device where it is installed. If it contains a special compound, it is encased inside the bushing itself. The usage of oil and the other special types of compounds offers higher insulation strength, good cooling properties, and eventually has a higher breakdown voltage. These characteristics provide higher withstanding capability during its operation and in the event of abnormal voltage rise.

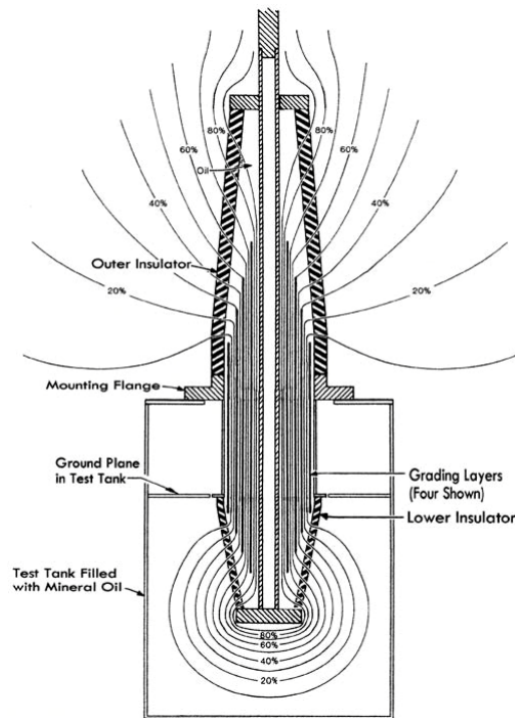
Non-condenser bushings are suited for lower kV applications and are not applicable for applications that require handling voltage higher than 90 kV at 60 Hz frequency. This type is cost-effective when installed for lower kV apparatus. Also, the electric field distribution is non-uniform in this type of bushing and, therefore, it is not recommended for HV installations. The simple geometry of a solid-type bushing is shown in the Figure 2.4 [3][2][7].

### 2.1.1.7 Condenser or Capacitance graded bushing



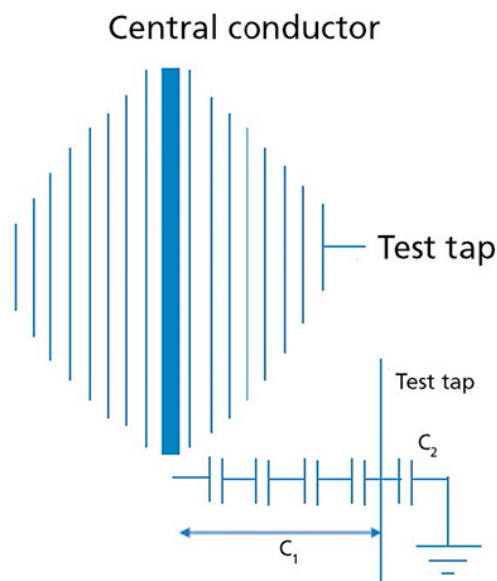
**Figure 2.5:** Construction of capacitance graded bushing - Oil filled [3]

The standard ANSI/IEEE Std. C57.19.00 defines the capacitance graded bushings as "in which metallic or non-metallic conducting layers are arranged within the insulating material for the purpose of controlling the distribution of the electric field of the bushing, both axially and radially" [4]. In simple words, the condenser type bushing comprises a conductor that carries current, wound by paper insulation, wherein the conducting layers are placed at specified distances radially alternatively with the insulating papers. The simple geometry of the capacitance-graded type bushing is shown in the Figure 2.5. The purpose of this pattern of construction is to obtain the uniform electric field and electric potential distribution by forming a chain of capacitance in series connection. The formation of series capacitance is depicted in the Figure 2.6.



**Figure 2.6:** Equipotential capacitance graded bushing [3]

The uniform distribution of the electric field and electric potential is achieved by forming an equal capacitance across each conductive layer. This entire setup is constituted as a condenser core and is present in the gap between the conductor and the outer insulating layer. The formulation of capacitance in series fashion inside the core is shown in the Figure 2.7. The test tap that is shown in the figure will be discussed in the upcoming Section 2.1.2.6.



**Figure 2.7:** Simplified representation of condenser core [14]

In previous years, the manufacturers constructed the core by arranging the metallised porcelain cylinders in concentric form or placing tube-shaped pressboards having conductive layers inserted within them. The majority of the bushing manufacturers in recent years have adapted to a condenser core design with the conductive layer of aluminium or copper together with oil-immersed kraft paper [3][2]. Instead of aluminium or copper layers, some manufacturers use printed semi-conductive ink, conductive paint or semi-conductive paper [3][7]. Hitachi Energy Sweden AB uses conductive layers made of aluminium, termed as foils. Therefore, in the forthcoming explanations, the term foils will be used instead of conductive layers in the core. Based on the insulation system in the core, the bushings are classified into four, namely

1. Resin-Bonded Paper Bushing RBP
2. Oil Impregnated Paper Bushing OIP
3. Resin-Impregnated Paper Bushing RIP
4. Resin-Impregnated Synthetics Bushing RIS

#### **(a) Resin-Bonded Paper bushing RBP**

In RBP bushing type, the core comprises resin-coated papers and each layer is adhered to the next consecutive layer by resin. Further, the core undergoes a curing process that brings bonding between the layers. The presence of voids in RBP-type bushing results in the occurrence of Partial Discharge(PD), and hence the application of RBP becomes obsolete [4][7].

#### **(b) Oil Impregnated Paper bushing OIP**

In OIP bushing type, the core comprises kraft papers and the aluminium foils inserted at pre-defined intervals. The gap between the OIP core and the outer insulator layer in the bushing is also filled with oil [4]. In here, the oil is filled under vacuum, and hence the formation of voids can be prevented. Some cases like misalignment of foils in the core cause the formation of gas cavities in the oil due to the higher field stress developed at the layers. This may eventually lead to breakdown of insulation [7].

#### **(c) Resin Impregnated Paper bushing RIP**

In RIP bushing type, the core comprises crepe papers and the aluminium foils inserted at pre-defined intervals. The benefits of this type are void-free, absence of gas cavities, and dry in nature. Overall, it exhibits lower losses in the insulation and is free of PD [7].

#### **(d) Resin Impregnated Synthetic Bushing RIS**

In RIS bushing type, the core comprises a synthetic polymer and the aluminium foils are inserted at pre-defined intervals. The core is then impregnated with resin under vacuum, resulting in a core which is close to PD-free and with very low dielectric losses [4].

### 2.1.2 Important parts of condenser type bushing

The important parts of the transformer bushing are a condenser core with a current-carrying conductor and the OIP/RIP/RIS insulation; outer insulation layer, metal flange, oil reservoir, corona ring and taps [11]. Bushings are designed, manufactured and tested in such a way that they exhibit higher withstanding capability to the mechanical, thermal, and electrical stresses when in service. Condenser-type bushings are the most suitable for HV applications since they uniformly distribute the stress in the bushing parts. The testing and maintenance help in developing an efficient and reliable bushing design, resulting in the maximum tolerance of stress that can be experienced by each material while maintaining normal bushing operation. This eventually increases the life time of the bushing to a minimum of 40 years [2].

#### 2.1.2.1 Conductor

In any type of bushing, the conductor is the main component which is designed to conduct the rated current and operate normally at rated voltage. The rated current determines the dimension of the conductor, which implies that the larger the rated current to carry, the larger the conductor diameter. The skin depth of the material influences the choice of the material and the dimensions of the conductor. The current-carrying conductor generates power loss, which affects the choice of the material and dimension of the conductor as well. Globally, most of the bushing manufacturers choose copper or aluminium for the conductor material, which depends on the end application. Usually, the different conductor diameter for different current ratings is defined by the bushing standards in IEEE/ANSI, and the manufacturers choose the diameter values by referring to these standards. If the conductor is designed to have larger diameter, they tend to endure high mechanical forces and have higher withstanding voltage [7].

#### 2.1.2.2 Outer Insulation Layer

The dimension, basically the width and length of the insulation layer, depends on the insulation medium and the type of core construction, either the condenser or non-condenser type. The length and size of the insulation layer should be designed to endure the normal voltage during the operation, transient over voltages during natural events such as lightning, and over voltages due to switching events in the power system network. For the applications with two different insulation media, the selection of the insulation length is determined by the insulation medium with the lesser dielectric strength. Air, Oil, SF<sub>6</sub> are examples of insulation media, and one among them will be chosen depending on the application [7].

#### 2.1.2.3 Oil Reservoir

Generally, higher kV bushing application requires this oil reservoir, also well known as an expansion chamber. At higher temperatures, an expansion chamber is necessary to encompass the mineral oil so that it contracts or expands depending on its temperature. Secondly, it is necessary to immerse the OIP insulation to retain its

insulating characteristics. In real time, an oil gauge is used to measure the oil level in the reservoir to ensure that a sufficient oil level is maintained [3][7].

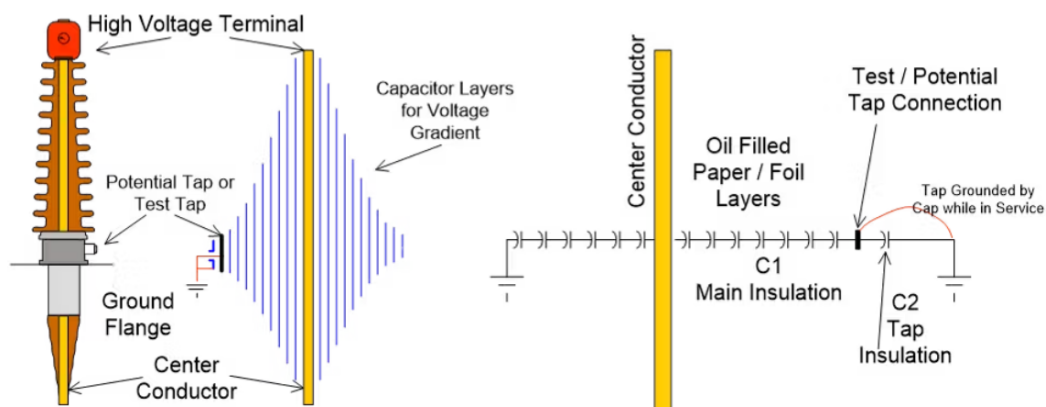
#### 2.1.2.4 Corona Ring

The main purpose of the corona ring is to prevent the corona discharge around the bushing head. The corona ring is popularly known in other terms as the corona shield or toroid. Corona discharge is an electrical discharge that arises due to the ionization of air around the sharp edges that are conductive in nature. It is a luminous and audible discharge with a hissing sound. In real time, the corona shields are larger in diameter, spherical in shape, and have smooth, polished surfaces to prevent corona discharge. An increase in operating voltage increases the diameter of the corona shield. The material of the corona ring is made of aluminium in HV bushings [12].

#### 2.1.2.5 Metal Flange

The primary function of the flange is used to install the bushing in the devices where it is required to be mounted. The other function is to accommodate the gasket. The material of the flange can be cast aluminium, steel, aluminium or non-magnetic materials. The flange of non-magnetic material is used for high-current bushings to nullify the magnetic losses in the flange. The metal flange also incorporates the tap housing that facilitates the provision for mounting the tap electrode, which will be used for online and offline testing procedures [3][7].

#### 2.1.2.6 Taps



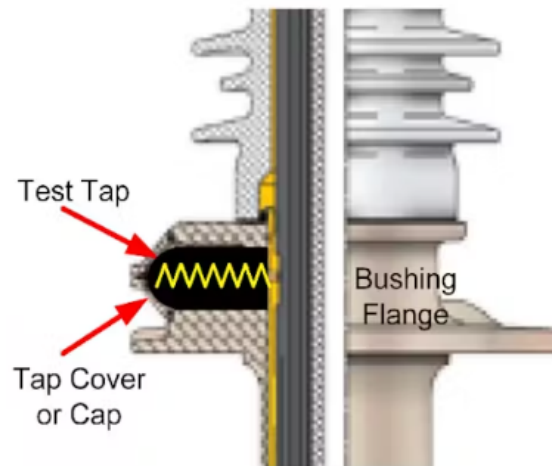
**Figure 2.8:** Electrical Representation of Capacitance Graded Bushing [15]

The bushing tap connection is configured in a way that it forms a voltage divider by splitting the total capacitance of the bushing into two separate capacitances  $C_1$  and  $C_2$ . The capacitance  $C_1$  is the total of all the capacitances from the central conductor to the tap electrode, and  $C_2$  is the capacitance from the tap electrode to the grounded flange. The Figure 2.8 depicts how the capacitances are splitted by the bushing tap [15][18].

### [i] Test Tap

According to IEC 60137, the test tap is defined as the connection that is insulated from the metal flange, as shown in the Figure 2.9 [15]. This tap can be accessible from outside of the bushing and connected to the outermost foil of the capacitance graded bushing type. The test tap facilitates the measurements of DF, capacitance, and PD while the flange is grounded. According to IEEE std, the bushings with Basic lightning-impulse Insulation Level (BIL)  $\leq 350$  kV are provided with a test tap, whereas according to IEC standard, the bushing should always be equipped with a test tap. The test tap is tested at 2 kV [16][4].

For the bushings with test tap,  $C_1$  is the capacitance between the conductor and the test tap, and  $C_2$  is the capacitance formed between the test tap and the grounded metal flange [17].



**Figure 2.9:** Test Tap [15]

### [ii] Voltage Tap

According to IEC 60137, the voltage tap is defined as the connection that is insulated from the metal flange, as in the Figure 2.10 [15]. This tap can be accessible from outside of the bushing and connected to the second outermost foil of the capacitance graded bushing type. The voltage tap acts as a voltage source for the external power equipment while the bushing is in operation, and also facilitates the measurements of DF, capacitance, and PD [16]. According to IEEE standard, the bushings with BIL  $>350$  kV is provided with voltage tap. The voltage tap is tested at 20 kV.

For the bushings with a voltage tap,  $C_1$  is the capacitance between the conductor and the voltage tap, and  $C_2$  is the capacitance formed between the voltage tap and the outermost foil [17]. Also, the  $C_2$  value is more reliable when the measurement is done at a voltage tap. This is because, at the voltage tap, the capacitance  $C_2$  is measured between the second outermost foil and the last foil which is connected to the grounded flange [4].

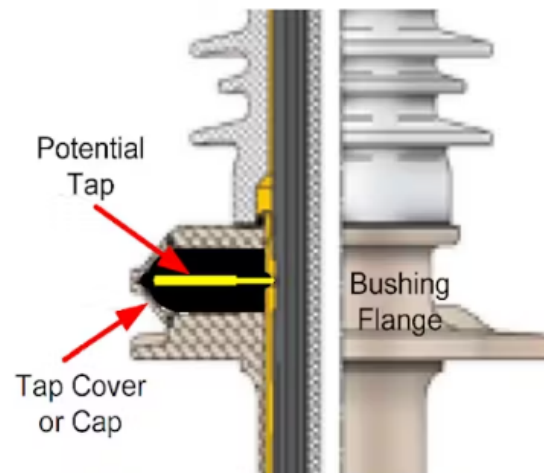


Figure 2.10: Potential or Voltage Tap [15]

## 2.1.3 Capacitance and Dissipation Factor (DF)

### 2.1.3.1 Capacitance

In HV condenser type bushing, it consists of two capacitances, the main capacitance  $C_1$  and the tap capacitance  $C_2$  as shown in the Figures 2.7 and 2.8. The definitions of  $C_1$  and  $C_2$  with respect to test and voltage tap are explained in the Section 2.1.2.6 accordingly. If there is insulation degradation in the bushing insulation system, it reflects in the capacitance value and PF from its nameplate value, which is stated by the bushing manufacturer. The online measuring system that is installed in the bushings measures the capacitance and PF.

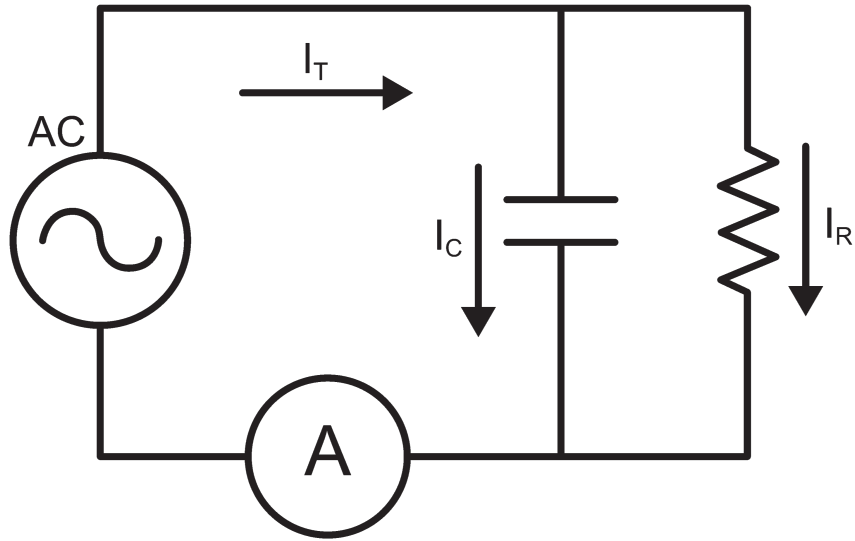
### 2.1.3.2 Dielectric Losses and PF

Dielectric losses in the insulation body are measured in watts. Various causes generate heat within the insulation material, and the generated heat causes losses to occur. The main causes are listed below

1. Resistance property of the material
2. Material type
3. Moisture ingress and contamination
4. Ionization of gas that leads to PD

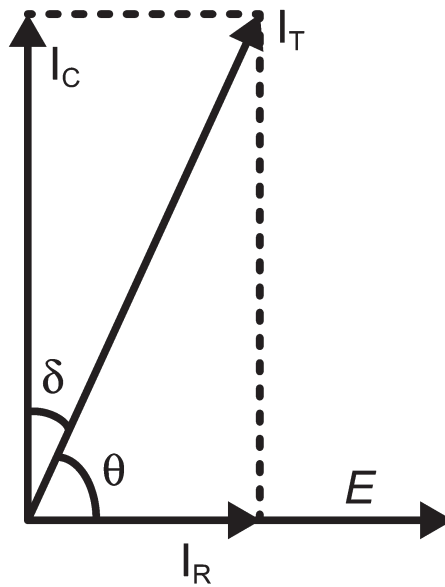
These losses vary depending on the amount of dielectric material, and it is difficult to compare the loss values between the bushings of different manufacturers and sizes. Therefore, most industries use PF to evaluate the condition of the bushing insulation system. PF increases with an increase in dielectric losses. From an electrical point of view, the capacitive current  $I_C$  flows, which leads the applied voltage by  $90^\circ$  when the dielectric material is applied with external voltage. The resistive current  $I_R$  starts flowing in phase with the voltage when dielectric loss starts to occur within the dielectric material. PF is the cosine of the phase angle between the applied voltage across the capacitance and the total current that is flowing through the capacitance. DF or loss factor is the phase angle relationship between the  $I_R$  and  $I_C$ . The following

Figure 2.11 shows the electrical circuit representation of the insulation system, and the corresponding phasor diagram is shown in the Figure 2.12.



**Figure 2.11:** Electrical Circuit Representation of Insulating material [6]

From the phasor diagram 2.12, the PF and DF expressions are formulated as given in the equations 2.1, 2.2.



**Figure 2.12:** Phasor Representation of PF and DF [6]

$$\cos \theta = \frac{I_R}{I_T} \quad (2.1)$$

$$\tan \delta = \frac{I_R}{I_C} \quad (2.2)$$

where

$$\delta = (90^\circ - \theta) \quad (2.3)$$

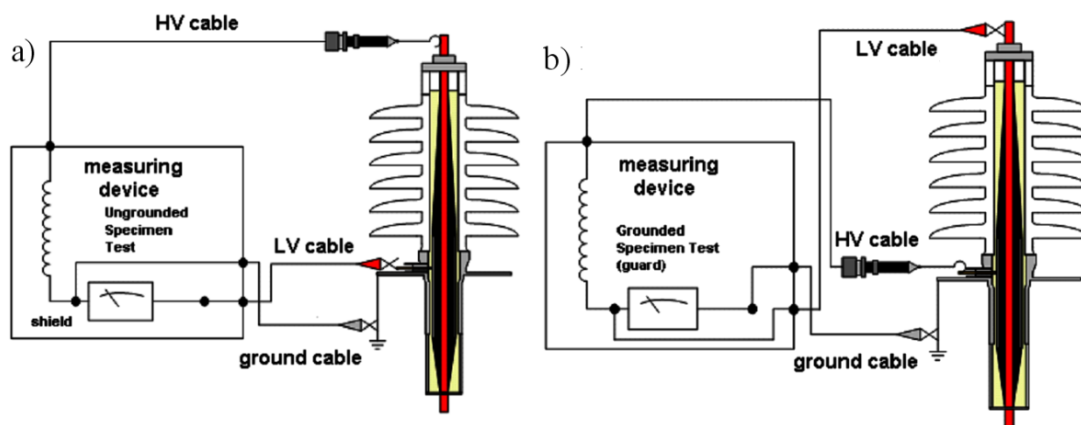
The values of PF and DF are very close for the value of  $\delta$  is less than  $5^\circ$  [6][23].

## 2.2 Offline Testing Technique

The failure in bushings is one of the major contributors to the unplanned transformer outage or catastrophic transformer failure. According to CIGRE WG A2.43 information, it is found that the calamitous failures accompanied by fire or explosion, accounted for 56%. In most cases, the offline testing of bushing aids in the early identification of any potential or progressing defects inside the bushings, and this in turn prevents the failure by taking the bushing to further investigation. Nonetheless, these periodic offline tests are not sufficient, especially for the bushing in service for more than 20 years. Hence, the condition of bushing can be evaluated by performing the offline testing more often or mounting the online monitoring system, which will be discussed in the next Section 2.3 [19].

This section discusses the offline testing techniques and procedures. The frequency of offline testing varies depending on the installed site of the bushing or the preference of the customer. But, it is recommended to investigate the bushing condition every six months or once a year to ensure its normal operation [21]. In general, the two main parameters that exhibit the overall insulation condition of bushing are DF and capacitance. DF is otherwise called  $\tan\delta$  or loss factor. Both parameters are measured between the conductor and the taps in the bushing. The offline method involves monitoring the bushing by taking the transformer out of operation and then the assessment is carried out in the following two configurations.

1. From line tap to insulated test tap 2.13(a)
2. From test tap to the grounded line tap 2.13(b)



**Figure 2.13:** Circuit arrangement for measuring capacitance and  $\tan\delta$ -Offline  
(a)UST (b)GST [19]

In accordance with the IEC 60137 standards, the recommended limit for the loss factor is 0.007 or 0.7% for the condenser type bushings in service at the reference temperature of  $20^\circ\text{C}$  [21]. For the capacitance  $C_1$ , the measured value should not differ

more than 10 % when compared to the name plate value stated by the manufacturer. The Figure 2.13(a) shows the circuit arrangement of Ungrounded Specimen Test (UST) to obtain the  $\tan\delta_1$  and capacitance  $C_1$  and the Figure 2.13(b) shows the circuit arrangement of Grounded Specimen Test (GST) to obtain the  $\tan\delta_2$  and Capacitance  $C_2$  [19].

### 2.2.1 Ungrounded Specimen Test (UST)

In this arrangement, the UST means the bushing under testing is ungrounded. The *guard* connection automatically provides the tester to measure the desired parameter out of many parameters in the entire insulation system. The benefit of UST is that the guard connection also provides ground provision for the setup [20]. The following steps show the testing connection to measure  $\tan\delta_1$  and capacitance  $C_1$ ,

1. The crocodile clip of the HV cable from the equipment is connected to the top terminal of HV/LV bushing
2. The test tap cover should be removed, and the pin needs to be inserted in the central test tap hole and stud by pressing the plug for the 245kV OIP bushing.
3. Earth strip is unscrewed from the flange
4. LV lead is connected to the test tap of the bushing specimen through a screened cable.
5. Ground the metal flange of the bushing
6. Repeat the procedure for the entire body by only altering the LV cable from the test kit to the test tap [20].

### 2.2.2 Grounded Specimen Test (GST)

In this arrangement, one of the terminals of the test specimen is grounded. The measurements are only possible by ungrounding the circuit of the measuring instrument, since most of the power system equipments are grounded. the GST test is suitable for the power system devices that are in installed condition. The latest testing instrument offers GST with guard-GSTg, which helps to measure the single component out of many components of a grounded insulation system [20]. The following steps show the testing connection to measure  $\tan\delta_{12}$  and Capacitance  $C_1$ ,

1. The crocodile clip of the HV cable from the equipment is connected to the test tap of the bushing
2. The LV lead from the cable is connected to the ground.
3. Top terminal of the bushing is connected to the guard terminal of the measuring instrument [20].

## 2.3 Online Monitoring System

The transformers in the power system are experiencing failure up to 17% due to the unattended faults in their installed bushings [21]. During normal operation, bushings experience high thermal, mechanical, and electrical stresses. According to the review data of transformer failure from the Doble Conference Questionnaires and North American Utilities, it can be found that around 40% of transformer failures

are caused by bushing failures. Besides, 52% of the failures are of a catastrophic nature, involving fire and collateral damage [22]. The two main causes of bushing failures are due to the presence of moisture content and the occurrence of PD in the insulation system of the bushing. The ingress of moisture results in an increase in the loss factor. When the degradation in the bushing continues to develop, the capacitive layers undergo breakdown and induce the partial discharge to occur.

Traditionally, the offline tests are carried out periodically to detect any abnormality in the bushing insulation. However, the causes of bushing failure are temperature and voltage-dependent. Also, the failure mechanisms develop very quickly, which leads to a complete breakdown of the bushing. On the other side, the offline testing of bushings is carried out at the ambient temperature by applying 10 kV from the test instrument. Also, the interval between each offline testing procedure is quite long. With all these potential drawbacks, the asset management professionals sense a lower degree of reliability with the test results from the offline method [22]. Therefore, the continuous monitoring of bushings is becoming of greater importance among the customers to detect the defect at its early stage and thereby improve the lifetime of bushings. If the defects go unmonitored or captured at a later stage of bushing deterioration, massive losses could occur, and they are accompanied by

1. the replacement cost of the bushing
2. the maintenance or replacement cost of a transformer in the event of subsequent failure of the transformer
3. the disturbance and loss of stability and reliability in the power system network affecting the consumers [21].

Currently, the incorporation of an online monitoring system on the bushings is being developed to assess the bushing insulation in real-time operating conditions [23]. It is proven that the online measurements of loss factor and capacitance are more reliable and aid the asset manager to predict the bushing performance when in service.

The significant advantages of employing an online measurement system are listed as follows

1. Transformer and bushing continued to be in service, and there is no outage planned to perform measurements.
2. Since the measurements are carried out at the real-time operation of the bushing, it takes a short period of time to detect the actual bushing behavior.
3. The obtained results from the online system are more reliable for specific defect types, as it was taken at the operating temperature of the bushing.

There are many investigations on bushings' failure that were carried out by authors wherein most of the bushings studied are installed with the online monitoring system [24]. Through the online method, the real-time measurements from the test tap are based on one of the following two methods,

1. Comparative (reference) method
2. Sum of currents method



# 3

## Competitor Analysis and Benchmarking

As of 2023, the market value of transformer bushings stands at USD 1.8 billion, and it is forecasted to attain USD 3.0 billion. From 2024, the bushing business is emerging at the rate of 5.1% Compound Annual Growth Rate (CAGR) till 2033 [25]. The enormous growth rate is due to the continuous investments to build a decentralized power system network by increasing renewable energy integration into the grid, expanding HVDC transmission networks, and bringing up smart grid solutions across the world.

The market segment of Direct Current(DC) transformer bushings is becoming the leader among other bushing types in the market. It is experiencing a growth rate at 5.4% CAGR as the demand for expanding and building new HVDC transmission systems is increasing [26]. On the other hand, the market segment of bushings that are installed in circuit breakers and shunt reactors also experiences a tremendous growth from USD 2.69 billion in 2023 to reach USD 4.05 billion by 2033 [27].

As stated by financial times, Hitachi Energy is the global leader in manufacturing transformers and the critical components associated with it [28]. According to the 2024 global market insight reports, Hitachi Energy holds over 40% of the porcelain electrical bushing market [29], and a similar dominant share across the wider bushing market. However, together with Hitachi Energy, other companies hold a recognizable position in the bushing market. This chapter provides insights into the competitors background, bushing portfolio, the latest R&D innovation, and their difference in strategy with other manufacturers in the market. The competitors presented in the analysis are listed as follows:

### 3.1 Trench Group (including Haefely and HSP)

Trench Group, the parent company of the Haefely and HSP brands, is a leading European-based manufacturer of products for HV insulation requirements. The partners in Triton highlight that, “Trench Group is a world leader in power engineering and the design of specialized HV electrical products” [30]. The company’s bushing business rooted back to 1937 when Emil Haefely patented OIP condenser bushings [30]. Today, it still stands at the forefront of bushings, coils, and instrument transformers. After Siemens transmission products, Triton acquired Trench in 2024

[32]. Currently, Trench (and HSP brand) employs approximately 2400 workers at nine plants in Austria, Bulgaria, Canada, China, France, Germany, and Italy [30].

Trench boasts an extensive and technically advanced lineup of transformer bushings from state-of-the-art dry-type solid resin bushings to "eco-fluid" bushings (RIP designs with silicone oil) [31]. They have a portfolio of explosion-proof designs with increased mechanical strength and overloading capability [31], which positions them in the market for more safety and longer lifespans. They are well known in the market for customization and reliability in their products. For example, they offer 1:1 replacement design to replicate existing designs on-site for older transformers, needing retrofits and maintenance [31]. In addition, Trench's marketing also includes a sustainability initiative, "REGENERA™," that aligns with circular economy goals, which implies their inventions are of a broader perspective. In simpler terms, the Trench stands out among other companies due to their technical expertise, wider portfolio of bushings (RIP, RIS, RIG, and oil-filled bushings for AC/DC applications), and long-term business relationship with utilities around the world [30][31].

## 3.2 GE Grid Solutions (Passoni & Villa)

The other leading company is GE Vernova's Grid Solutions division (previously known as GE Grid/Alstom Grid). They have their global footprint with HV/high power transmission systems. GE's historically legacy Passoni & Villa plant in Sesto San Giovanni (Milan), Italy, partly brings their expertise in bushings. The facility's 100 years of bushing innovation was celebrated in May 2023, as GE highlighted that "This site has been acknowledged for its excellence, quality, and its team's proficiency in HV equipment" [33]. The Sesto San Giovanni, the bushing hub for GE's Grid Solutions, functions as a production plant and R&D center, which exhibits the investment by the company in the long run.

The entire HV ratings are covered by the transformer bushing product line from GE Grid. According to GE product information, it possesses RIP condenser bushings for power transformers up to 550 kV and smaller RIP bushings up to 36 kV for generators [34]. It has OIP condenser bushings up to 1200 kV for Ultra High Voltage (UHV) transformers [34]. Furthermore, GE has SF<sub>6</sub>-insulated transformers for GIS substations covering up to 800 kV. In addition, the GE Line accommodates HVDC bushings, both through wall gas-insulated and a hybrid OIP/SF<sub>6</sub> up to 800kV [34]. The GE-manufactured bushings require no special maintenance and possess longer lifetime and higher reliability [34].

GE Grid's competitive advantage develops from this scope and lineage. Their bushings are used across the globe and supplied to the biggest projects. The few important projects are the Italy-Montenegro DC interconnector, the North Sea DolWin3 offshore wind connection, and the Lower Churchill HVDC line in Canada [33]. GE Grid Solutions is positioned to be a reliable supplier for quality bushings by having Alstom's 90-year bushing legacy (Passoni & Villa) and its independent R&D center. Moreover, their 2023 press release states that since 1923, "GE's bushings have

been synonymous with excellence, quality and competence" with high voltage [34]. Indeed, GE Grid can offer bushing solutions to standard and custom applications based on its installed base globally, the Italian engineering center, and the support of a multinational conglomerate.

### **3.3 Nanjing Electric (Group) – NARI (Including Zhinda)**

Nanjing Electric (Group) Co., Ltd., also known as Nanjing Electro-Ceramic Factory, was founded in 1936, and it is one of the oldest insulator and bushing manufacturers in China. In 1958, it was the first Chinese factory to trial-produce the transformer bushings of condenser type [35]. Over the decades, Nanjing Electric has built a reputable presence locally, and it claims that it has manufactured hundreds of thousands of HV bushings, which are approximately 50% of in-service bushings in China [35]. It has an exclusive thunder-lighting trademark and is a significant supplier of glass and porcelain insulators for the power industry.

Nanjing Electric is bringing innovation even in the 21st century. For instance, it produced the first fiberglass reinforced dry-type condenser bushing in 2001, establishing a new material and composite design in the market [35]. In 2012, Nanjing Electric HV Bushing Co. was established to bring more focus to this new technology. Currently, they produce all the major types of bushings required for utilities: OIP and OIP-to-SF<sub>6</sub> condenser bushings; oil-to-oil and dry-type (RIP/RIS) bushings. For instance, the transformer bushings are available from 12 kV up to 550 kV with current ratings up to 6,000A [36]. They also make generator lead-out bushings and GIS-type bushings.

The competitive advantage of Nanjing Electric relies on historical insight and technical expertise. Nanjing Electric owns its R&D labs and has been a part of the national fiberglass insulation standards committee. It exerts pressure for a stable aftermarket and holds extensive relationships with large-scale Chinese utilities. While it slowly broadened its export, its customer base is still transformer manufacturers and utilities within China. Thus, Nanjing Electric (NARI) competes on a heritage of 80+ years in bushings, a domestic scope that can produce at mass volume and constant advancements in bushing technology [35][36].

The company Zhinda is also part of the Nanjing group, Nanjing Zhinda Electric Co., Ltd. Its offering include transformer bushings, porcelain insulators, and current transformers. They supply to big international and important Chinese utility companies. Its US-based subsidiary's Peak Demand is stated to be "a global supplier of electrical transmission and distribution products, including insulators, bushings, and current transformers" [37]. Zhinda expanded to North Carolina in 2016 to establish Peak Demand headquarters to service American clients [37]. Zhinda honors being a "high-tech enterprise" operating in HV components sector, focusing on quality with a focus on R&D [37].

## 3.4 Moser-Glaser Ltd. (MGC) – Pfiffner Group

Moser-Glaser Ltd, popularly known as MGC, is a Swiss company that supplies HV insulation and is part of the greater Pfiffner Group. It was established in 1914 in Basel, Switzerland, and this company was the first to develop "solid insulation" [38]. In the 1950s, Moser-Glaser brought up RIP insulation and branded it DURESCA® for bus-bars and subsequently for transformer and wall bushings [38]. Today, Moser-Glaser specializes in two complementary products: rigid bus bar systems, HV transformer and wall bushings [38]. The entire design and manufacturing units are located in Kaiseraugst, Switzerland [38].

The bushings from MGC are typically epoxy-resin (dry-type) constructions using RIP insulation for power and instrument transformers and rated up to several hundred kV. The company represents "Swiss quality combined with global experience" [38]. Moser-Glaser is a relatively small company, and they offer highly customized solutions that can be created and manufactured quickly. It holds ISO 9001/14001/45001 certification for quality and safety [39]. Its competitive advantage comes from its proprietary knowledge of RIP technology (60+years of field data) and stands as an independent supplier. MGC is a smaller player, which means it is not tied to any transformer OEMs like its larger competitors, which may appeal to utility companies that search for alternative offerings. Therefore, the value that Moser-Glaser brings is its RIP-based products under the name of DURESCA® brand and quick-turn Swiss competence [38].

## 3.5 Yash High Voltage Ltd.

Yash High Voltage Ltd. is an Indian producer that has established itself as a prominent supplier of transformer bushings within India in a short span of time. It was established in the 2000s, and it delivers to Indian utilities and OEMs with its specializations in condenser bushings and high-current connectors. Its product line consists of OIP condenser bushings, RIP/RIS (epoxy resin) bushings, wall bushings, and high-current lead-out bushings. Significantly, the company has 35,000 bushings installed across more than 60 countries [40], implying a strong international presence despite being a new player in the industry.

Yash focuses more on indigenous technology. For example, it states that it was the first in India to own RIP condenser bushings. Furthermore, it shows significant shipment sizes over recent years: 4,000 RIP/RIS ( $\leq 245$  kV) bushings since 2016 and more than 16,000 indigenously developed OIP condenser and high-current bushings sent both nationally and internationally [41]. The bushings are tested for 14,000 impulse tests, 10-year field testing at Yash's lab, and they prove the longevity and reliability of their bushings [40].

By 2024, Yash had received utility approvals for widespread use and opened itself to customers globally. It signed distribution agreements for Europe and Africa and

publicized its partnership with Weidmann, a transformer insulation expert based in Switzerland. Yash went public on the Bombay Stock Exchange in December 2024, which speaks of the status of the company in its growth phase. In terms of market positioning, Yash is a small and low-cost manufacturer of bushings. In terms of strengths, engineering resources are located within India, with manufacturing plants, and it has largely penetrated the Indian market (specifications for state grids and PSUs have been awarded). It has a lower brand recognition relative to global counterparts; an advantage is quality management's testing reliability record and extensive installed base. The key takeaway here is that the value of Yash comes from native solutions, field experience in Indian conditions, and a full portfolio of latest HV bushing offerings [40][41].

## 3.6 Jiangsu Shemar Power Co., Ltd. (Shemar Group)

Jiangsu Shemar Power, which operates as Shemar Group, is a Chinese private company (founded in 1996) that specializes in composite insulators and other high-technology bushing solutions [42]. The difference between Shemar and traditional porcelain is the new material design concept. For example, for transformer bushings, Shemar features full-composite and explosion-proof bushings: these are hollow fiberglass insulators with gas insulation that prevent any failures like internal explosions and tracking permanently. Their products include hollow composite substation insulators, gas-filled composite bushings, and a “new explosion-proof transformer composite bushing” specific to the transformer [43].

Shemar wants to partner with the global grid OEMs. Its website states that its products are supplied to over 100 countries, many via partnerships with foreign equipment manufacturers like ABB, GE, and Siemens [42]. This indicates that Shemar functions as a secondary contractor providing insulation parts (including bushings) to large manufacturers of transformers and switchgears. For example, within China, the company has tried to bridge the technological gap by creating products that comply with international standards. Its competitive advantages are in materials (composite vs porcelain), safety requirements (anti-flashover, explosion prevention), and reliability in adverse weather. Thus, its competition within niche markets is providing “next-generation” insulation applications for products that do not exist with established porcelain bushing manufacturers for customers seeking lightweight, maintenance-free alternatives [42][43].

## 3.7 TBEA

TBEA Co., Ltd. (Ticker: 600089.SS) is a powerful Chinese energy equipment group and a listed company in power transmission and energy transformation. It's a national high-tech enterprise, one of the largest grid equipment manufacturers in China [44]. TBEA's three main businesses include high-end power T&D equipment,

silicon-based new-energy materials, and aluminum-based new materials with 21 industrial parks in China, and in foreign countries [44]. TBEA's transformer output has ranked among the highest globally for many years, and TBEA is the top 20 ENR global Chinese engineering company [44].

TBEA's product range covers the entire power T&D chain. It produces power transformers for transmission and distribution, HV switch gear (HV circuit breakers, HV switch selectors, etc.), converter valves, cables, wires, bushings, and insulation-related accessories [45]. Its equipment is utilized among power grids, the renewable energy sector, rail transit, and large data centers; thus, it frequently offers complete turnkey project delivery (survey, design, construction, commissioning, and training) in more than 30 countries [45]. In the renewable sector, TBEA has established a complete photovoltaic supply chain (from polysilicon to inverters): it has a 100,000-ton polysilicon plant and has installed about 18 GW of wind/solar plants worldwide; it also offers over 32 GW of inverters shipped [45]. TBEA manufactures aluminum foil and other advanced materials for electronics and automotive purposes [45].

TBEA highlights its R&D and innovation activities. They dedicate 4% of annual turnover to research activities. TBEA possesses an Ultra-High-Voltage (UHV) Transformer Research Center, numerous state-level laboratories, a post-doctoral scientific research station, and an academic workstation [44]. TBEA has undertaken and completed over 100 national-level R&D projects with independent breakthroughs in 126 independent research projects [44]. It has over 2,012 patents pending and is the enterprise leader in compiling greater than 210 enterprise standards [44]. Furthermore, TBEA has won countless national science-and-technology innovation awards.

## 3.8 China XD Group (XD)

China XD Group Co., Ltd. is a central-state-owned enterprise that was founded in 1959 and is China's flagship T&D equipment manufacturer [46]. It is the only central enterprise in China in the whole power transmission and distribution industry. It is the largest R&D, manufacturing, test, and service base in China for medium and UHV AC/DC grid equipment [46]. China XD has grown into a big corporate group with more than 60 subsidiaries (inclusive of two publicly listed companies—China XD 601179. SH, Shaanxi Baoguang 600379.SH) and more than 16,000 employees (inclusive of 3,000+ engineers and technicians) [46].

The product capacity of XD covers all HV electrical equipment. The product portfolio includes generators, transformers, switchgears, insulators, and other equipment for power transmission and distribution [47]. Such products have been deployed in national key projects in China, e.g., the Three Gorges Dam, the West-East UHV power corridors, and the national UHV AC/DC grid. and electric power projects in over 80 countries worldwide [46]. As for business performance, China XD is regularly ranked No.1 among China's electric-equipment manufacturers. It has a national "May Day" award and national science progress awards. It has AC/DC grid test labs

in its research institutes, and it participates in international standards bodies such as IEC, CIGRE, showing its strong capacity in innovation [46]. An overview of the information discussed is summarized in the Appendix A.

The above sections provide a detailed analysis of competitors in the bushing market. When considering the existing dual tap solution in the market, the competitors like Moser Glaser, Trench, TBEA, GE, and other Chinese manufacturers have dual tap in their offerings, which was found through internal sources. However, there is no clear information about the dual tap solution available online. Only Moser Glaser provides brief information about their dual tap solution in their product brochures. It is found that the Camlin Group (or Camlin Energy), which is popularly known for its transformer diagnostic solutions and other sensor technologies for transformer bushing, provides a dual tap solution in the form of a splittable adapter. This splittable adapter facilitates a common interface for both online and offline monitoring systems.



# 4

## Methods

In this chapter, the step-by-step procedures from concept generation, concept screening, to the final prototyping are explained.

### 4.1 Circuit Diagrams

The requirement for dual taps from customers has been there for a very long time, and it has been timely arising over the course, but until now it hasn't concluded, except for a 2012 internal study by Dan Gustavson to incorporate it into their product portfolio by doing some modifications to the GSB product line while the company was still a part of ABB Components. However, the discussion didn't evolve as the demand was limited. The major problem associated with the dual tap configuration is the electrical complication associated with it. Therefore, to understand the electrical challenges involved with it, the first step in the development process was to study all the possible configurations associated with the dual taps design. For this, the configurations were developed, encompassing the online monitoring system and the offline monitoring system, and this drew a design boundary within which the design could be developed.

### 4.2 Concept Generation

The first step in the product development process is to attain a clear idea about the functionality and operation of the desired product. This can be obtained from the clear-cut needs and requirements of the customer. The process of concept generation involves bringing up the possible configurations and creative solutions for the development of dual taps so that they meet their functionality. The upcoming sections will explain the steps involved to generate the desired concepts to achieve the intended functionality.

#### 4.2.1 Functional Analysis

A black box was created to determine the functionality associated with the dual tap design on bushings. The creation of a black box is similar to a transfer function, where one end of the black box is given with inputs such as material, energy, or signal that varies depending on the product to be developed. The assigned inputs pass through a series of processes and may vary to meet the intended outcome. This results in the output that underwent modification from its initial stage. Eventually,

the functional analysis for the development of dual taps was obtained in this step [49].

### 4.2.2 Morphological Matrix

The sub-solutions are then formulated to meet each function that is obtained from the previous functional analysis step. The obtained solutions for each corresponding sub-function are required to be combined by using a method called *morphological matrix*. The different concepts are generated by tabulating the feasible solutions for each function in the matrix form [48]. For formulating the matrix, a tool called *Morpheus* was used. The sub-solutions for each function are tabulated with their corresponding image and description in the Morpheus tool. By using the incompatibility feature, the sub-functions that are not correlated with one another are eliminated in this process. After eliminating some sub-solutions that are not in synergy, the next step is to further narrow down the feasible number of concepts by applying inbuilt features in the tool that assist the user in applying strategies, namely *Thematic Strategy* and *Pragmatic Strategy*. The *Thematic Strategy* is used to narrow down the sub-solutions based on applying the theme that fits the requirements, and the *Pragmatic Strategy* works based on priority given to available sub-solutions for each functionality. The number of concepts is reduced by a significant number as an outcome of the Morpheus tool.

## 4.3 Circuit Configuration Analysis

With the concepts generated from the Morpheus tool, circuit simulations were performed in the LTspice software to verify whether the circuits yield the same output as predicted earlier during the formation of the circuit diagrams as mentioned in the Section 4.1. The circuit simulations involve the formation of circuits associated with the bushing tap configuration and analyzing them during service, during measurement of  $C_1$ , and during measurement of  $C_2$  for all the developed circuit configurations. The circuit connections in the simulation are based on the double's procedure for testing bushings with both the test tap and potential tap. Following that, a frequency sweep analysis is also carried out for one of the circuit configurations to understand its behavior in case of transient conditions. The simulation results present themselves as an affirmation of the decision taken later during the screening phase. Overall, the circuit simulations helped to understand the circuit configuration better and facilitated arriving at a firm conclusion whether the circuits formed would work and solve the intended problem.

## 4.4 Concept Screening

The generated concepts are combined and evaluated using different matrices to obtain the concept that fulfills the requirements of the customer. The concept screening section involves screening the generated concepts through the elimination matrix, the Pugh matrix, and the Kesselring matrix, which are discussed in the upcoming

sections. The criteria for these matrices were formed by a stimuli technique that involves brainstorming within through a series of spurring questions related to the dual tap configuration, and with the help of AI tools.

#### 4.4.1 Elimination Matrix

The concepts generated from the Morpheus tool were high in number, and therefore, they need to be narrowed down further. The process of bringing down the number of generated concepts was done by specifying the *must-have* criteria in the elimination matrix, and the concept was assessed for the assigned criteria accordingly. The concepts that are carried forward should fulfill the defined criteria in the matrix. If the criteria were not met by the concept, those concepts were eliminated [48]. In the elimination matrix, the formulated criteria that define the requirements of higher significance were listed as columns, whereas the concepts generated from the morphological matrix were listed as rows of the matrix. Thereafter, the listed concepts in the rows were assessed against each criterion in the column and eliminated if the concept did not fulfill the requirement. This evaluation was carried out through the entire matrix, and this in turn reduces the number of concepts to a smaller number, which were carried forward to the Pugh Matrix.

#### 4.4.2 Pugh Matrix

The concepts that are available after evaluation in the elimination matrix are further assessed using the Pugh matrix. The criteria are tabulated as rows, and the remaining concepts from the elimination matrix are tabulated as columns in the Pugh matrix. The next step is the evaluation of the listed concepts against a reference concept for which the existing solution is defined as the reference concept. Pugh matrix is based on assigning a rank to each criterion by comparing it with the reference concept. The rank of "+" is given if the concept is better than the reference, rank "-" is assigned if the concept is worse than the reference, and rank "0" is given if the concept is similar to the reference concept. By ranking in this way, the entire matrix is filled, and then the total value for each concept is evaluated. Based on these values, the ranking of concepts is obtained [50].

#### 4.4.3 Kesselring Matrix

The concepts that were obtained after the Pugh matrix evaluation need to be further assessed and channelled through the Kesselring matrix. In general, the Kesselring matrix was used to evaluate the concepts based on technical feasibility and manufacturability. The matrix was formulated by listing the defined criteria, and the specific weights were assigned to each one of the criteria by performing a relative comparison against each other. The primary step before the formulation of Kesselring was the formation of a pair-wise matrix. Each cell was assigned with values that signify the relative importance of one criterion to another. The values were assigned from most important (1) to least important (0) by evaluating one criterion relative to another criterion. Thereafter, a three-scale grading system was formed. Then, according to the relevant parameters for the defined criteria, the

values were made to fit in the grading system, which implies the performance of the concept in relation to each criterion. After forming the grading system, the final part of the Kesselring matrix evaluation involved evaluating the concepts along with the ideal concept, which stands highest of all in the grading system in all criteria. Then, the weighted sum of each concept was computed, and the concept with the highest sum was chosen as the best concept for proceeding to the prototyping stage.

### 4.5 Requirement Specification

The scope of the project does not include the traditional process of converting the target specification to a requirement specification. Instead, the requirements were adapted from the existing bushing tap to account for the new requirements. Additionally, the specifications that are significant during the execution of the final concept were also incorporated in the requirement specification.

### 4.6 Prototyping

Once the concept T-MechTap was finalized through the screening matrices, the next step was to work on the concept. This was done by going through several mechanical switching-related ideas and mechanisms that were available online, irrespective of the application in which they were used. After analysis of the existing ideas, some own rough ideas were formulated for the intended application through a number of rough sketches. Subsequently, these ideas were presented to the design team here at Hitachi Energy to receive their feedback. Based on the feedback received, a new idea was developed by integrating all the positive feedback from several proposed ideas. Keeping the updated idea as a foundation, a digital prototype was developed in a CAD software, called PTC Creo with the support of existing CAD models from Hitachi Energy product portfolio, along with some design tweaks to the last formed design. The developed model was then simulated with the mechanism package in Creo to validate its operational feasibility.

# 5

## Results

The chapter "Results" explains the detailed methodology in obtaining the final intended digital prototype for dual tap on transformer bushings.

### 5.1 Circuit Diagrams

As mentioned earlier in the Section 4.1, the need for dual taps has existed for quite a while; however, the purpose of them was not clearly defined, and even the internal study that Dan Gustavson did was not based on the purpose but rather on the requirement. Hence, it is necessary to understand the purpose. From our study and internal sources, the need for dual taps was identified, which has been defined as the aim of the project. For this, the different circuits associated with the dual tap layout have to be studied. This section describes the four configurations in accordance with the dual tap design. The following figures present a rough cross-section of a capacitive graded bushing with the outermost conductive layer ( $n^{\text{th}}$  layer) and the second outer-most conductive layer ( $(n-1)^{\text{th}}$  layer), along with the two systems, i.e., the online Monitoring system and the offline equipment.

#### 5.1.1 Configuration 1

The Figure 5.1 shows the circuit configuration with two taps where the tap connected to the  $(n-1)^{\text{th}}$  layer (i.e. similar to voltage tap) is equipped with the online monitoring system and the tap connected to the  $n^{\text{th}}$  layer (i.e. similar to test tap), which will be clamped to the LV lead from the offline equipment during manual testing. In this configuration, it was assumed that no drawbacks in the functioning of the online monitoring system during normal service, as the tap intended for the manual testing will be shorted by the ground cover. However, in the case of manual testing, the HV lead is clamped to the bushing terminal, and the LV lead to the tap connected to the  $n^{\text{th}}$  layer, which would result in a measurement of a combined capacitance of  $C_1$  and  $C_2$ , which is not the desired value of capacitance to be measured.

**System connected to different Taps, different foils n: offline / n-1:online**

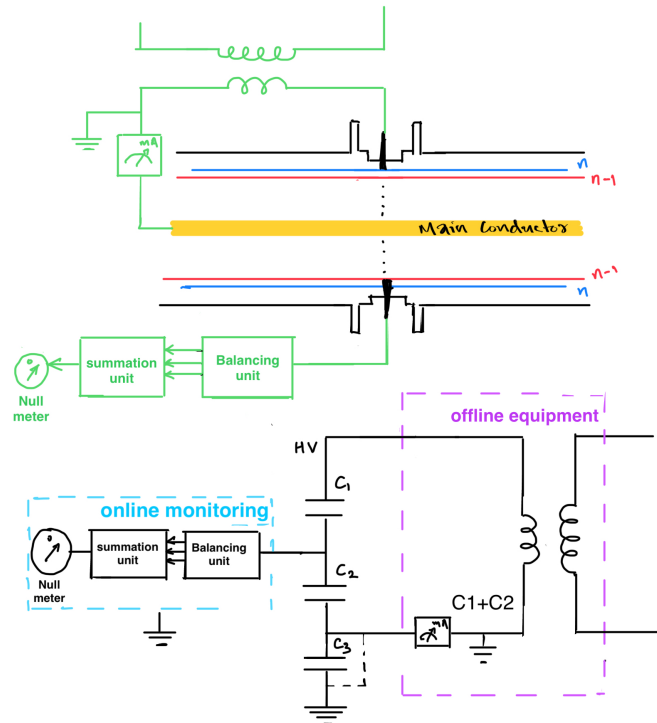


Figure 5.1: Offline system to  $n^{\text{th}}$  layer & online system to  $(n-1)^{\text{th}}$  layer

### 5.1.2 Configuration 2

**System connected to different Taps, different foils n: online / n-1:offline**

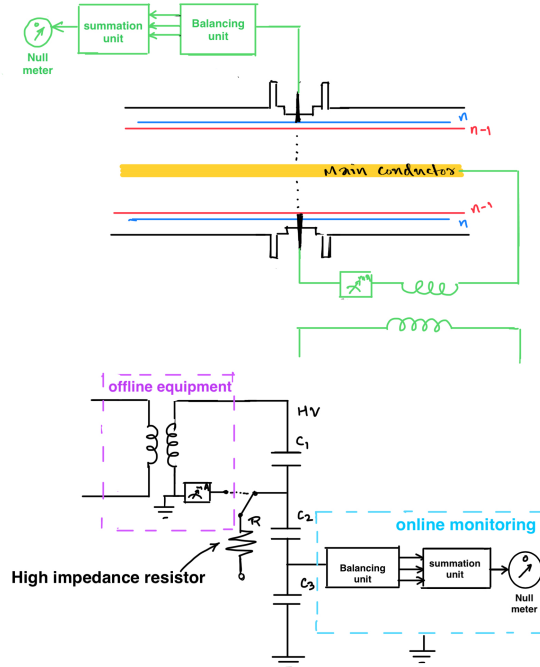
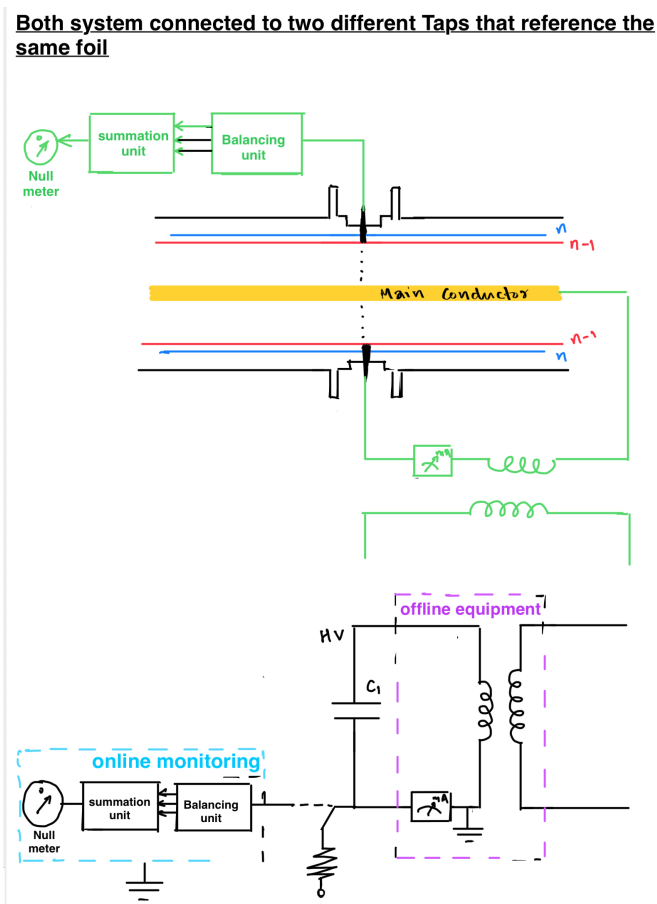


Figure 5.2: Offline system to  $(n-1)^{\text{th}}$  layer & online system to  $n^{\text{th}}$  layer

The second configuration shown in the Figure 5.2 is an inverse of the previous configuration, as the online monitoring system and offline equipment swap their connections with the foil layers. This is one of the promising circuits to connect both systems in parallel; however, this is not the intended solution that the customer expects from us. When bushing in service, the tap intended for offline equipment is not shorted; instead, it is capped with a highly insulated cover, as shorting would bring the online monitoring system to a halt.

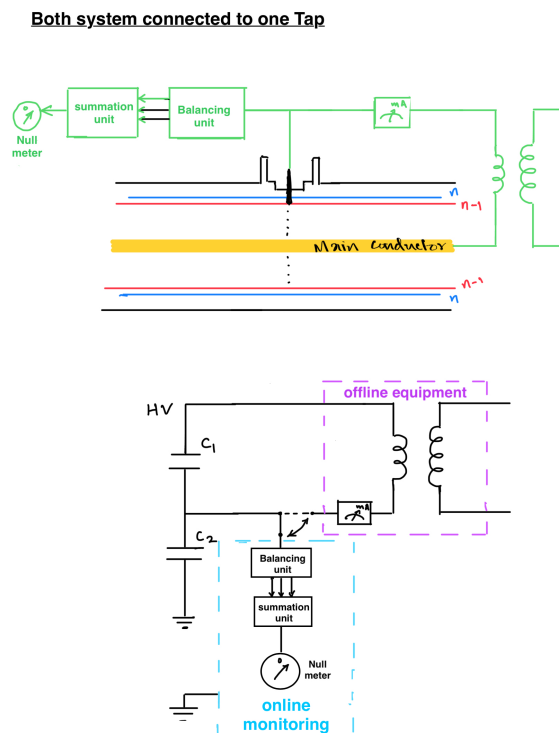
### 5.1.3 Configuration 3



**Figure 5.3:** Offline system & online system to same foil layer -  $n^{\text{th}}$  layer or  $(n-1)^{\text{th}}$  layer

The third configuration, as shown in the Figure 5.3 is about two taps connected to the same foil; it can be the  $n^{\text{th}}$  layer or  $(n-1)^{\text{th}}$  layer which doesn't make any significance. During service, the online monitoring system is connected to one of the taps, while the floating potential in the other tap will be protected with a non-grounded heavily insulated cap. However, during offline testing, the tap in which the online monitoring system is connected must be switched to a non-grounded, heavily insulated cap like the offline tap during service. This switching brings complexity to the circuit configuration.

### 5.1.4 Configuration 4



**Figure 5.4:** Offline system & online system to single tap

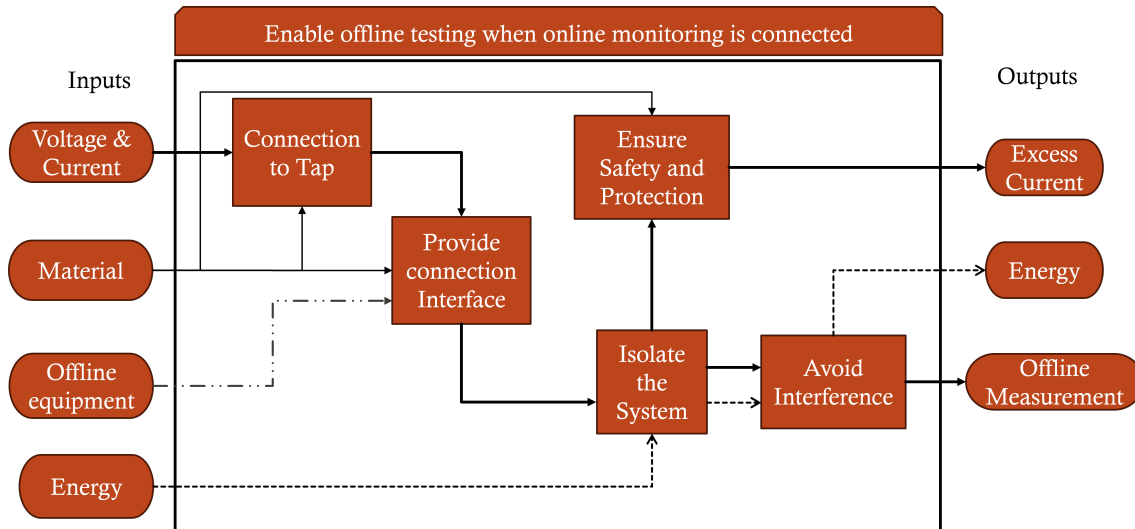
The Figure 5.4 illustrates the fourth and final configuration, where there is a single tap to which both online and offline systems are connected by means of an adapter that has some kind of switch to swap between the two systems whenever required.

## 5.2 Concept Generation

The section presents a detailed explanation of the generation of concepts through functional analysis and morphological matrix.

### 5.2.1 Functional Analysis

The circuit diagrams that are presented in the Section 5.1 played a vital role in identifying the functions associated with the problem. It provides an overall idea of the functions that are essential for the tap functionality. In line with this context, a black box, as shown in the Figure 5.5, was developed to visually understand the functional decomposition of the bushing tap. The main function is to “Enable offline testing in parallel with an online monitoring system connected” that forms the system boundary, enclosed in that are the following sub-functions: “Connection to tap”, “Provide connection interface”, “Ensure safety and protection”, “Isolate the system”, and “Avoid interference”.



**Figure 5.5:** Functional Analysis - Black box

The inputs enter the function block “*Connection to tap*”, which defines the tap connection to the bushing foil. Following that, the inputs enter the functional block “*Provide connection interface*”, which ensures the connection of the offline equipment. After that, the functional block “*Isolate the system*” ensures that the online system remains isolated in this process, then the module “*Ensure safety and protection*” is a supportive module that ensures the overall safety of the systems and testing personnel. Lastly, the module “*Avoid interference*” ensures that measurements taken are reliable and accurate. Additionally, inputs like material and energy are fed in various stages of the functional flow to support the overall function. The primary output from the black box is the “*Offline measurement*”, along with secondary outputs “*Excess current*” that is shorted to the ground and “*Energy*” that is remaining from the transformation process.

## 5.2.2 Morphological Matrix

Once the sub-functions, namely "provide access", "isolate the system", "ensure protection", "connection to the tap", and "avoid interference" are derived from the black box, and are listed vertically as rows of the morphological matrix. Across each column, the multiple sub-solutions that are illustrated through hand-drawn images are mapped, and each image is aligned with its corresponding sub-function as briefed in the Section 4.2.1. For example, three distinct sub-solutions were developed for the sub-function to provide access: a splitter, two taps, and an adapter. To get a complete picture, refer to the Figure 5.6, which clearly illustrates the structure and formation of the morphological matrix. The final morphological matrix is given in the Appendix C. As mentioned in the Section 4.2.2, the tool Morpheus, which was developed by Chalmers, was used to arrive at the possible solution set. With the defined sub-functions and sub-solutions, the initial number of combinations was around 480. Upon defining 30 incompatibilities, such as between config-3 & splitter, and between two taps & mechanical switches, the solution set was reduced to 22. This was followed by the application of the thematic strategy, where the theme *User-Centric* was chosen.

## 5. Results

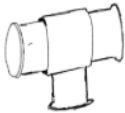
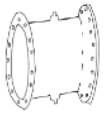



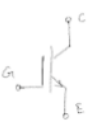




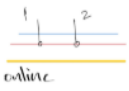
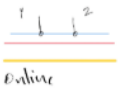
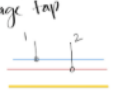
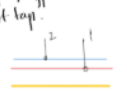
| Enable offline testing, with online monitoring connected |  |   |  |  |  |
|--|--|---|--|--|--|
| Sub-Functions  | Sub-Solutions  |   |  |  |  |
| Provide access   | <b>Splitter</b><br>T-Junction / Splitter<br>  | <b>two taps</b><br>Two Separate Interface<br>                                    | <b>adapter</b><br>common interface port<br>   |  |  |
| Isolate the system                                       | <b>Mechanical Switch</b><br>Mechanical Switch<br>                                   | <b>Relay</b><br>Relay<br>  | <b>IGBT</b><br>IGBTs<br>  | NA   | <b>High Impedance Resistor</b><br>High Impedance Resistor<br> |
| Ensure protection  | <b>GND Cover</b><br>GND COVER<br>   | <b>Spring loaded return</b><br>spring loaded switch<br>                          | <b>Component Protector</b><br>Surge Protectors<br>  | N/A  | Sub-Solution 3.5   |
| Connection of tap  | <b>config-1</b><br>Both connected to voltage tap<br><br>1 - online<br>2 - offline | <b>config-2</b><br>Both connected to test tap<br><br>1 - online<br>2 - offline | <b>config-3</b><br>Online connected to test tap & offline connected to voltage tap<br><br>1 - online<br>2 - offline | <b>config-4</b><br>online connected to voltage tap & offline connected to test tap<br><br>1 - online<br>2 - offline |  |
| Avoid interference                                       | <b>Gaurding</b>  | N/A   |  |  |  |

Figure 5.6: Morphological Matrix in Morpheus Tool

The idea behind this theme was to arrive at user-friendly solutions. As a result, complex sub-solutions such as IGBTs and Config-2 were excluded, bringing down the solution set to 20. The final refinement was done using the pragmatic strategy, which involved ranking the sub-functions based on priority and defining the desired number of final solutions. The outcome of this refinement resulted in obtaining a final set of 5 concepts- referred to as *Plug & play*, *T-MechTap*, *T-ElecTAP*, *2T-2F*, *2T-1F*.

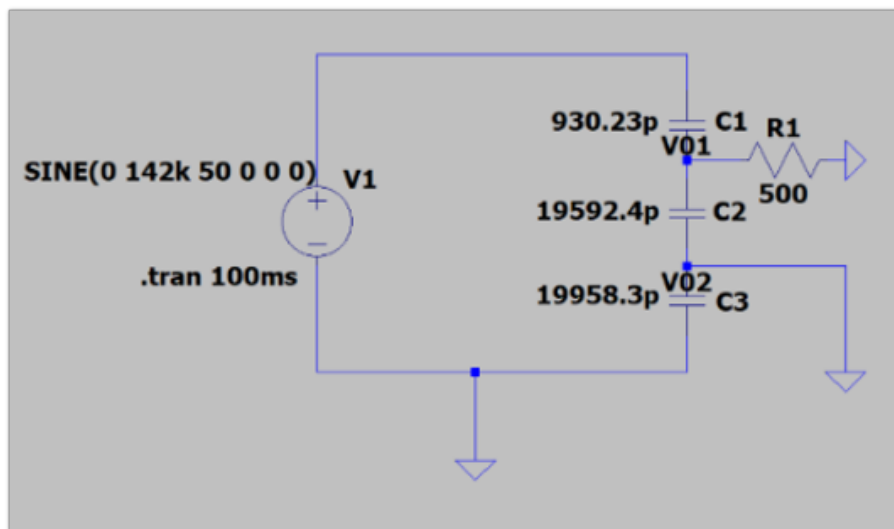
### 5.3 Circuit Configuration Analysis

As stated in the Section 4.3, before proceeding to the concept screening phase, it was of utmost importance to analyze the circuits illustrated in the Section 5.1, whether they yield the same anticipated results. To analyze the circuit, the capacitance values associated with a 245 kV-rated capacitance-graded bushing having 142 kV on the central conductor were taken as the input. The equivalent circuit for concept 2T-2F represents the exact solution that the customer expects. The Figure 5.7

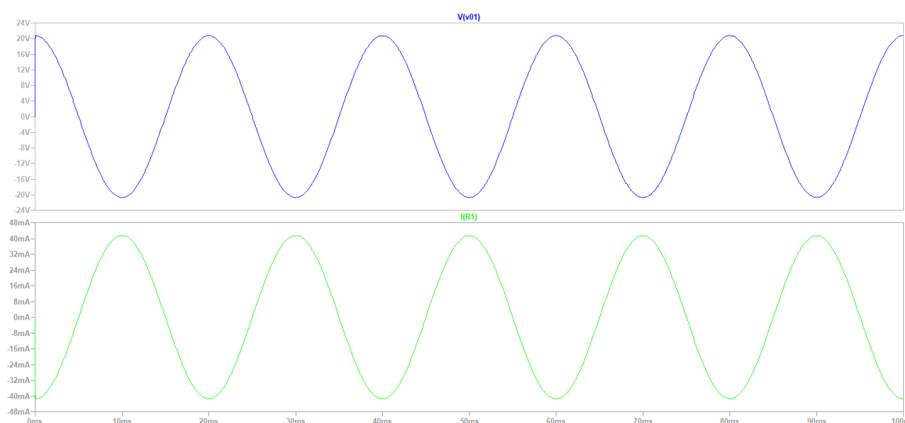
shows the representation of circuit configuration-1 in the LTspice environment during service. The following circuit is built in such a way that the tap is connected to the  $(n-1)^{\text{th}}$  layer, commonly referred to as a voltage tap or potential tap, and it is equipped with an online monitoring system, represented as a resistive load  $R_2$  of  $500 \Omega$  and safeguarded through grounding. The voltage of  $142 \text{ kV}$  at  $50 \text{ Hz}$  is given as input for  $100 \text{ ms}$ , and the voltage and current are observed at the nodes and the branch, respectively. The Figure 5.8 represents the simulation results by plotting voltage across voltage tap ( $V_{01}$ ) vs time, voltage across test tap ( $V_{02}$ ) vs time, and current through  $I(R_1)$  vs time. The values of the voltage and current results from the simulation are presented in the Table 5.1 as follows

| Parameter                                 | Value |
|---|-------|
| Voltage across potential Tap ( $V_{01}$ ) | 20 V  |
| Voltage across test Tap ( $V_{02}$ )      | 0 V   |
| Current through $R_1$ ( $I_{R1}$ )        | 39 mA |

**Table 5.1:** Simulation results for circuit configuration 1



**Figure 5.7:** Representation of circuit in LTspice - Configuration 1

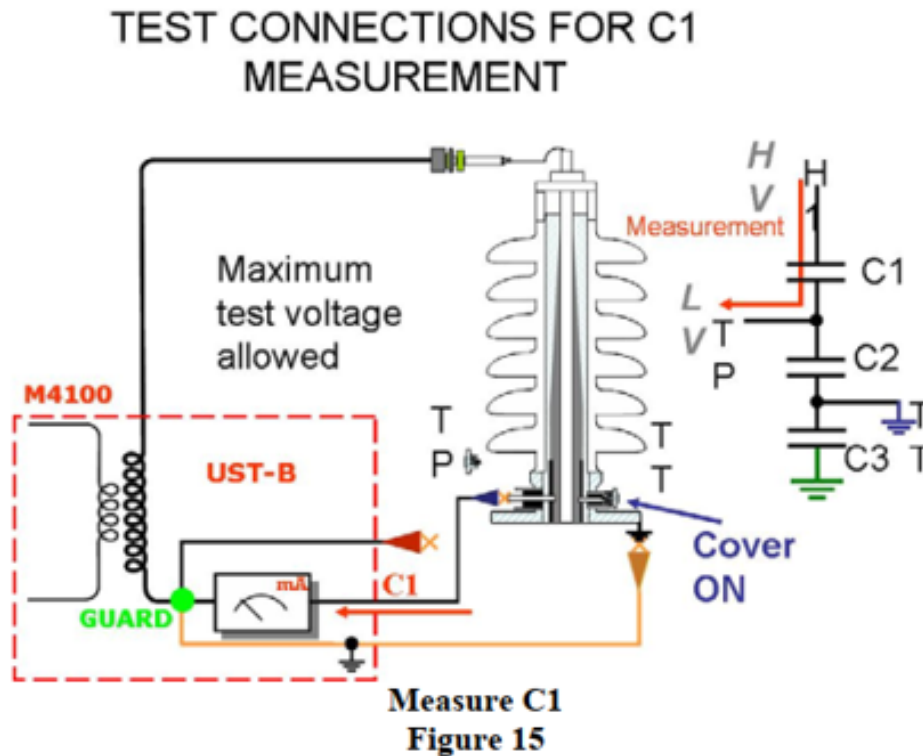


**Figure 5.8:** Simulation results for configuration 1

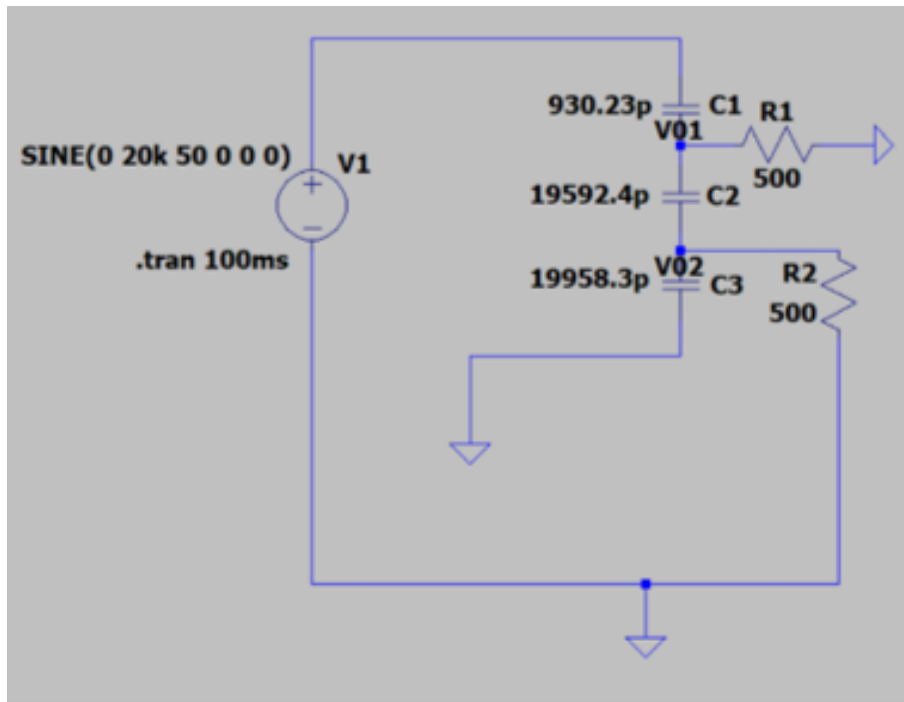
It can be observed that the simulations haven't provided the desired voltage output across  $V_{02}$  as expected earlier in Section 5.1. However, the normal operation of the bushing is not affected. Hence, it was necessary to verify the circuit behavior in the case of manual testing. The paper from Doble on "Procedure for testing bushings with both a test tap and a potential tap" presents the guidelines to conduct manual testing in case of two taps, and based on this, the setup for manual test cases was done. The Figure 5.9 shows the test connection for  $C_1$  from the Doble paper. The Figure 5.10 shows the circuit arrangement in LTspice to perform  $C_1$  measurement. The HV lead from the testing equipment is connected to the top terminal of the bushing, and the LV lead is connected to the test tap. Then a test voltage of 20 kV @ 50 Hz is given as input, and the resultant output is represented in the Figure 5.11. The values of the voltage and current results from the simulation are presented in the Table 5.2 as follows

| Parameter                                 | Value |
|---|-------|
| Voltage across potential Tap ( $V_{01}$ ) | 3 V   |
| Voltage across test Tap ( $V_{02}$ )      | 0 V   |
| Current through $R_1$ ( $I_{R1}$ )        | 6 mA  |
| Current through $R_2$ ( $I_{R2}$ )        | 0 A   |

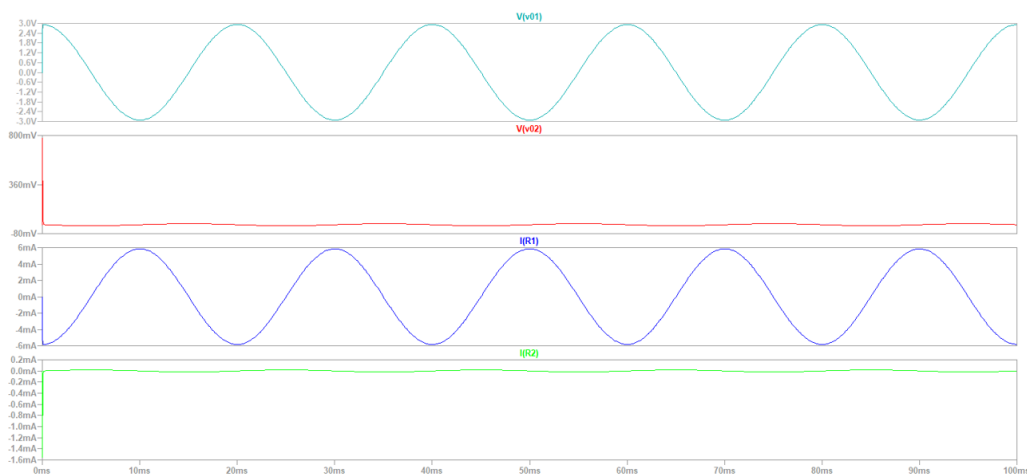
**Table 5.2:** Simulation results for circuit configuration 1 - Measurement of  $C_1$



**Figure 5.9:** Representation of circuit connection -  $C_1$  measurement in Doble



**Figure 5.10:** Representation of circuit in LTSpice - Configuration 1-  $C_1$  measurement

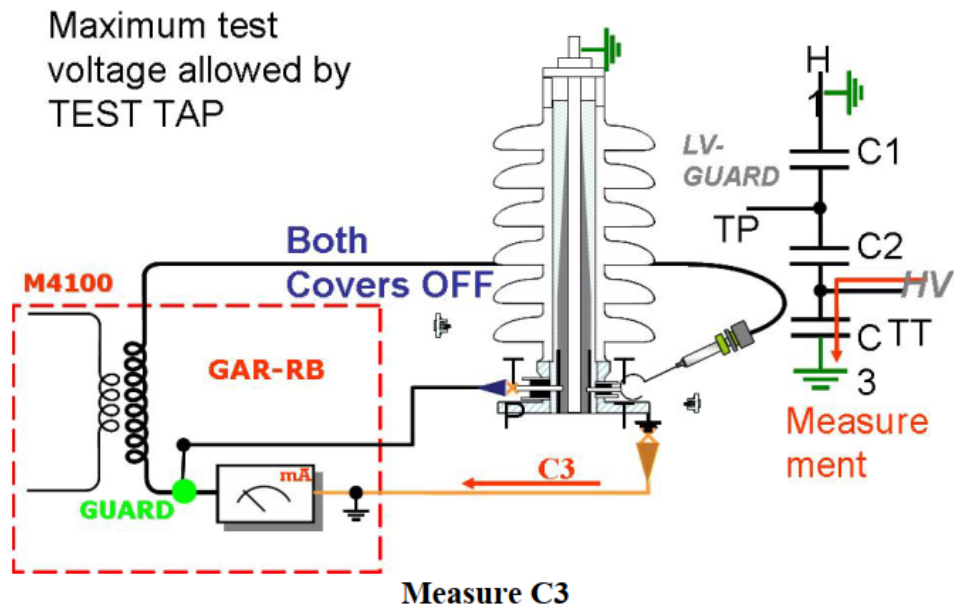


**Figure 5.11:** Simulation results for configuration 1 -  $C_1$  measurement

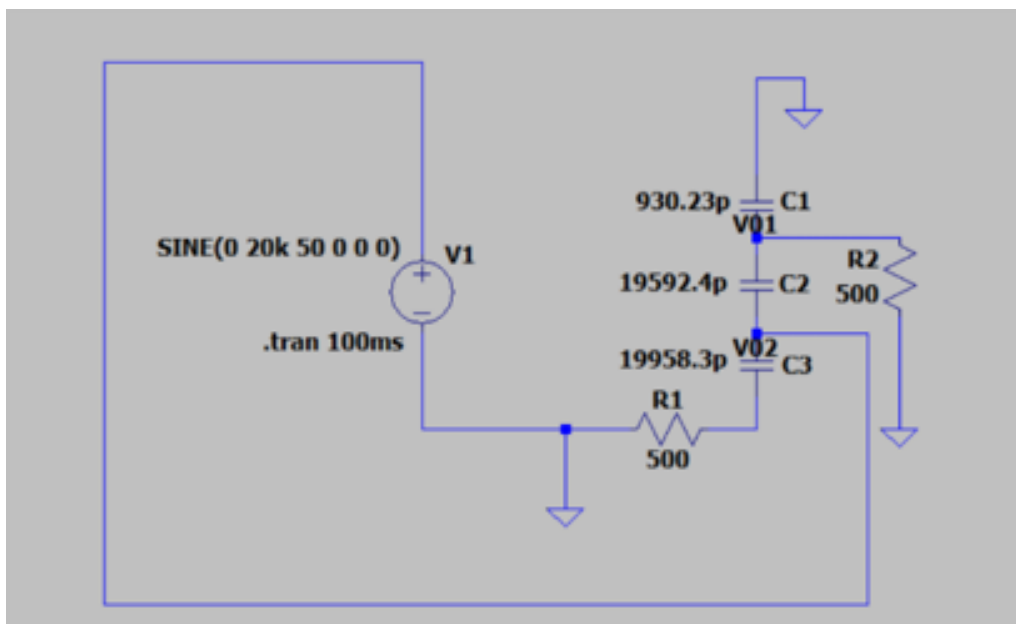
From the Table 5.2, it can be observed that the voltage across the offline equipment is 0V and the current flowing through the offline equipment is 0A as well. Hence, it could be concluded that this configuration cannot be used for measuring  $C_1$ . Moving on to the next test case  $C_3$  that is assumed to be  $C_2$ , where the HV lead is connected to the test tap and the LV to the grounded flange, and the same test voltage of 20 kV @ 50Hz is given as input. The Figure 5.13 shows the circuit arrangement in LTSpice to perform  $C_2$  measurement. The Figure 5.12 shows the test connection for  $C_2$  from the Doble paper. The resultant output from simulation is represented in the Figure 5.14. The values of the voltage and current results from the simulation are presented in the Table 5.3 as follows

| Parameter                                 | Value    |
|---|----------|
| Voltage across potential Tap ( $V_{01}$ ) | 60.5 V   |
| Voltage across test Tap ( $V_{02}$ )      | 20 kV    |
| Current through $R_1$ ( $I_{R1}$ )        | 123.5 mA |
| Current through $R_2$ ( $I_{R2}$ )        | 123.5 A  |

**Table 5.3:** Simulation results for circuit configuration 1 - Measurement of  $C_2$

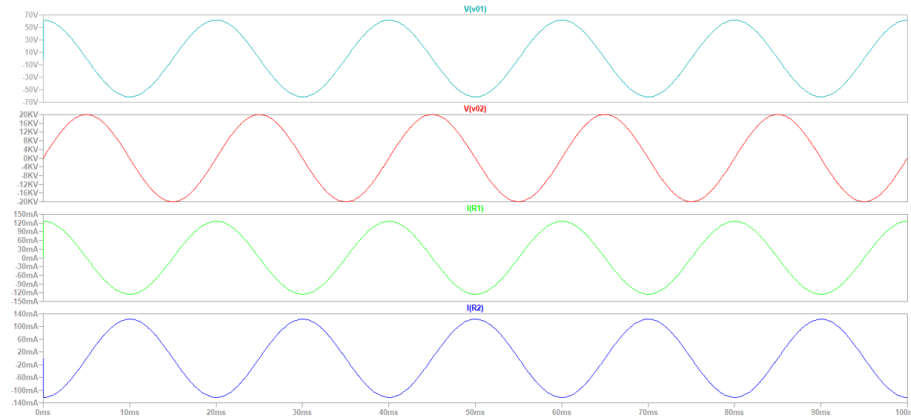


**Figure 5.12:** Representation of circuit connection -  $C_3$  measurement in Doble



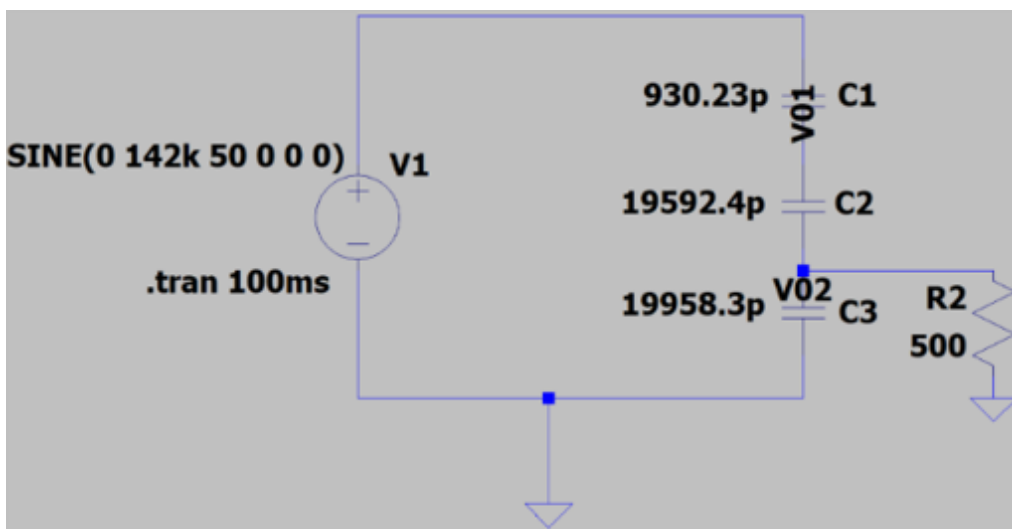
**Figure 5.13:** Representation of circuit in LTSpice - Configuration 1-  $C_2$  measurement

The setup induces a voltage ( $V_{01}$ ) and current ( $I_{R1}$ ) across the online monitoring system. Even though the monitoring system withstands the induced voltage and current, it is expected to create an imbalance in the measurement based on the knowledge about the online monitoring system.



**Figure 5.14:** Simulation results for configuration 1 -  $C_2$  measurement

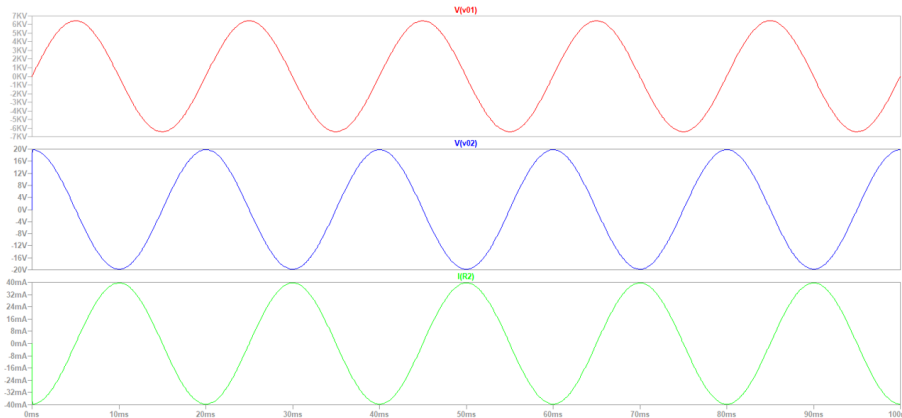
The next circuit analysis is for an alternative arrangement of 2T-2F. It is basically a recreation of circuit configuration 2. The tap is connected to the  $n^{\text{th}}$  layer, commonly referred to as the test tap, which is equipped with the online monitoring system. It is represented as a resistive load  $R_1$  of  $500 \Omega$  and safeguarded through grounding. The Figure 5.15 shows the representation of circuit configuration-2 in the LTspice environment during service. Similarly, the same Voltage of  $142 \text{ kV} @ 50 \text{ Hz}$  is given as input for  $100 \text{ ms}$ , and the voltage and current are observed at the nodes and the branch, respectively. The Figure 5.16 represents the simulation results by plotting voltage across voltage tap ( $V_{01}$ ) vs time, voltage across test tap ( $V_{02}$ ) vs time, and current through  $I(R_2)$  vs time. The values of the voltage and current results from the simulation are presented in the Table 5.4 as follows



**Figure 5.15:** Representation of circuit in LTspice - Configuration 2

| Parameter                                 | Value |
|---|-------|
| Voltage across potential Tap ( $V_{01}$ ) | 6 kV  |
| Voltage across test Tap ( $V_{02}$ )      | 19 V  |
| Current through $R_2$ ( $I_{R2}$ )        | 40 mA |

**Table 5.4:** Simulation results for circuit configuration 2

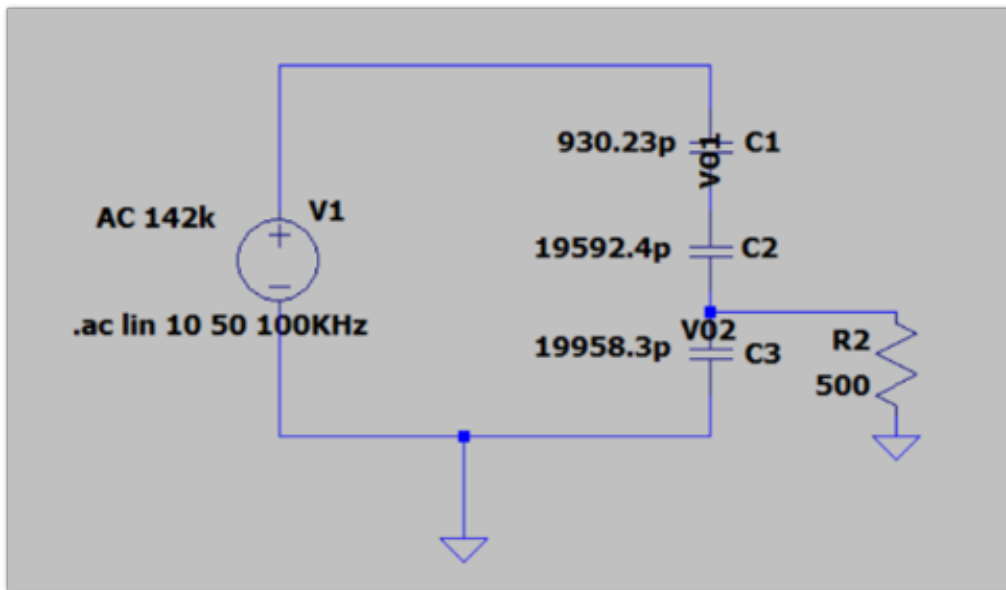


**Figure 5.16:** Simulation results for configuration 2

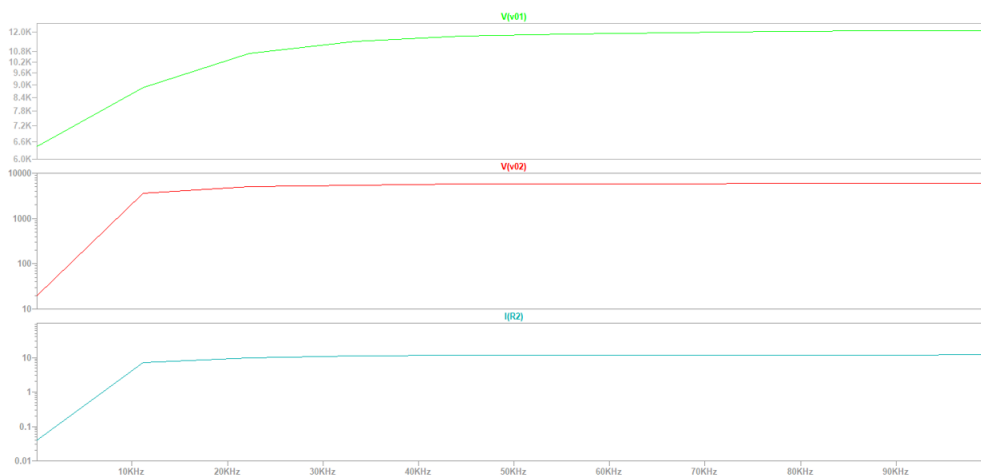
It can be observed that the simulations give the expected voltage output across  $V_{01}$ . Therefore, it could be concluded that the bushing functions normally during service. However, it doesn't provide any insights into the circuit behavior in case of surges, and also, as mentioned earlier, it is believed to be a promising circuit to satisfy the intended requirement. Hence, a frequency sweep analysis, shown in the Figure 5.17, was also performed for the same circuit by changing the mode of analysis to AC sweep analysis over the frequency range 50 Hz - 1 MHz, which is typical a scenario during lightning event. The Figure 5.18 shows the plot of the resultant frequency sweep analysis. From the plot, it could be observed that as the frequency increases, the respective voltage across  $V_{01}$  and  $V_{02}$  also rise linearly but only up to a certain frequency. After that, it almost saturates, witnessing a maximum voltage of 12 kV at the potential tap & 7 kV at the Test tap, and the maximum current flowing through the online Monitoring system is found to be 12 A, which is presumed to be withstood by the online Monitoring system. As far as the taps are concerned, the customers demand that the online Monitoring system has to be connected to a potential tap, as they presume that the development of failure in case of 20 kV insulated tap is comparatively lower than a 2 kV insulated tap, This is because the 2 kV test tap has relatively lower potential across the monitoring system. The values of the voltage and current results from the simulation are presented in the Table 5.5 as follows

| Parameter  | Value      |
|--|------------|
| Voltage across potential Tap ( $V_{01}$ @ 6 kV, 50 Hz) | Upto 12 kV |
| Voltage across test Tap ( $V_{02}$ @ 20 V, 50 Hz)      | Upto 7 kV  |
| Current through $R_2$ ( $I_{R2}$ @ 40 mA, 50 Hz)       | Upto 12 A  |

**Table 5.5:** Simulation results for circuit configuration 2 - Frequency sweep analysis



**Figure 5.17:** Representation of circuit in LTSpice - Configuration 2 - Frequency sweep analysis

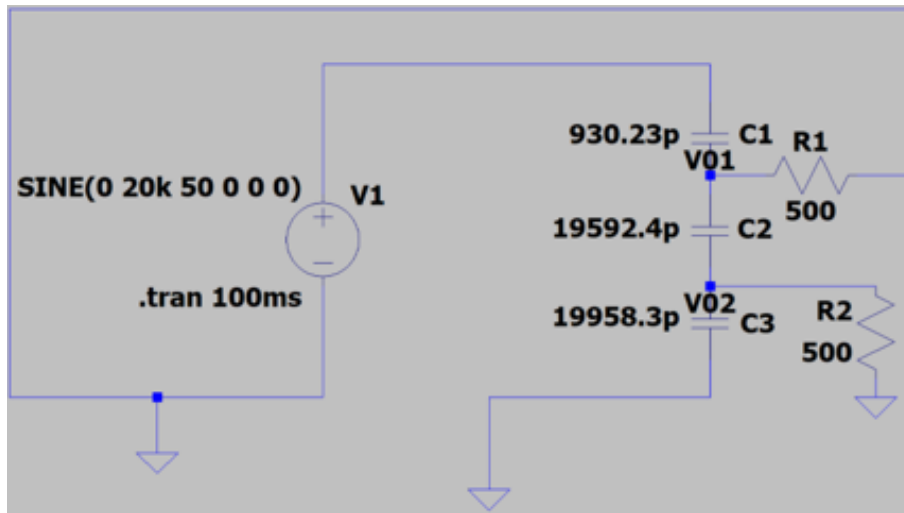


**Figure 5.18:** Simulation results for configuration 2 - Frequency sweep analysis

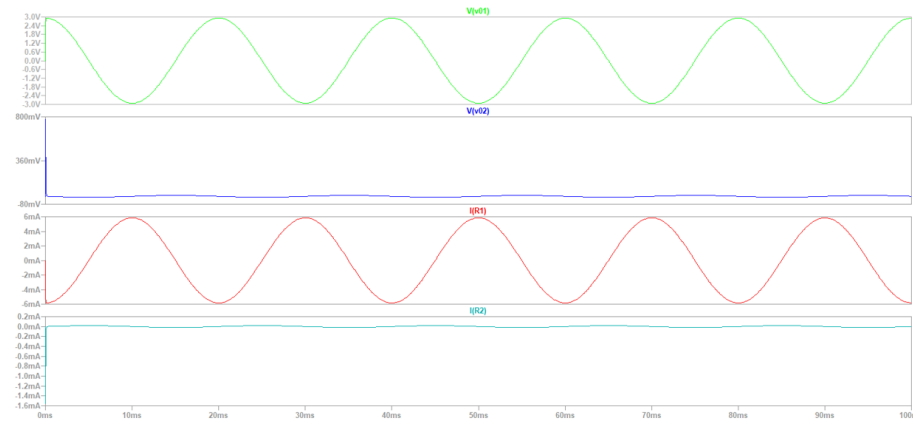
Subsequently, the voltage  $V_{02}$  does not seem to exceed 20 kV, hence it could be concluded that the tap is reliable during transient conditions. However, the same could not be said for  $V_{01}$ , if we consider a test tap, the voltage exceeds the maximum insulation level of 2 kV. But instead, if the tap is replaced with a voltage tap, as described before, then it could sustain transient conditions. It is important to note, as mentioned earlier, that this is not the exact solution expected by the customer. The next simulation associated with this configuration is the manual test cases. The Figure 5.19 illustrates the circuit arrangement for measurement of  $C_1$  in the LTSpice environment. The resultant output is represented in the Figure 5.20. The values of the voltage and current results from the simulation are presented in the Table 5.6 as follows

| Parameter                                 | Value |
|---|-------|
| Voltage across potential Tap ( $V_{01}$ ) | 3 V   |
| Voltage across test Tap ( $V_{02}$ )      | 0 V   |
| Current through $R_1$ ( $I_{R1}$ )        | 6 mA  |
| Current through $R_2$ ( $I_{R2}$ )        | 0 A   |

**Table 5.6:** Simulation results for circuit configuration 2 - Measurement of  $C_1$



**Figure 5.19:** Representation of circuit in LTspice - Configuration 2 -  $C_1$  measurement

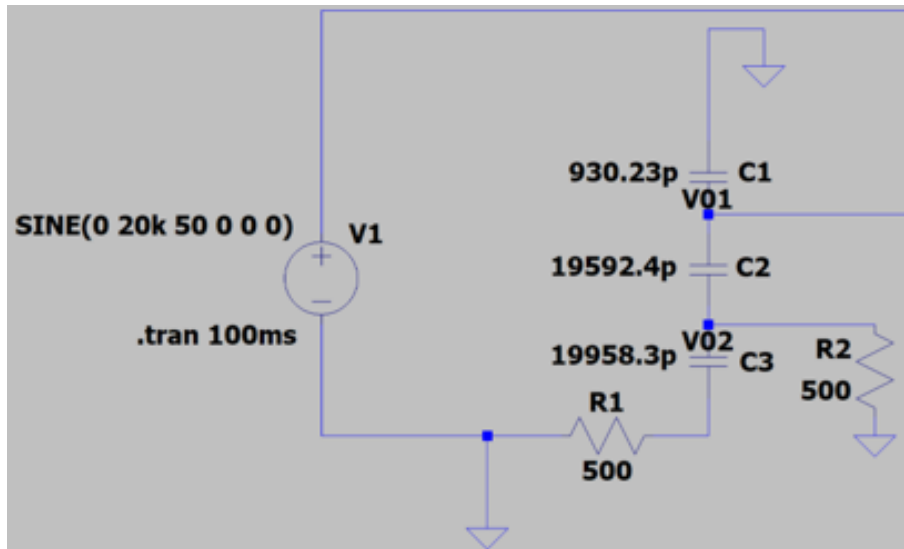


**Figure 5.20:** Simulation results for configuration 2 -  $C_1$  measurement

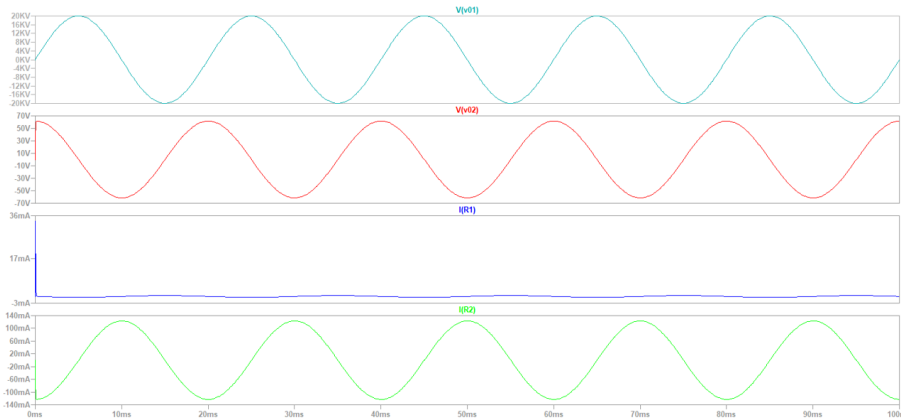
Unlike in the previous case, these simulation results indicate that this configuration could be used to measure  $C_1$ , as there are no current flows and voltage across the online monitoring system, ensuring it remains safe during measurement. However, if the testing personnel accidentally conduct  $C_2$  measurement, like in the case of a single tap as illustrated in the Figure 5.21, then this configuration is not recommended to perform  $C_2$  measurement. It could cause failure in the online monitoring system as indicated by the simulation results from the Figure 5.22. The values of the voltage and current results from the simulation are presented in the Table 5.7 as follows

| Parameter                                 | Value  |
|---|--------|
| Voltage across potential Tap ( $V_{01}$ ) | 20 kV  |
| Voltage across test Tap ( $V_{02}$ )      | 68 V   |
| Current through $R_1$ ( $I_{R1}$ )        | 0 A    |
| Current through $R_2$ ( $I_{R2}$ )        | 139 mA |

**Table 5.7:** Simulation results for circuit configuration 2 - Measurement of  $C_2$



**Figure 5.21:** Representation of circuit in LTSpice - Configuration 2-  $C_2$  measurement



**Figure 5.22:** Simulation results for Configuration 2 -  $C_2$  measurement

Similar to the previous configuration, during measurement of  $C_2$ , the applied test voltage will induce a current and voltage across the online monitoring system, which can cause it to malfunction.

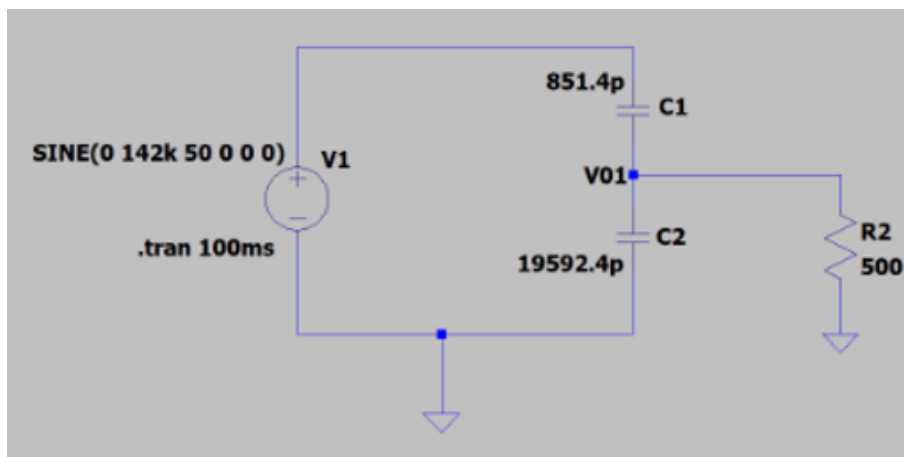
The equivalent configuration for the concept 2T-1F is the circuit configuration-3 described in the Section 5.1. The Figure 5.23 illustrates the representation of this arrangement in the LTSpice environment. Like the previous configuration, an input of 142 kV @ 50 Hz is given as input voltage while the online monitoring system is

## 5. Results

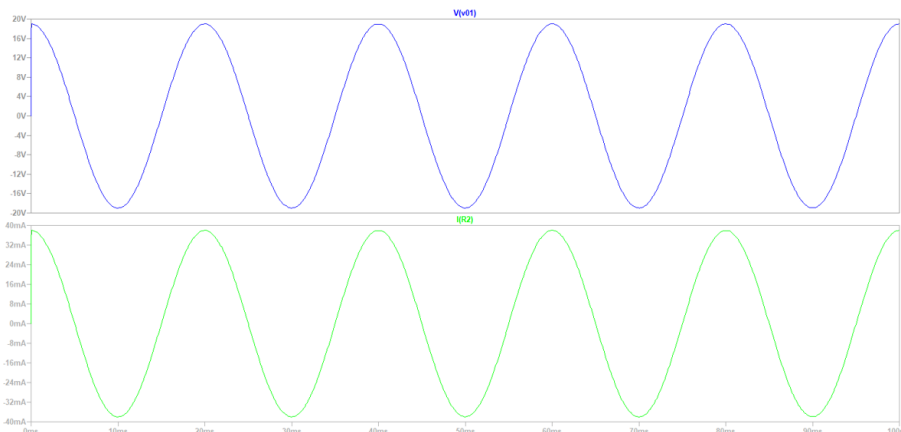
connected to any one of the taps, represented here as the resistive load  $R_2$  of  $500 \Omega$  and safeguarded by grounding. The Figure 5.24 represents the simulation results by plotting voltage across the voltage tap ( $V_{01}$ ) vs time, and current through  $R_2$  vs time. The values of the voltage and current results from the simulation are presented in the Table 5.8 as follows

| Parameter                                 | Value |
|---|-------|
| Voltage across potential Tap ( $V_{01}$ ) | 19 V  |
| Current through $R_2$ ( $I_{R2}$ )        | 39 mA |

**Table 5.8:** Simulation results for circuit configuration 3



**Figure 5.23:** Representation of circuit in LTspice - Configuration 3

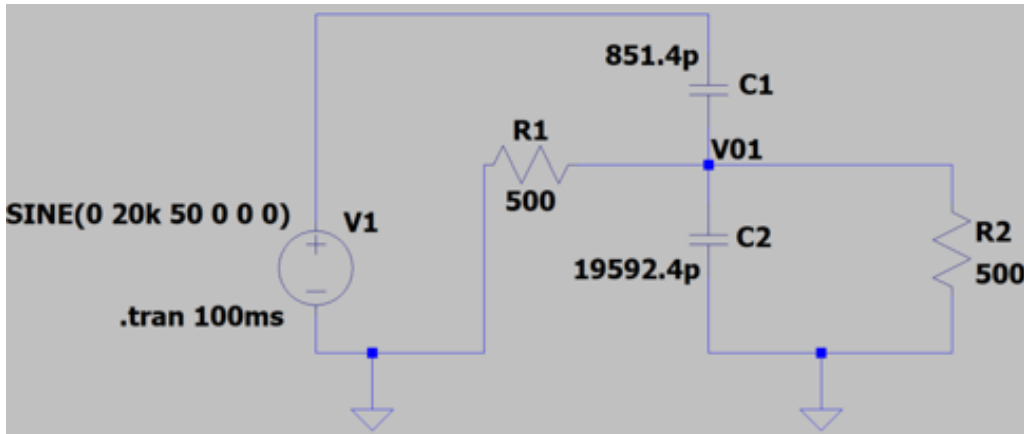


**Figure 5.24:** Simulation results for configuration 3

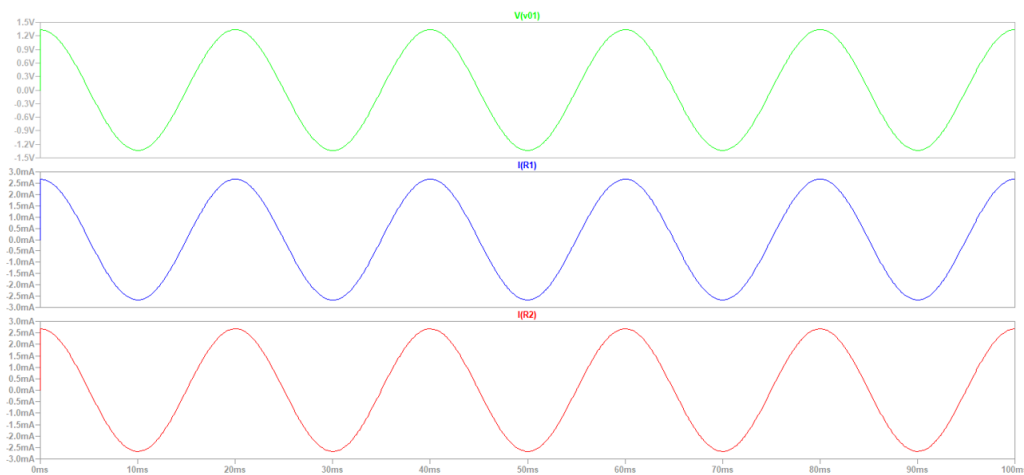
From the Table 5.8, the bushing exhibits normal operation only if the other tap is left floating. The Figure 5.25 illustrates the circuit arrangement for measurement of  $C_1$  in the LTspice environment. The resultant output is represented in the Figure 5.26. The values of the voltage and current results from the simulation are presented in the Table 5.9 as follows

| Parameter                                 | Value  |
|---|--------|
| Voltage across potential Tap ( $V_{01}$ ) | 1.4 V  |
| Current through $R_1$ ( $I_{R1}$ )        | 2.9 mA |
| Current through $R_2$ ( $I_{R2}$ )        | 2.9 mA |

**Table 5.9:** Simulation results for circuit configuration 3 - Measurement of  $C_1$



**Figure 5.25:** Representation of circuit in LTSpice - Configuration 3 -  $C_1$  measurement

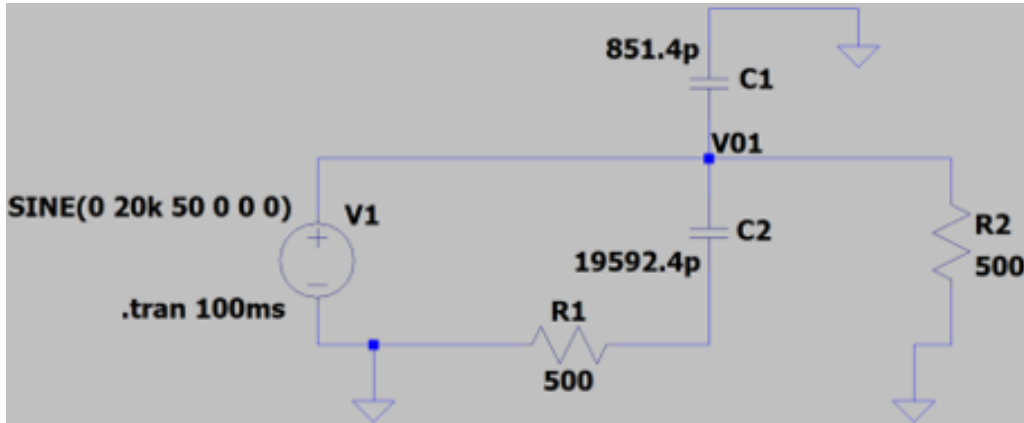


**Figure 5.26:** Simulation results for configuration 3 -  $C_1$  measurement

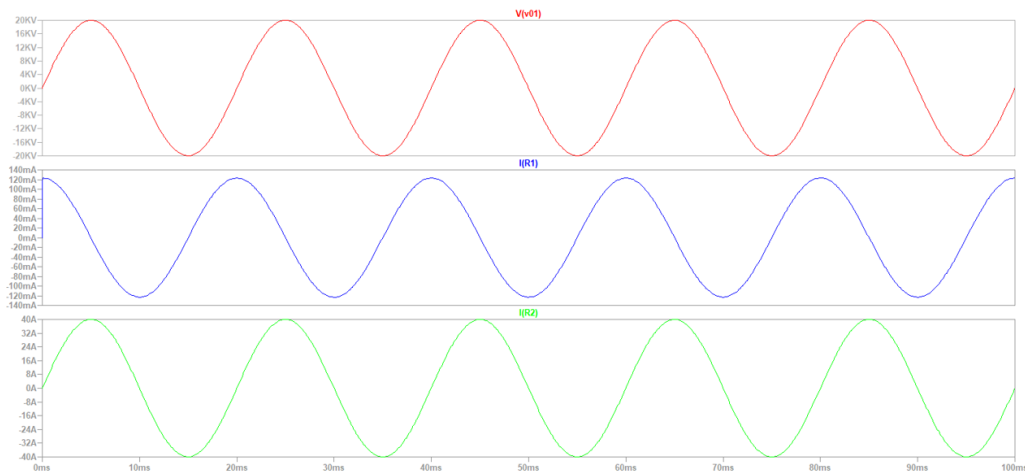
As seen from the Table 5.9, the same current flows through  $R_1$  and  $R_2$  as they form a parallel circuit and has the same potential across them. This brings the discrepancy in the measurements of  $C_1$ . Therefore, this configuration is not recommended for  $C_1$  measurement. For the measurement of  $C_2$ , the Figure 5.27 shows the circuit arrangement in the LTSpice. The resultant output from simulation is represented in the Figure 5.28. The values of the voltage and current results from the simulation are presented in the Table 5.10 as follows

| Parameter                                 | Value  |
|---|--------|
| Voltage across potential Tap ( $V_{01}$ ) | 20 kV  |
| Current through $R_1$ ( $I_{R1}$ )        | 130 mA |
| Current through $R_2$ ( $I_{R2}$ )        | 40 A   |

**Table 5.10:** Simulation results for circuit configuration 3 - Measurement of  $C_2$



**Figure 5.27:** Representation of circuit in LTspice - Configuration 3 -  $C_2$  measurement



**Figure 5.28:** Simulation results for configuration 3 -  $C_2$  measurement

From the Table 5.10, it can be inferred that the current flows through the online system during the offline testing of  $C_2$ . It causes the error in the measurements of  $C_2$  during offline testing, and therefore, this setup is not recommended to measure  $C_2$ .

## 5.4 Concept Screening

This section explains the detailed screening procedure that are carried out to arrive at the final concept.

### 5.4.1 Elimination Matrix

Based on the assigned *must-have* criteria, the generated concepts from morphological matrix were evaluated in the elimination matrix. There are five concepts generated after the refinement from the Morpheus tool, as mentioned in the Section 5.2.2. The generated five concepts are named as presented in the Table 5.11.

The criteria that are decided as *must-have* are listed as follows

1. Compatibility with existing system
2. Facilitate offline and online measurement
3. Applicable to Hitachi Energy internal requirements
4. Ensure the protection of online monitoring system
5. Facilitate the measurement of primary capacitance  $C_1$
6. Maintain non-discrepancy in measurements
7. Ensure bushing normal operation
8. Manufacturing feasibility
9. Safe testing

The concept that is to be developed should be compatible with the existing monitoring system. Hence, the *Compatibility with existing system* is set as one of the must-have criteria. The next criterion *Facilitate offline and online measurement* defines the purpose of this thesis work, which is actually the customer demand. The third criterion *Applicable to Hitachi Energy internal requirements* is important as the concept should satisfy the internal requirements to maintain the company's reputation in terms of safety & quality. Then the fourth criterion *Ensure the protection of the online monitoring system* explains the necessity of the concept design to protect the online monitoring system.

In general, the measurement of the primary or main capacitance  $C_1$  is critical during manual testing, hence it is defined as one of the important criteria. The next criterion *Maintain non-discrepancy in measurements* defines the significance of the similarity between the measured value during testing and the standard value. The design of the concept should make sure that the normal operation of the bushing is maintained; therefore, the criterion *Ensure bushing normal operation* is considered a vital one. One of the critical aspects of the concept that is to be developed is to be manufacturable; hence, the criterion *Manufacturing feasibility* is considered as one among the must-have criteria. Finally, as a global manufacturer of bushings, Hitachi Energy never compromises on the safety of the personnel and therefore *safe testing* is listed as one of the important criteria.

| S.No | Concept Name | Concept Description   |
|------|--------------|---|
| 1    | Plug & Play  | Creating a common adapter interface that is compatible with both offline and online systems.  |
| 2    | 2T-2F        | Two identical individual interfaces for the two systems, and the taps are connected to different foil layers where the isolation is provided by a heavily insulated cover.  |
| 3    | 2T-1F        | Two identical individual interfaces for the two systems, and the taps are connected to the same foil layers, where the isolation is provided by a heavily insulated cover.  |
| 4    | T-ElecTap    | A common dock having two interfaces for each system where the isolation is handled by an electromechanical relay, which is protected by GDT, MOV, etc.  |
| 5    | T-MechTap    | A common dock having two interfaces for each system where the isolation is handled by a mechanical switch (operated by lever, slider, rotary, or knob) and returned back to the initial position using a spring after the testing is completed. |

**Table 5.11:** List of the concepts from Morpheus matrix

Based on the above criteria, each concept resulting from the morphological matrix is assessed against each criterion listed in the columns. By evaluating in this fashion, it was found that the concept *2T-1F* failed to meet one of the assigned criteria *Facilitate the measurement of primary capacitance  $C_1$*  as already explained in the Section 5.3. Therefore, this concept was eliminated and was not carried forward to the next step in the screening process. The elimination matrix, which was formulated, is presented in the Appendix D

## 5.5 Pugh Matrix

The remaining four concepts from the elimination matrix are further screened using the Pugh matrix. In the Pugh Matrix, the current solution is taken as reference, and each concept is evaluated against the reference concept and given a ranking accordingly. The formulated Pugh matrix is attached in the Appendix E. The current solution comprises a single tap interface as defined in the standard IEC 60137 to provide a tap for higher kV bushings. This single tap provision is used to perform both online and offline (manual) testing. In this matrix, each concept is ranked by comparing with the single tap interface as a baseline of reference. The concepts are evaluated for the following criteria in the Pugh Matrix.

1. Duration for offline setup
2. User-friendly interface
3. Measurement accuracy
4. Wear rate

- 
5. Consistent functionality
  6. Compatibility with existing system
  7. Compliance with IEC and IEEE standard
  8. Ensure safe testing
  9. No manual switching
  10. Facilitate the measurement of capacitance  $C_2 / C_3$
  11. Cost
  12. Hassel-free interchanging of system

The first criterion *Duration for offline setup* is given a positive score for all four concepts, as it was decided that they all require less time for setting up the offline equipment for testing when compared to the reference solution. For the *user-friendly interface*, the concept 2T-2F was given a negative score because the introduction of two taps creates confusion in testing to the personnel, as it involves new guidelines to conduct the manual testing. On the other hand, the concepts T-MechTap and T-ElecTap are given a positive score, as they require familiarization and one-time user interaction to switch between offline and online.

For the criterion *Measurement accuracy*, the concept 2T-2F is given a negative score, as observed from the simulation results in the 5.3, there was some amount of leakage current that flows through the online device during offline testing. This results in a discrepancy in measurements to a considerable extent when compared to other concepts in the matrix. For the criterion *Wear rate*, the concepts T-MechTap and T-ElecTap were given a negative score because they involve switching operations by a mechanical switch or by an electromechanical relay for switching between the online and offline equipment. This operation will definitely cause friction between the components, which increases the probability of wear. Similarly, for the next criterion *Consistent functionality*, the concepts T-MechTap and T-ElecTap were given a negative score as both the concepts involve moving components, hence it has chances to lose their functionality over time when compared to the reference solution. Coming to the next criterion *Ensure safe testing*, the concept 2T-2F poses a significant compromise on the safety of the testing personnel, as explained in the Section 5.3, hence it was ranked negative.

In the evaluation of the criteria *No manual switching*, among the four concepts, the concept 2T-2F was given a positive score because other concepts require manual intervention, either by mechanical or electrical means. Coming to the criterion *Facilitate the measurement of capacitance  $C_2 / C_3$* , the concept 2T-2F was given a negative score because the capacitance  $C_2$  cannot be measured using this configuration as already explained in the Section 5.3.

When the criterion *cost* is concerned, all four concepts were given a negative score as all four involve the development of a new solution that will eventually add up to investment when compared to the reference concept. In the evaluation of the criterion *Hassel-free interchanging of system*, except for the Plug & Play, the other three concepts were given a positive score when compared to the reference concept.

This is because they ease the process of interchanging between online and offline systems to a considerable extent.

The rest of the matrix is filled with 0, as it was found that there were no significant changes when compared to the current solution. Eventually, as a result of this screening, the 2T-2F concept was eliminated, and the other three concepts were promoted for the next step in the concept screening process.

### 5.6 Kesselring Matrix

The first step of Kesselring matrix was to assign the weights for each criteria. To determine the weights associated with each criteria, a pair wise matrix was formulated as mentioned in the Section 4.4.3. The total weight was fixed as 100, and each criterion is given with a weight value based on its relative importance with respect to the other. From the pairwise matrix, the criterion *Degree of Fulfillment* was given with the highest weight value of 17 because it tells to what extent the formulated concept fulfills the intended outcome. Followed by, the criterion *safe testing* was assigned with weight of 16 as it is the considered as the utmost priority while concerning about the potential risk involved in HV application. The third highest weight value, 13 was given to *Degree of reliability* because it describes to what extent the concept performs its intended function without any failure. Then the criterion *Cost-material & manufacturing* and *Endurance to harsh environments* were given equal importance and weighted equally with a value of 11. The bushings that are manufactured are installed in high altitudes and exposed to harsh climatic conditions. Hence, the concept that is yet to be developed should also be able to withstand harsh environmental conditions, and therefore, to manufacture such a product with high durability, the cost involved in procuring materials and in the manufacturing process is also equally important. The subsequent criterion *Manufacturability* was given with the weight value of 10, as the formulated concept must ensure that it can be manufactured to implement it in real-time usage. Following that, the remaining criteria were given with respective weights based on their relative significance to each other. The resultant table of the assigned weights is attached in the Appendix F.

The next step in the Kesselring matrix is to define the parameters relevant to each criteria as already explained in the Section 4.4.3. Then they are categorized and assign the value to fit in the defined three scale grading system. The complete value matrix is presented in the Appendix G. Based on this, the criterion *Manufacturability* was defined by the parameter "Feasibility level" and categorized as high for simple design, medium for moderate design and low for complex design. Subsequently, they were given values of 3, 2, and 1, respectively. Then the second criterion *Maintainability* was defined by the parameter "Maintenance period" and classified as occasional, periodical, and frequent, and given with values of 3, 2, and 1, respectively. The third criterion *Design Complexity* was defined by the parameter "Complexity level" and classified as simple, moderate, and complex and assigned with values of 3, 2, and 1, respectively. The fourth criterion *Production Complexity* was labeled by the parameter "No. of Stages" in production and categorized as <5 stages,

5-10 stages, and >10 stages and assigned with values of 3, 2, and 1, respectively. The fifth criterion *Scalability* was defined by the parameter "Scalability level" and classified as high, medium, and low and assigned with values of 3, 2 and 1, respectively.

The sixth criterion *Degree of reliability* was labeled by the parameter "Functional years" and classified as 40 years, 20 years, and <20 years, and given with values of 3, 2, and 1, respectively. The seventh criterion *Cost* was defined by the parameter "Estimated cost" and classified as low, moderate, and high, and assigned with values of 3, 2, and 1, respectively. The eighth criterion *Endurance to harsh environment* was defined by the parameter "Operating temperature" and classified as -60 deg to +60 deg, -40 deg to +40 deg, and -20 deg to +30 deg, and assigned with values of 3, 2, and 1, respectively. The ninth criterion *Safe testing* was labeled by the parameter "Safety level" and classified as risk-free, basic, and unsafe, and assigned with values of 3, 2, and 1, respectively. The final criterion *Degree of fulfillment* was defined by the parameter "Satisfactory level" and classified as high, moderate, and low, and assigned with values of 3, 2, and 1, respectively.

The final process in the Kesselring matrix is to evaluate each concept against each criterion by comparing the ideal concept. The ideal concept is the one that holds the highest value of the grading system against all the criteria. For the criterion *Manufacturability*, all the concepts are given the values of 2 when compared to the ideal concept. This is because the listed concepts are completely new and require detailed analysis before it is manufactured. The next criterion *Maintainability*, the concept Plug & Play was given the highest value in the grading scale of 3, while the concept T-MechTap was given a value of 2, as it involves mechanical movements, and the T-ElecTap was given the lowest value of 1, since it involves both electrical & mechanical components in it. For the evaluation of third criterion *Design Complexity*, all other concepts involve some design challenges when compared to the ideal one. Hence the Plug & Play was given 2 and 1 for both T-MechTap & T-ElecTap, since there was a similar solution for Plug & Play already existing in the market.

For assessing the criterion *Production Complexity*, the Plug & Play was assigned with 3, as it involves easy production with a lesser number of stages. While the concepts T-MechTap & T-ElecTap were given with 2 & 1, respectively, as T-MechTap contains complex components that cause challenges in the production process, and T-ElecTap is much more complex because of the electrical components in it. For the criterion *Scalability*, all the proposed concepts were given the value of 3, as they can be installed in the entire range of bushing portfolio. For the next criterion *Degree of Reliability*, the concepts Plug & Play and T-MechTap were given a value of 2 in comparison with the ideal concept, since it is subjected to wear and tear during their utilization. On the other hand, the concept T-ElecTap was assigned a value of 1, as it contains additional electrical components, which are influenced by external factors, causing problems to its normal functionality.

For evaluating the criterion *Cost-material & manufacturing*, the concepts Plug & Play and T-MechTap were given a value of 2 when compared to the ideal one.

Both concepts are entirely new and need additional components for real-time usage, which eventually impacts the cost of required materials and their manufacturing. The impact on the cost by T-ElecTap is more prominent, as it contains electrical components as well. For assessing the criterion *Endurance to harsh environment*, the concept T-ElecTap was given the lowest value of 1, as it contains electrical components that are more prone to damage at the elevated operating temperatures. While for the concept Plug & Play and T-MechTap were given a value of 2, since their capability to withstand harsh climatic conditions is high when compared to T-ElecTap. Coming to the next criterion *Safe testing*, the highest value of 3 was given for Plug & Play and T-MechTap, as the probability of bringing up the fool-proof design was high. While the other concept was given a value of 2, since the probability of malfunctioning seems to be high. For the evaluation of the final criterion *Degree of Fulfillment*, the value 1 was assigned to Plug & Play, as it doesn't fulfill the requirement completely. However, the other two concepts, T-MechTap & T-ElecTap, were given with 2 because they satisfy the requirement and solve the intended purpose indirectly. The resultant matrix of the assigned values is attached in the Appendix H. Based on the final value that is obtained after the evaluation of each concept against the ideal concept, T-MechTap topped among the three concepts, and it was decided to design a prototype with the T-MechTap configuration.

Note, since the screening is carried out at a very early stage of the development, the criteria defined here are also at a preliminary level, as not much information is known.

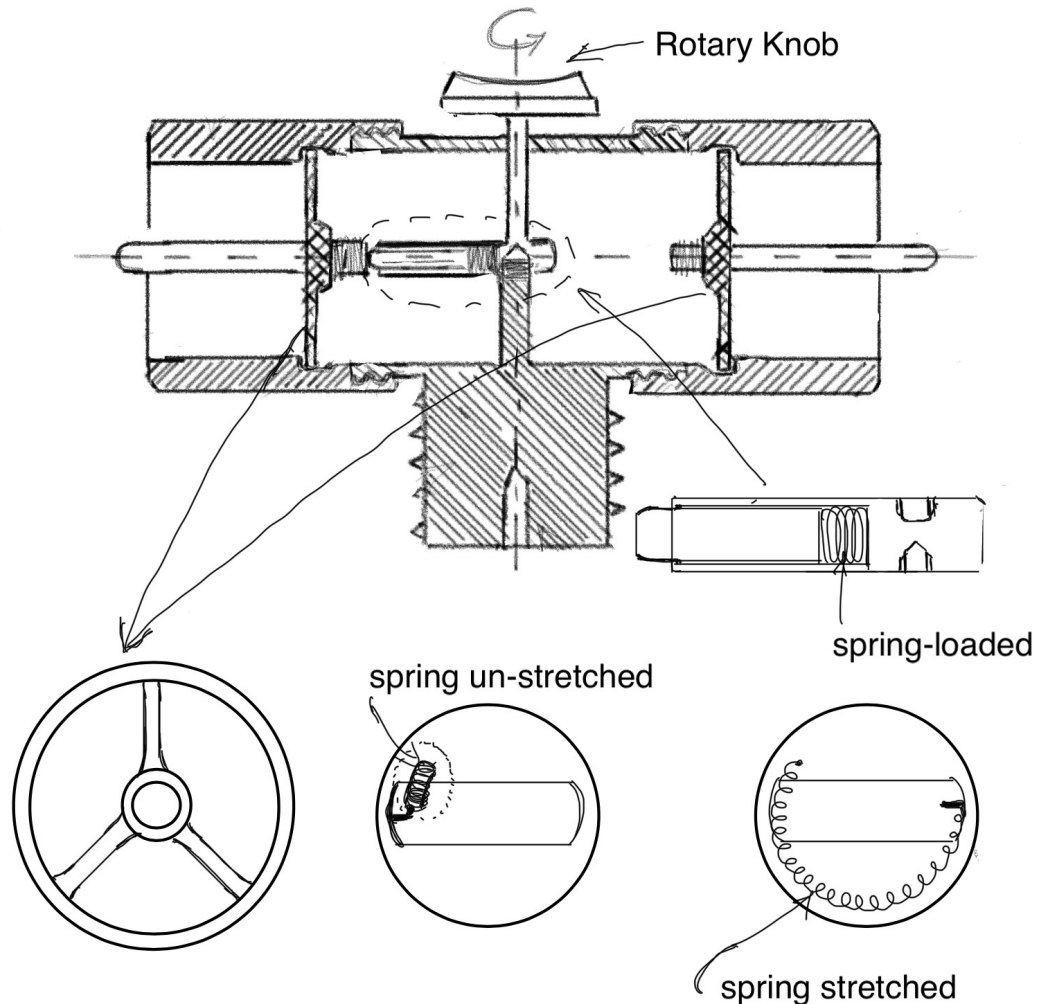
### 5.7 Requirement Specification

The requirement specification is classified into seven different categories as listed below. The criteria are formed based on the new requirement incorporated, as well as from the knowledge acquired during the literature study. The criteria are then separated into demands (D) or wishes (W), where the former is required to fulfill and the latter would be advantageous, but not necessary to fulfill. Next, the wishes are given importance on a scale of 1-5 based on the degree of importance, where 5 is the most important wish and 1 is the least important wish. The requirement specifications are attached in the Appendix I. Based on the type of criteria and the relevant IEC standard, the units are specified accordingly.

### 5.8 Embodiments of T-MechTap

As mentioned above in the Section 5.6, it was decided to proceed with T-MechTap for the prototype design. The next step involves a similar idea generation process, like explained above, but at a simpler level. The idea behind the T-MechTap is merely a mechanical switch; hence, this process mainly involves developing as many different T-MechTap embodiments as possible. These are explained in detail in the following subsections and illustrated through simple hand sketches.

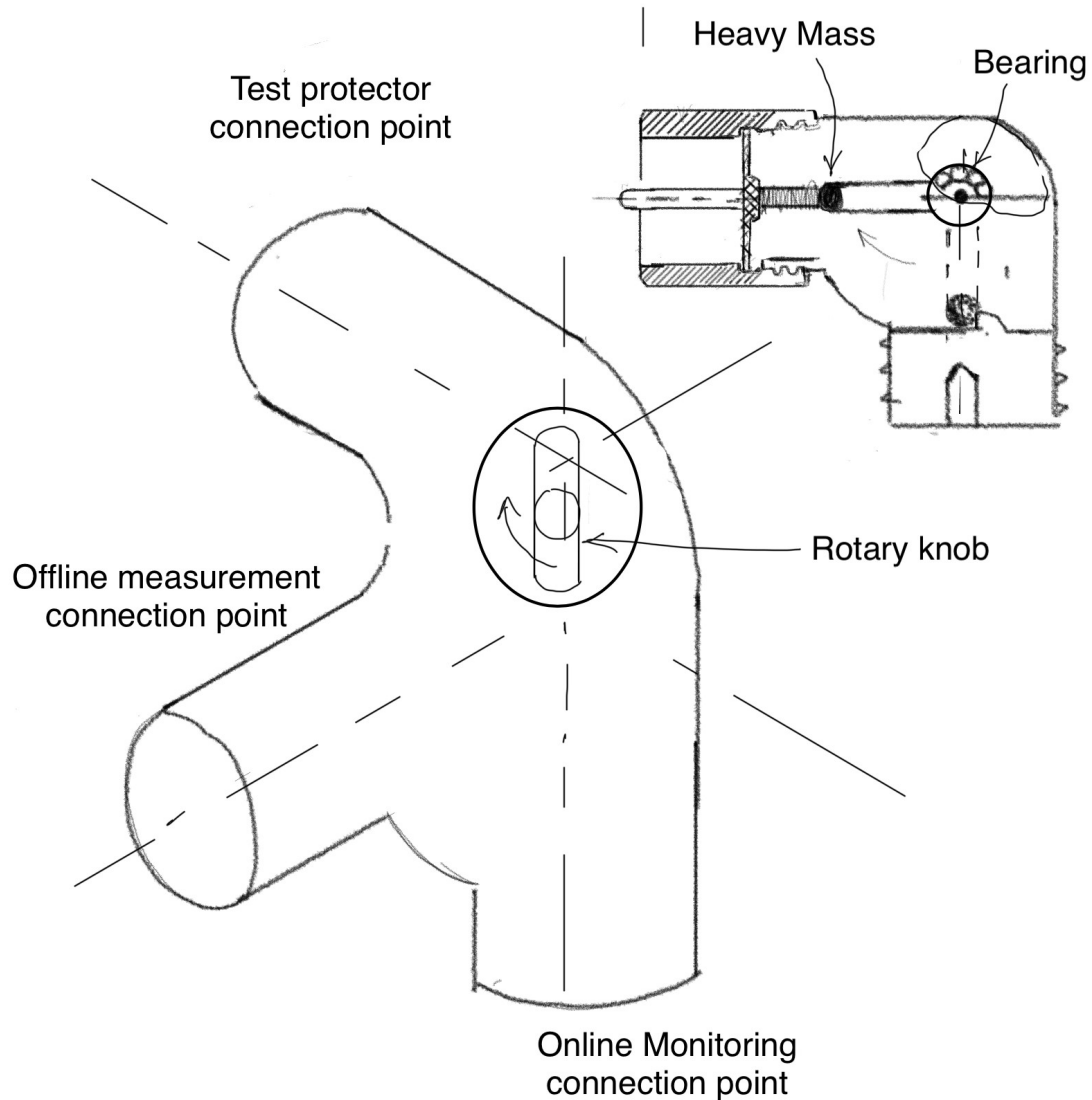
### 5.8.1 Embodiment 1 - Rotary Switch



**Figure 5.29:** Embodiment 1 - Rotary Switch

The first embodiment, "Rotary switch," comprises three flanges. The first flange is intended to connect to the test protector or the bushing tap, the second is to connect to the online monitoring system, and the third flange is used to conduct offline measurements. The contact pin from the bushing tap makes electrical contact with the first contact pin present inside the first flange. Then the second contact pin is pivoted to the first contact pin of the first flange. The second contact pin is similar to a plunger, which consists of a spring for self-adjusting its length. Then the second and third flanges are connected at either end of the first flange, wherein each flange consists of stationary third and fourth contact pins, respectively, through the supporting ring. Following that, a rotary knob is connected to the second contact pin that facilitates the rotating mechanism that helps to switch between the modes. The corresponding hand sketch that represents the rotary switch is illustrated in the Figure 5.29.

### 5.8.2 Embodiment 2 - Pendulum



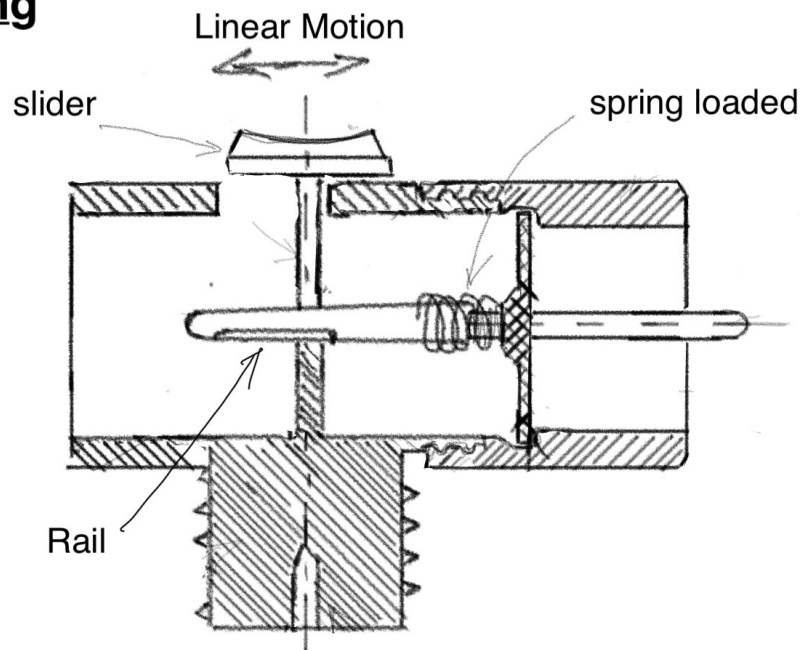
**Figure 5.30:** Embodiment 2 - Pendulum

As the name implies, the second embodiment, "Pendulum," is inspired by the pendulum's action. It resembles a three-way female elbow and comprises three connection points. One is connected to the test protector or the bushing tap, the second connection point, which is in the direction of gravity, is equipped with the online monitoring system, and the third connection is used to conduct offline measurements. Inside the elbow, a rotatable conductor is equipped with heavy mass at the ends, and the end is equipped with a bearing positioned at the intersection of three connection points to enable free rotation. Then, a rotary knob is also present at the intersection and connected to the bearing of the rotating conductor. The corresponding hand sketch that represents the Pendulum design is illustrated in the Figure 5.30.

### 5.8.3 Embodiment 3 - Slider Switch

The Embodiment 3 "Slider Switch" has two variants: Embodiment 3A with a spring and Embodiment 3B without a spring, which will be explained as follows.

#### With spring



#### Without spring

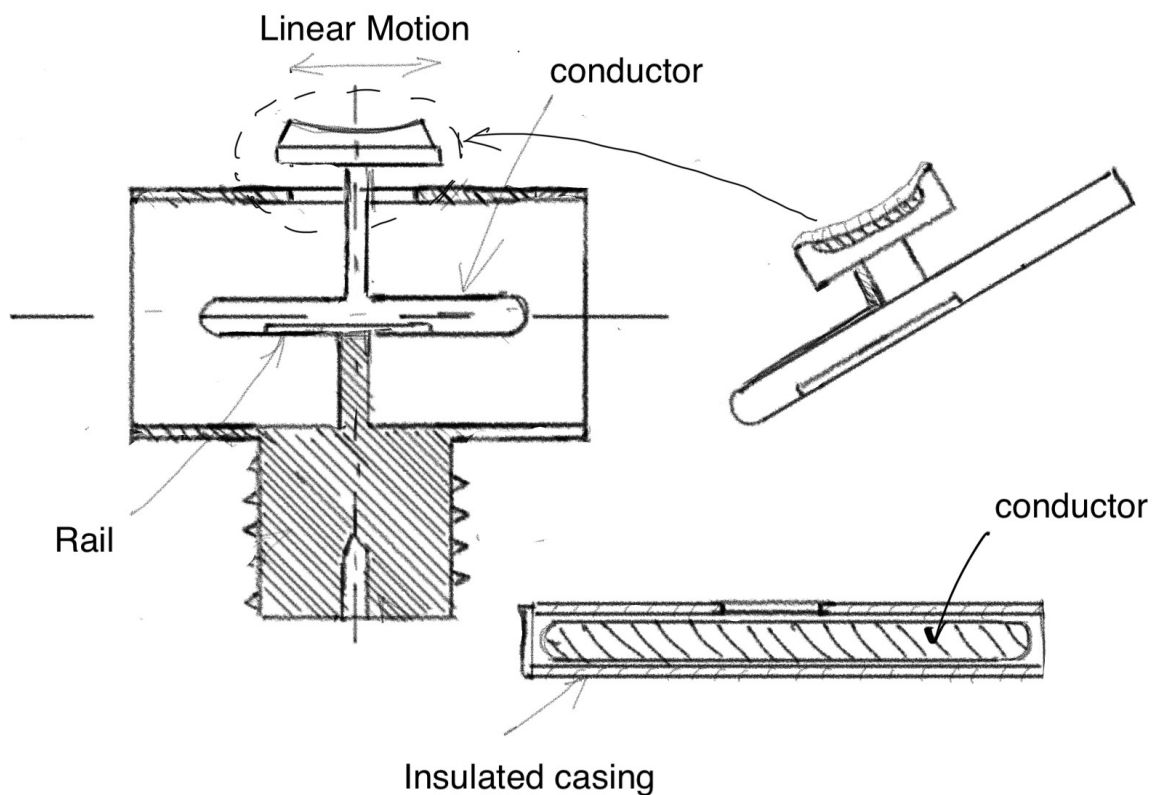


Figure 5.31: Embodiment 2 - Slider switch

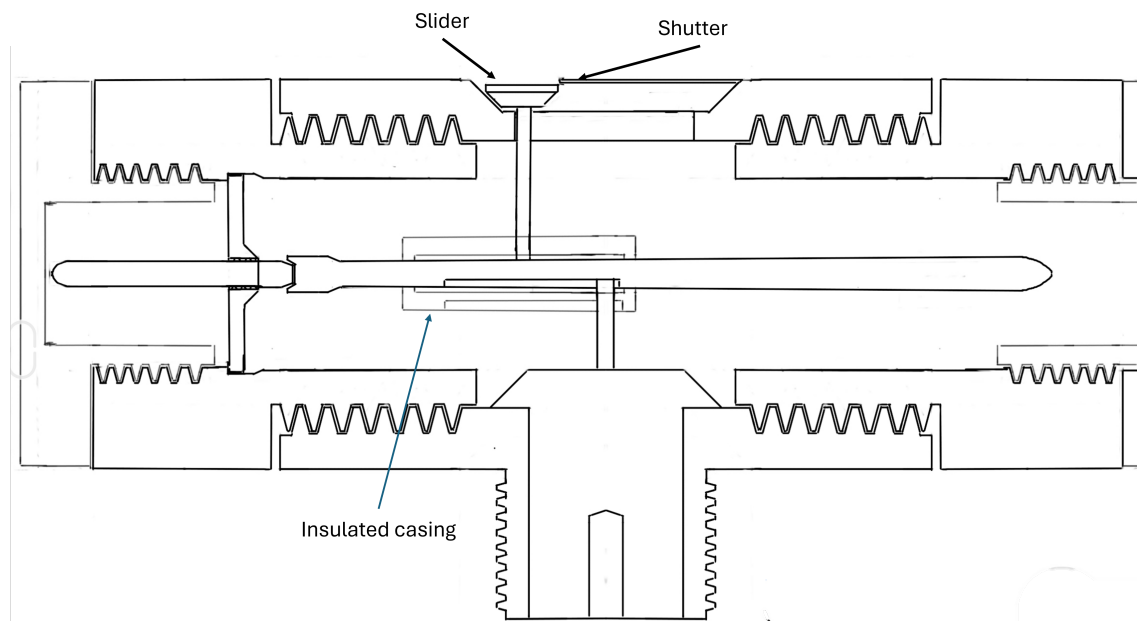
**(i) Embodiment 3A with spring**

It comprises two flanges, and the first flange consists of two connection points—one is connected to the test protector or the bushing tap, and the other connection point is to the second flange. The second flange consists of a contact pin, which is positioned using a support ring. Then, a movable conductor is present in which one end of the pin is connected to the spring of the support ring in the second flange. A rail provision is provided in the movable conductor that enables it to rest on the conductor of the first flange. A slider is attached to a movable conductor, which facilitates the linear motion, thereby switching between the offline and online systems. By default, it is connected to the online monitoring system due to the spring provision at the second flange. The corresponding hand sketch that represents the slider switch with spring is represented in the Figure 5.31.

**(ii) Embodiment 3B without spring**

It comprises one T-shaped flange—one is connected to the test protector or the bushing tap, while the other two are connected to the offline and online systems accordingly. A movable contact pin that is equipped with the slider rests upon the contact pin of the flange. This enables linear motion, which facilitates switching between the offline and online systems. The corresponding hand sketch that represents the slider switch without a spring is represented in the Figure 5.31.

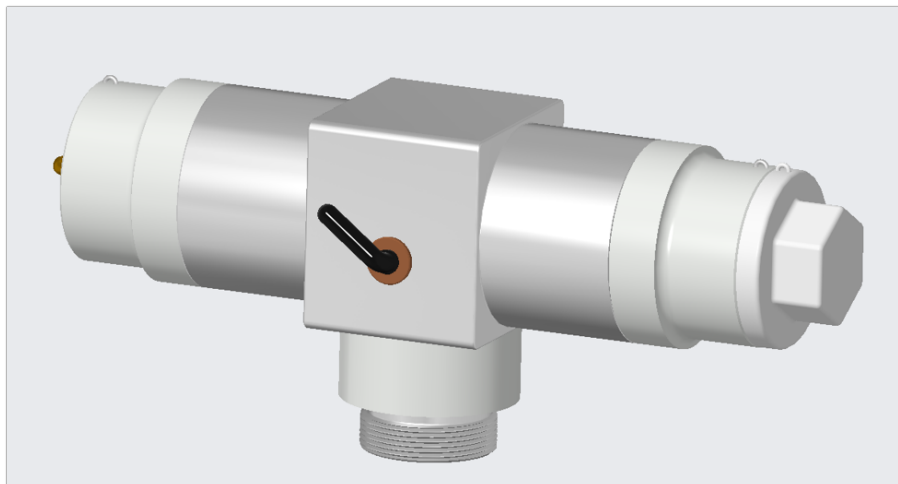
Additionally, in both the embodiments 3A and 3B, an insulated casing can also be integrated for the movable contact pin for the prevention of arcing.

**5.8.4 Embodiment 4 - Improvised switch**

**Figure 5.32:** Embodiment 4 - Improvised switch

This embodiment, as highlighted in the header, is an improvised switch. It is a cumulation of all the positive feedback gathered for the previous embodiments from the Bushing design team. It consists of two flanges and a T-shaped junction. Inside the T-shaped junction is a movable conductor that is enclosed in an insulator casing. The movable conductor rests on the conductor that transfers the electrical connection from the contact pin of the bushing tap, using a rail provision provided in it. This enables the slider to move linearly. To control the linear position, a slider interface is provided, and it is connected to the movable conductor. Since there is a high probability of moisture ingress through the slit provided for the slider functioning, a retractable shutter provision is provided to protect the slit when there is no need for switching operation. Then, there are the two flanges, which are connected at either end of the T-shaped junction to connect the online monitoring system and offline measurement equipment, respectively. The flange intended for the online monitoring system consists of a contact pin through a support ring to connect the online monitoring system, whereas for the other flange, the movable conductor acts as the contact pin to clamp the offline equipment, as represented in the Figure 5.32. When the offline measurement is required, the test cover of the offline flange is removed, and then the shutter is opened, following that the slider interface is moved to the extreme position, which intends to move the movable conductor along with the insulated casing for carrying out the measurement. Once the testing is completed, the slider is moved to its initial position and the cover is put back.

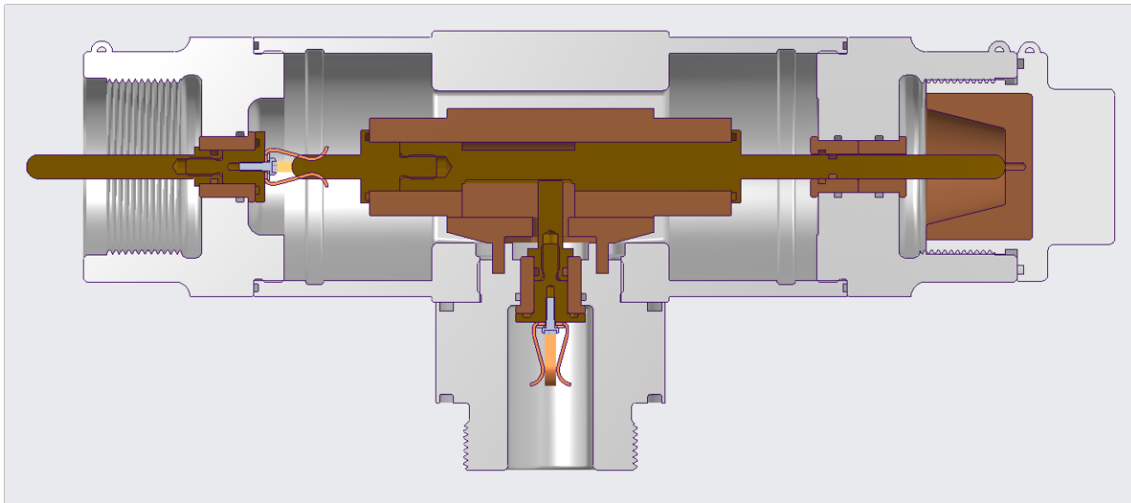
## 5.9 Final Design



**Figure 5.33:** Final embodiment of T-MechTap

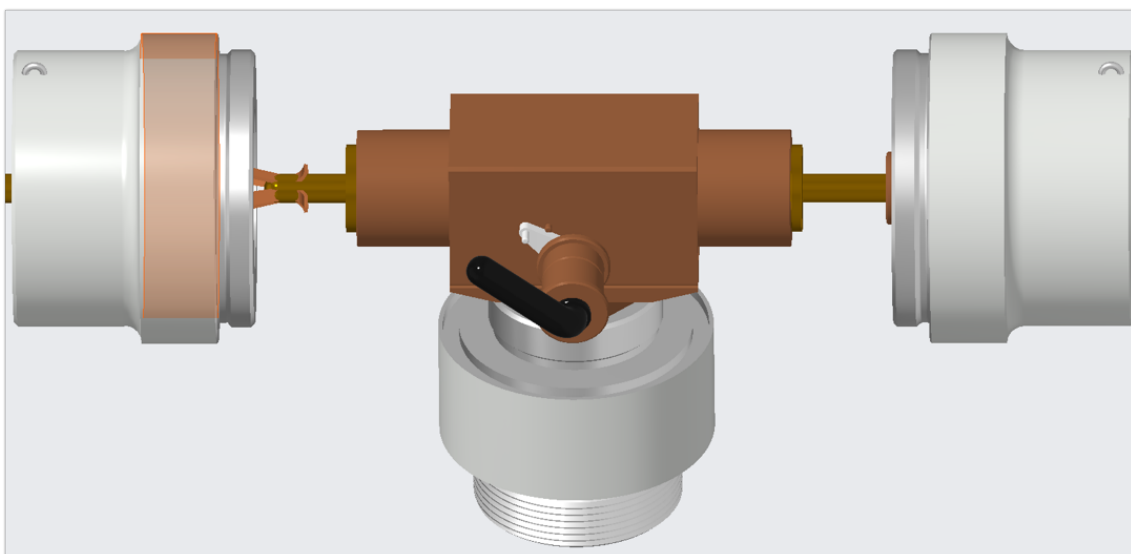
The final design is a mechanical switch with a rotating lever arm that transfers rotational displacement into linear displacement. The mechanical switch comprises three connection flanges: one to connect the test protector or the bushing tap, a second to connect the online monitoring system, and a third to connect the offline equipment. These three flanges are connected to a T-junction. Enclosed inside the T-junction is a slider and a cam responsible for the switching operation. The contact

pin from the test tap protector or bushing tap comes in contact with the contact spring inside the flange that is intended for the test tap protector or the bushing tap.



**Figure 5.34:** Vertical cross-section when the product is in online state

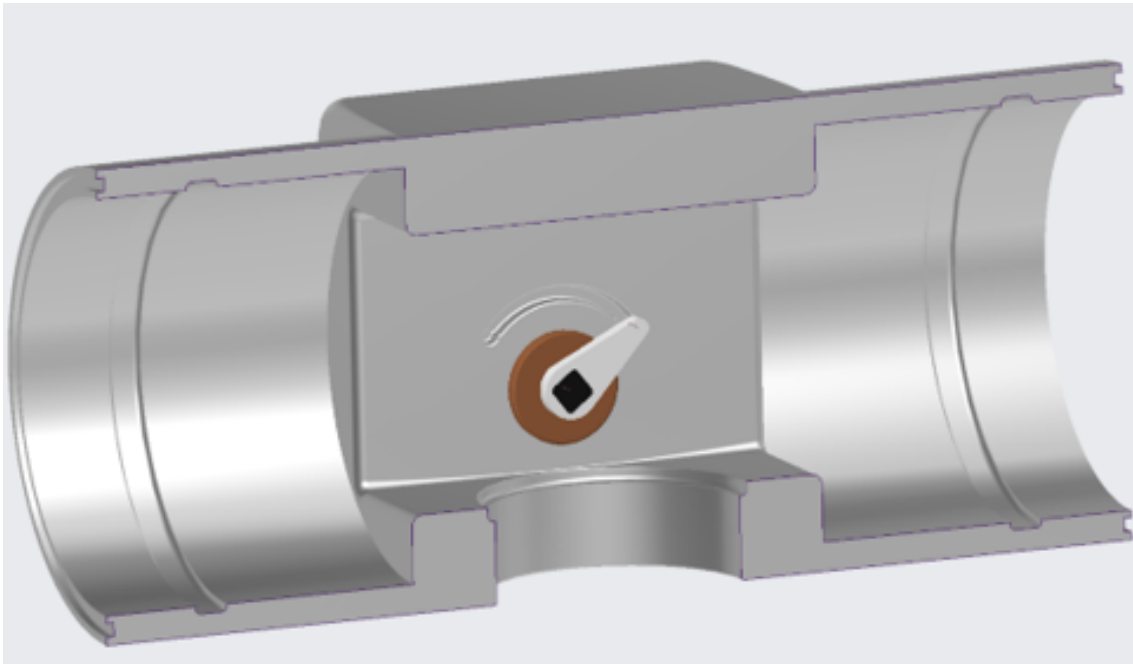
Eventually, a connection is made to the conductor, which is enclosed inside the slider, through a guide pin. The conductor position itself accurately in the guide pin with the support of a guide groove within the conductor. The slider itself resides on a glide platform that acts as a fixed frame of reference for linear motion, which is achieved through fixing the glide platform to the flange intended for the test protector. Both the slider and the glide platform are made up of insulating material. The conductor coming out from one end of the slider is connected to the contact spring of the flange, which is intended for an online monitoring system. While the conductor, coming out from the other end of the slider, is partly exposed to provide the provision for clamping the offline equipment as represented in Figure 5.34.



**Figure 5.35:** Switching operation

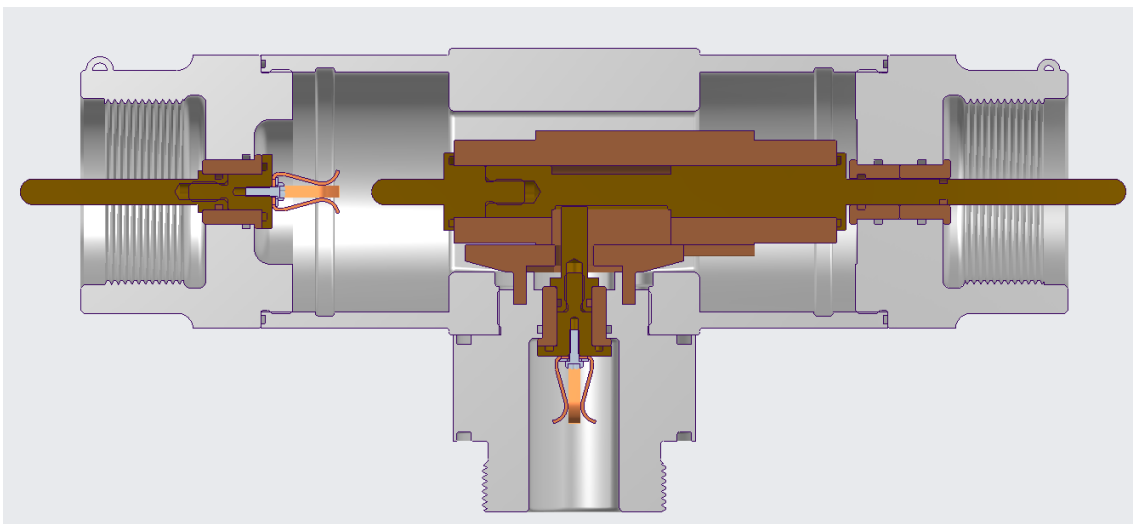
The linear motion of the slider is controlled by a cam which forms tangential contact

with the pin, protruding from the slider, as shown in Figure 5.35. The cam is designed in such a way that it allows linear displacement of 22 mm, considering 1 mm/kV.



**Figure 5.36:** Groove engraved in the T-junction to limit and lock the position

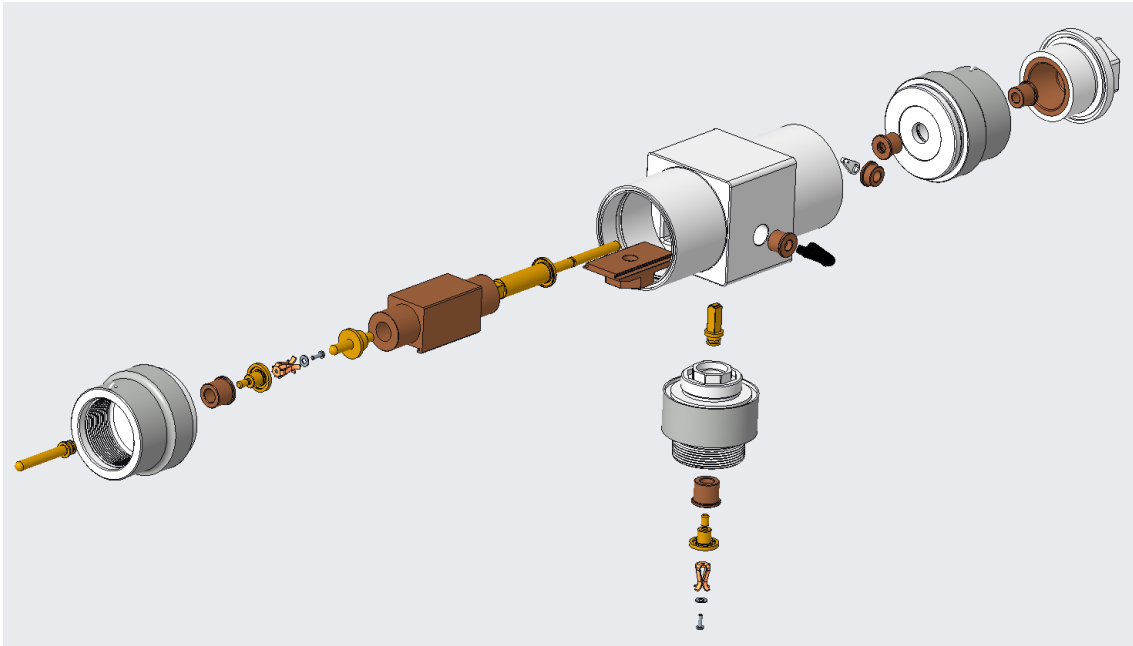
The cam movement is controlled via a lever connected to the cam and the groove engraved in the T-junction, as represented in Figure 5.36, which limits and locks the cam's angular position. Figure 5.37 shows the adapter switched to its offline state.



**Figure 5.37:** Vertical cross-section when the product is in offline state

The lever is the only part where the user interaction takes place to swap between the online monitoring system and the offline equipment. After the offline testing is completed, upon closing the redesigned tap cover that is partly filled with insulating

material, brings the lever to the initial position. All the parts described can be witnessed from the exploded view shown in Figure 5.38.



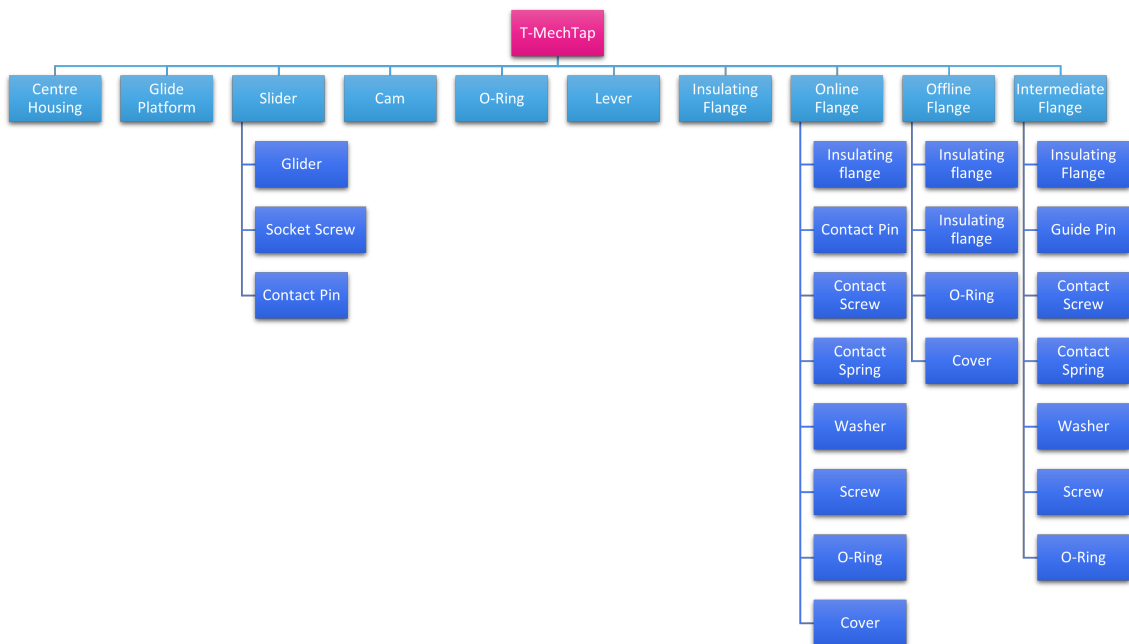
**Figure 5.38:** Exploded view of T-MechTap

# 6

## Commercial Assessment

This chapter presents an estimated financial overview of the developed adapter - T-MechTap. The commercial assessment for the developed design encompasses explaining the product structure, Bill of Materials (BOM), and the associated cost calculations. The cost calculations are carried out based on the present and the forecasted market demand.

### 6.1 Product Structure



**Figure 6.1:** Product Structure of the T-MechTap

In general, the product structure illustrates the complete list of components associated with the adapter. The product structure should be well understood as it plays a vital role in estimating the manufacturing cost, assembly cost, and the man hours involved to develop the product. The main components that are associated with the developed T-MechTap adapter are as follows

1. Centre Housing
2. Glide Platform

3. Slider
4. Cam
5. O-Ring
6. Lever
7. Insulating Flange
8. Online Flange
9. Offline Flange
10. Intermediate Flange

The detailed illustration of the product structure is shown in the Figure 6.1.

### 6.2 Bill of Materials (BOM)

The BOM is structured in a way that it lists all the sub-assemblies and parts associated with the T-MechTap as rows, whereas the columns are specified with the information required to compute the total cost, including the direct cost and indirect costs that are crucial in determining the total cost of the product. The sub-assemblies and their associated parts have been taken from the product structure, which is shown in the previous Section 6.1. In BOM, the column "Material" lists the type of material that has been referred from a similar HV product available at Hitachi Energy Sweden AB. The exceptional materials are polyetheretherketone (PEEK) for its excellent insulation and wear-resistant properties at high temperature, which is assigned for the glide platform, cam, and insulating flange, and the other material, polytetrafluoroethylene (PTFE)-glass filled, is chosen for the glide for its insulation properties, ultra-low wear rate, and low coefficient of friction, thereby forming an excellent pair with the glide platform to facilitate smooth sliding motion [66][68][67]. The material cost for each material that is assigned to each component and its parts was taken from GRANTA Edupack. The next column, "Type of Manufacturing," indicates what kind of manufacturing technique the part requires, and it is given as machining for most of the parts. A few parts, like the contact spring, washer, and screw, do not require machining, as they come with standardized sizes. Then, the weights for each component are derived from the developed CAD model in PTC Creo.

The manufacturing cost includes direct material & direct labor cost, and it is calculated based on the machining hours and the average labor cost [53] [54]. According to the Swedish labor wages information, the average salary is found to be 314 kr per hour, including the employer contributions of 31.42%, and the machining time for each part is estimated based on the part complexity involved [51] [52]. The material cost for individual components is calculated based on the weight and price of each material, respectively. The complete structure of BOM is attached in the Appendix J. Then the manufacturing overhead cost is computed to include the other indirect costs, which are unavoidable with the manufacturing such as indirect material and indirect labor cost [53] [54]. Hence, to incorporate the overhead cost, it is decided to obtain by considering 150% of manufacturing cost from the previous column, followed by, the total manufacturing cost is calculated by summing up the material cost, manufacturing cost, and manufacturing overhead cost [57]. In the next column,

the miscellaneous cost is obtained by accounting for the 2% of material scrap cost, 25% of cost that is required for programming the machine to perform the desired operation, and also considering a profit margin to be 10% [59] [60] [62] [63]. The miscellaneous cost comprises costs that are incurred due to maintenance, quality assurance, administrative burden, union dues, training, energy, taxes, and facility depreciation [53] [54]. The summation of total manufacturing cost and miscellaneous cost against each part that is listed in the BOM structure gives the total cost to manufacture each part associated with the adapter. Subsequently, the final cost of one product is calculated by summing up the total cost that is required to manufacture the product, along with the assembly cost associated with it [61]. Finally, the investment cost of the product comprises the cost involved in the entire stages of product development and the cost that takes part in the sales activities. The development cost is approximated to be 2.5 MSEK, and the approximation is done by multiplying the one-month salary of the engineers involved in the development process, for example, in this case, it is considered that three to four engineers are involved, while the remaining is taken for carrying out tests. Then the cost in sales and marketing related activities is anticipated to be 1 MSEK.

### 6.3 Market Competitiveness

This section discusses the product competitiveness and its position in the targeted market segment and the potential of its expansion in other market segments. One of the significant elements to consider in a market study is the Break-even Point (BEP). According to the BOM, the cost of one T-MechTap is about 5,560 SEK, which is about 580 USD. This is because only the cost involves in the major parts of the adapter are considered and the cost for the standardized products are excluded when formulating BOM. Based on the estimation from BOM, it can be observed that the cost required to produce one product is approximately 5600 SEK upon including the assembly and manufacturing cost of all product specific parts and standardized parts.

For an electrical-related equipment, the gross margin is over 50%, and since this is an HV voltage accessory and considering its novelty, it would be reasonable to sell it for a gross margin of 60% [58]. The selling price of 14000 SEK is obtained by using the expression that relates the selling price and the gross margin of 60%. To find the BEP for a product, it is significant to obtain the number of products that are required to be sold in the market. By dividing the profit by the investment cost, the number of products that need to be sold to attain BEP will be obtained. If the number of products sold is greater than the number of products that were obtained earlier, then the profit can be achieved.

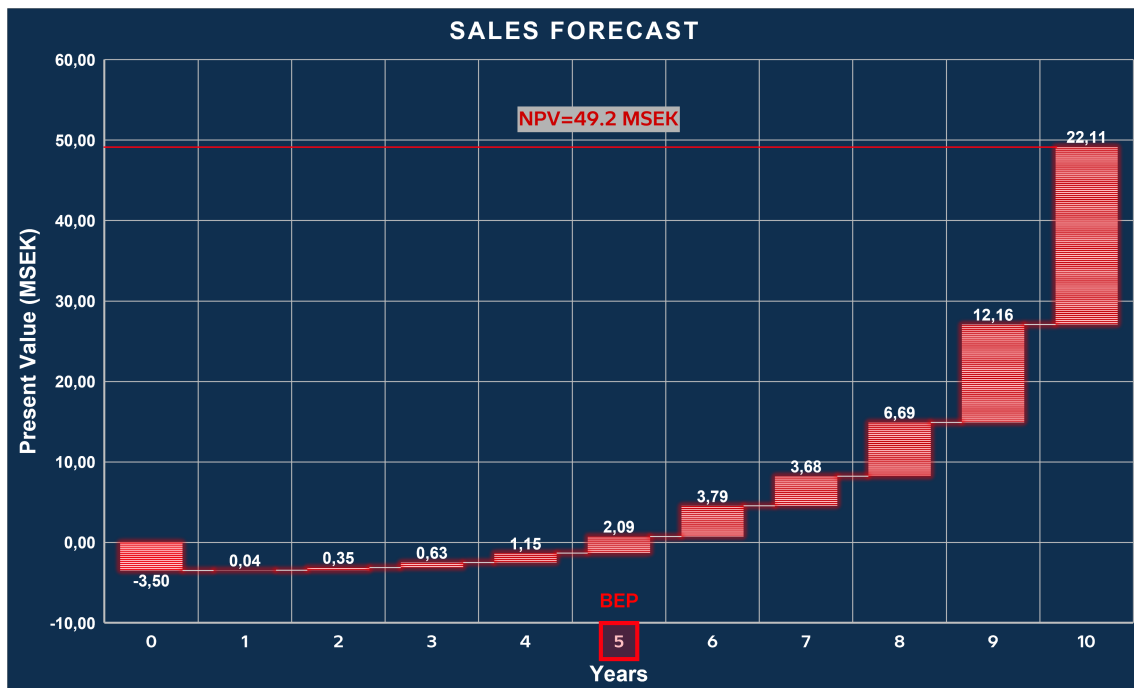
The adapter that is designed in this work is targeted at the Chinese market and companies that buy online monitoring systems. According to the 2023 sales data available, 200 units of online monitoring systems were sold in the Chinese market [55]. Also, the current sales of the online monitoring system are expected to be doubled in the coming years. Based on the estimated number of products to reach BEP,

the current and the forecast of online monitoring system sales, it is fair to presume that BEP could reach in 1 year of its sales in the market. Furthermore, the market for the adapter is expected to expand in the European market segment, where the current sales for online monitoring system sales are around 10,000 units per year [56]. Additionally, it is seen as a great benefit, since the adapter is the newest in the bushing market, and it has great potential to gain maximum advantage in the global market.

To determine the projects profitability over a long run, the Net present value (NPV) of the cash flow in 10 years is computed. The NPV is computed based on the estimation of all the future cash inflows which is sales revenue generated through the product and the cash outflow which is investments. The cash outflow, in this case, is the investment of 35 MSEK and the cash inflow is the profit earned per unit multiplied by the number of units sold per year. The formula for the NPV is given as follows:

$$NPV = -initial\ investment + \sum_{t=0}^N \frac{Cash\ flow}{(1+i)^t} \quad (6.1)$$

where 'i' is the the discount rate and 't' is the time period [64] [65]



**Figure 6.2:** Sales Forecast of T-MechTap

The discount rate signifies the interest rate reflecting the cost of capital invested in the project. In simple terms, it describes the future cash flow in present value [65]. As a common industrial practice in many capital-budgeting, as a rule of thumb, moderate risk level projects are computed with a 10% discount rate. Considering our project to be at a moderately risk level, it would be reasonable to assume the same. Based on the assumption and formula, an Excel that computes NPV could

be referred to from Appendix J. At year 0, an investment of 3.5 MSEK is made to bring the product into the market. By next year, upon introducing the product in the market, it is assumed that around 5 adapters have been sold during that year to the customers, who had initially demanded the product. In the following year, it is assumed that the number of units is subjected to increased to 50. Following that, it is increased twice in year 3. Then, in the upcoming years, it is assumed that the sales will be consecutively doubling compared to the previous year. By the 10th year, around 12,800 units are anticipated to be sold. and also as the number of products increases, the cost of producing one adapter reduces, as they are going to be produced in mass volumes. Hence, a discount of 20% is added to the cost for producing it. So, from year 7, the cost of producing one product would be around 4,480 SEK, thereby yielding a strong positive NPV of 49 MSEK, at the end of the 10th year, implying a strong return. When adapting the NPV approach, it brings a more realistic picture of the cash flow, and it can be inferred that the BEP could be achieved after the year 4. The overall sales trend is presented in the Figure 6.2.



# 7

## Conclusion

### 7.1 Discussion

In general, the requirement of dual tap arises to mitigate the implications posed, while using a single tap configuration for conducting online and offline measurements. Hence, the requirement from the customer was to develop the dual tap configuration conventionally. On the other side, the competitors offer a bushing variant with dual tap on the mounting flange in their portfolio. However, the actual purpose was identified, and it was evident that an existing dual tap solution in the market would not resolve the intended purpose of the customer. Through our simulation studies, it was also found that the conventional dual tap might compromise on safety aspect if it is utilized for the intended function from the customer's side. Having "SAFETY" as one of the licenses to operate at Hitachi Energy, and being the leading manufacturer of bushings globally, they never look the other way when it comes to safety. Hence, an alternative solution has been proposed that is simpler, foolproof, and serves the intended purpose by fulfilling the customer's requirement as well as complying with Hitachi Energy standards. To arrive at the desired solution, this thesis work illustrates a product development procedure that has been carried out. The product, in a way, is a dual tap, but not similar to the expected conventional solution from the customer. It is expected that this product might open a new market in the bushing monitoring systems segment. The idea behind the adapter is to sell it as a single unit by integrating with a recently developed product, which is a test tap protector.

Furthermore, the newly designed adapter will not affect the existing bushing assembly process, as it will be offered as an accessory for the bushing. In fact, the adapter is designed in such a way that it can be installed in most of the bushings offered by Hitachi Energy. In regards to the cost, if the existing bushing design has been modified to meet the customer requirement of dual tap configuration, then the overall cost of manufacturing the bushing would have seen a drastic increase due to complexities. This would introduce an entirely new bushings variant in the portfolio, which will be sold to a limited customers only. However, this is not the case with the designed adapter, as the existing bushing design remains unchanged. The detailed cost analysis is presented in the Chapter 6.

## 7.2 Future Work

The prototype showcased in this thesis work is a preliminary design, and further work is needed to redesign it for manufacturing and assembly. The next step in the development process would be performing Failure Mode and Effects Analysis (FMEA) to identify the potential causes of failure and the associated effects. The product will be tested to validate its intended functionality and pass through the various gates of the development process.

Furthermore, since Hitachi Energy is offering three different types of bushing taps, it would be important to modularize the current design so that it would be suitable for all three bushing tap configurations in the Hitachi Energy's bushing portfolio.

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# Appendices

# A Competitor Analysis

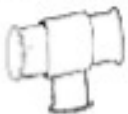










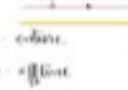
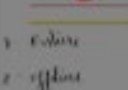
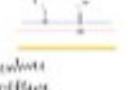
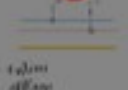

| Company           | Background   | Product Portfolio  | Technology   | Strengths  |
|-------------------|--|--|--|--|
| Trench Group      | <ul style="list-style-type: none"> <li>Founded 1937 on Emil Haefely's oil-paper patent</li> <li>Acquired by Triton in 2024</li> <li>2,400 staff in nine plants</li> </ul>                            | <ul style="list-style-type: none"> <li>Dry-type resin (RIP/RIS) for AC/DC</li> <li>"Eco-fluid" silicone-oil RIP</li> <li>Instrument transformers &amp; reactor coils</li> </ul>                  | <ul style="list-style-type: none"> <li>Explosion-proof resin cores</li> <li>Full RIP, RIS, RIG &amp; oil-filled designs</li> </ul>                     | <ul style="list-style-type: none"> <li>Drop-in replacements for legacy units</li> <li>REGENERA™ circular-economy initiative</li> <li>100+ years of R&amp;D heritage</li> </ul>         |
| GE Grid Solutions | <ul style="list-style-type: none"> <li>Part of GE Vernova (post-Alstom)</li> <li>Passoni &amp; Villa site: 100 years expertise</li> <li>Italian R&amp;D/manufacturing hub</li> </ul>                 | <ul style="list-style-type: none"> <li>RIP to 550 kV</li> <li>OIP to 1 200 kV</li> <li>SF<sub>6</sub> to 800 kV for GIS</li> </ul>   | <ul style="list-style-type: none"> <li>Hybrid OIP/SF<sub>6</sub> to ±800 kV (HVDC)</li> <li>Digital online monitoring</li> </ul>                       | <ul style="list-style-type: none"> <li>Deployed on major HVDC projects</li> <li>"Zero-maintenance, longer-life" design</li> </ul>  |
| Nanjing Electric  | <ul style="list-style-type: none"> <li>Established 1936; Thunder-Lighting leads China</li> <li>National R&amp;D labs under State Grid</li> <li>Zhinda (2001); "Peak Demand" US arm (2016)</li> </ul> | <ul style="list-style-type: none"> <li>OIP &amp; SF<sub>6</sub> bushings (12–550 kV)</li> <li>Dry-type RIP/RIS; GIS &amp; gen lead-outs</li> <li>Porcelain &amp; composite insulators</li> </ul> | <ul style="list-style-type: none"> <li>FRP-reinforced dry-type since 2001</li> <li>Advanced composite R&amp;D; 20+ patents</li> </ul>                  | <ul style="list-style-type: none"> <li>Deep State Grid collaboration</li> <li>Dedicated HV subsidiary; nationwide service</li> <li>Strong OEM partnerships</li> </ul>                  |
| Moser-Glaser      | <ul style="list-style-type: none"> <li>Swiss specialist since 1914 (Pflüger Group)</li> <li>Pioneered DURESCA® RIP in the 1950s</li> </ul>   | <ul style="list-style-type: none"> <li>DURESCA® RIP busbars</li> <li>Transformer &amp; wall bushings to 550 kV</li> </ul>  | <ul style="list-style-type: none"> <li>Pure epoxy-resin RIP technology</li> <li>All design &amp; production in Switzerland</li> </ul>                  | <ul style="list-style-type: none"> <li>Swiss precision engineering</li> <li>Rapid bespoke customization</li> <li>Fully independent from OEMs</li> </ul>                                |
| Yash Highvoltage  | <ul style="list-style-type: none"> <li>Founded 2002; IPO 2024; 35,000+ installations</li> </ul>  | <ul style="list-style-type: none"> <li>RIP/RIS ≤ 245 kV; oil-to-oil wall bushings</li> <li>High-current connectors (4–25 kA)</li> </ul>  | <ul style="list-style-type: none"> <li>In-house 1,500 kV impulse &amp; helium-leak labs</li> <li>Full IEC-compliant qualification</li> </ul>           | <ul style="list-style-type: none"> <li>"Make-in-India" cost leadership</li> <li>Fast turnkey retrofit solutions</li> </ul>   |
| Shemar Group      | <ul style="list-style-type: none"> <li>Founded 1996; composite-insulator specialist</li> </ul>   | <ul style="list-style-type: none"> <li>Hollow composite insulators; gas-filled bushings</li> <li>Explosion-proof transformer bushings</li> </ul>   | <ul style="list-style-type: none"> <li>Fiberglass-hollow + gas-seal designs</li> <li>Flashover prevention &amp; explosion containment</li> </ul>       | <ul style="list-style-type: none"> <li>Partnerships: ABB, GE, Siemens</li> <li>Lightweight, maintenance-free next-gen products</li> <li>Material innovation leadership</li> </ul>      |
| TBEA Co., Ltd.    | <ul style="list-style-type: none"> <li>Listed on Shanghai Exchange (600089.SH); national hi-tech</li> <li>21 industrial parks &amp; overseas bases</li> </ul>  | <ul style="list-style-type: none"> <li>Power transformers; switchgear; valves; cables; bushings; insulation</li> </ul>   | <ul style="list-style-type: none"> <li>Dedicated UHV transformer R&amp;D center</li> <li>Automated, 5G-enabled smart factory &amp; robotics</li> </ul> | <ul style="list-style-type: none"> <li>Turnkey grid projects in 30+ countries</li> <li>Vertical integration; extensive patents</li> </ul>  |
| China XD Group    | <ul style="list-style-type: none"> <li>State-owned since 1959; 60+ subs; 16,000+ employees</li> </ul>  | <ul style="list-style-type: none"> <li>Generators; transformers; GIS; breakers; bushings; CT/PT; arresters</li> </ul>  | <ul style="list-style-type: none"> <li>UHV AC/DC R&amp;D &amp; test labs; active in IEC &amp; CIGRE</li> </ul>   | <ul style="list-style-type: none"> <li>Central government backing</li> <li>Deployed on Three Gorges &amp; national UHV corridors</li> <li>Global footprint in 80+ countries</li> </ul> |

## B Mission Statement

| <b>MISSION STATEMENT</b>             |  |
|--------------------------------------|--|
| <b>Project Description</b>           | Designing a solution that reduces the challenges in offline testing where an online monitoring system is connected.  |
| <b>Benefit Proposition</b>           | <ul style="list-style-type: none"> <li>• Hassle free testing.</li> <li>• Reduction in offline equipment setup time.</li> <li>• Verification of online monitoring made simple.</li> <li>• Compatible with third-party monitoring/test systems.</li> </ul> |
| <b>Key business Goals</b>            | <ul style="list-style-type: none"> <li>• Meet the demand for dual taps.</li> <li>• Retain existing customers.</li> <li>• Capture new customers.</li> </ul>   |
| <b>Primary market</b>                | China  |
| <b>Secondary market</b>              | Other countries  |
| <b>Assumptions &amp; Constraints</b> | <ul style="list-style-type: none"> <li>• Third-party test/monitoring systems remain unchanged.</li> <li>• Can be implemented in existing bushing portfolio.</li> <li>• Compliance to HE's internal requirements.</li> </ul>                              |
| <b>Stakeholders</b>                  | <ul style="list-style-type: none"> <li>• Manufacturing and supply chain</li> <li>• Testing department</li> <li>• Marketing and Sales</li> <li>• Tester</li> <li>• New and existing customers</li> </ul>  |

## C Morphological Matrix

Enable offline testing, with online monitoring connected

| Sub-Functions      | Sub-Solutions   |  |  |   |  |
|--------------------|---|--|--|---|--|
| Provide access     | <b>Splitter</b><br>T-Junction / Splitter<br>   | <b>two taps</b><br>Two separate interfaces<br>  | <b>adapter</b><br>custom interface port<br>   |   |  |
| Isolate the system | <b>Mechanical Switch</b><br>mechanical switch<br>  | <b>Relay</b><br>relay<br>   | <b>IGBT</b><br>IGBT<br>   | NA  | <b>High Impedance Resistor</b><br>High Impedance Resistor<br> |
| Ensure protection  | <b>GND Cover</b><br>GND cover<br>   | <b>Spring loaded return</b><br>spring loaded switch<br>  | <b>Component Protector</b><br>surge protectors<br>   | N/A<br>   |  |
| Connection of tap  | <b>config-1</b><br>cables connected to voltage tap<br> <ol style="list-style-type: none"> <li>cables</li> <li>offline</li> </ol> | <b>config-2</b><br>cables connected to test tap<br> <ol style="list-style-type: none"> <li>cables</li> <li>offline</li> </ol> | <b>config-3</b><br>cables connected to test tap by offline connected to voltage tap<br> <ol style="list-style-type: none"> <li>cables</li> <li>offline</li> </ol> | <b>config-4</b><br>cables connected to voltage tap by offline connected to test tap<br> <ol style="list-style-type: none"> <li>cables</li> <li>offline</li> </ol> |  |
| Avoid interference | <b>Shielding</b>  | N/A<br>   |  |   |  |

# D Elimination Matrix

| Elimination Matrix   |   | Created: 18-03-2025<br>Modified: 21-03-2025   |  | page 1 |
|--|---|---|--|--------|
| Dual Taps On Transformer Bushings  |   | + Fulfills requirement<br>- Do not fulfill requirement<br>? Information is missing<br>! Revise target specification |  |        |
| Concept  | Elimination requirement*                                  | Comments  | Decision   |        |
| <b>Plug &amp; Play</b><br><b>2T-2F</b><br><b>2T-1F</b><br><b>T-Elec Tap</b><br><b>T-Mech Tap</b> | Compatibility with Existing Systems                       |   | Keep   |        |
|  | Faciliate offline and online measurement                  |   | Keep   |        |
|  | Applicable to Hitachi Energy internal requirements (Test) |   | Keep   |        |
|  | Ensure the protection of online monitoring system         |   | Remove   |        |
|  | Facilitate measurement of primary capacitance (C1)        |   | Keep   |        |
|  | Maintain non-discrepancy in measurements                  |   | Keep   |        |
|  | Ensure Bushing normal operation                           |   | Remove   |        |
|  | Manufacturing feasibility                                 |   | Keep   |        |
|  | Safe testing  |   | Keep   |        |
|  |   |   | Need to study the modification necessary in manufacturing process for placing the braids in the respective position<br>As from the simulation, it is not advisable to go with this solution, as it affects the measurement<br>We have to look out for the electric components. | Keep   |

## E Pugh Matrix

| Chalmers  | Pugh matrix (Relative decision matrix): |          |           |   |          |
|---|---|----------|-----------|---|----------|
| Hitachi Energy: Dual Taps on Transformer Bushings<br>IMSX30 |   |          |           | Created: 2025-03-21<br>Modified: 2025-03-21 |          |
| <b>Criteria</b>   | <b>Concept</b>                          |          |           |   |          |
|   | <b>Current</b>                          |          |           |   |          |
|   | <b>REFERENCE</b>                        |          |           |   |          |
| Duration for offline setup                                  | +                                       | +        | +         | +   | +        |
| User friendly interface                                     | 0                                       | -        | +         | +   | +        |
| Measurement accuracy  | 0                                       | -        | 0         | 0   | 0        |
| Wear rate   | 0                                       | 0        | -         | -   | -        |
| Consistent functionality                                    | 0                                       | 0        | -         | -   | -        |
| Comptability with existing system                           | 0                                       | 0        | 0         | 0   | 0        |
| Compliance with IEC/IEEE std                                | 0                                       | 0        | 0         | 0   | 0        |
| Ensure safe testing   | 0                                       | -        | -         | -   | -        |
| No manual Switching   | 0                                       | +        | +         | +   | +        |
| Facilitate measurement of capacitance C2/C3                 | +                                       | -        | -         | -   | -        |
| Cost  | -                                       | -        | -         | -   | -        |
| Hassle free interchanging of system                         | 0                                       | +        | +         | +   | +        |
| $\Sigma+$   | 2                                       | 3        | 4         | 4   | 4        |
| $\Sigma 0$  | 9                                       | 4        | 5         | 5   | 5        |
| $\Sigma -$  | 1                                       | 5        | 3         | 3   | 3        |
| Net value   | 0                                       | 1        | -2        | 1   | 1        |
| Ranking   | 3                                       | 1        | 3         | 1   | 1        |
| Continuation  |   | Yes      | No        | Yes   | Yes      |
| Decision  |   | Promoted | Eliminate | Promoted                                    | Promoted |

## F Kesselring weight Matrix

| Criteria                                     | A   |     | B   |     | C   |     | D   |     | E   |     | F   |     | G   |     | H   |     | I   |     | J   |     | SUM/tot | W (score*100) |
|--|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|---------|---------------|
|  | V   | V   | V   | V   | V   | V   | V   | V   | V   | V   | V   | V   | V   | V   | V   | V   | V   | V   | V   | V   |         |               |
| <b>Name</b>                                  |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |         |               |
| <b>A (Manufacturability)</b>                 | -   | 1   | 1   | 0,5 | 0,5 | 0,5 | 0   | 0   | 0,5 | 0   | 0   | 0,5 | 0   | 0   | 1   | 0   | 0   | 0   | 0   | 0   | 4,5     | 0,098         |
| <b>B (Maintanability)</b>                    | 0   | -   | 0,5 | 1   | 0   | 0,5 | 0   | 0   | 0   | 0   | 0,5 | 0   | 0   | 0   | 0   | 1   | 0   | 0   | 0   | 0   | 3       | 0,065         |
| <b>C (Design Complexity)</b>                 | 0   | 0,5 | -   | 0,5 | 0,5 | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 1,5     | 0,033         |
| <b>D (Production Complexity)</b>             | 0,5 | 0   | 0,5 | -   | 0,5 | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 1,5     | 0,033         |
| <b>E (Scalability)</b>                       | 0,5 | 1   | 0,5 | 0,5 | -   | 0,5 | 0,5 | 0   | 0,5 | 0,5 | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 4       | 0,087         |
| <b>F (Degree of Reliability)</b>             | 0,5 | 0,5 | 1   | 1   | 0,5 | -   | 1   | 0,5 | 0,5 | -   | 1   | 0,5 | 0,5 | 0,5 | 0,5 | 0,5 | 0   | 0   | 0   | 0   | 6       | 0,130         |
| <b>G (Cost-material &amp; manufacturing)</b> | 1   | 1   | 1   | 1   | 0,5 | 0   | -   | 0,5 | 0   | 0   | -   | 0,5 | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 5       | 0,109         |
| <b>H (endurance to harsh environments)</b>   | 0   | 1   | 1   | 1   | 0,5 | 0,5 | 0,5 | 0,5 | 0,5 | 0,5 | 0,5 | 0,5 | 0,5 | 0,5 | -   | 0,5 | 0   | 0   | 0   | 5   | 0,109   | 11            |
| <b>I (Safe Testing)</b>                      | 1   | 1   | 1   | 1   | 1   | 1   | 0,5 | 1   | 0,5 | 1   | 0,5 | 1   | 0,5 | 1   | 0,5 | -   | 0,5 | -   | 0,5 | 0,5 | 7,5     | 0,163         |
| <b>J (Degree of Fulfilment)</b>              | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 0,5 | 1   | 0,5 | 1   | 1   | 0,5 | 1   | 0,5 | -   | 0,5 | 8       | 0,174         |

## G Kesselring value Matrix

| A - Manufacturability              |       | B - Maintainability |       | C - Design Complexity    |       | D - Production Complexity |       | E - Scalability   |       | F - Degree of reliability |       | G - cost       |       |
|------------------------------------|-------|---------------------|-------|--------------------------|-------|---------------------------|-------|-------------------|-------|---------------------------|-------|----------------|-------|
| Feasibility level                  | Value | Maintenance period  | Value | Complexity level         | Value | No of stages(count)       | Value | Scalability level | Value | Functional years          | Value | Estimated cost | Value |
| High (simple design)               | 3     | Occasional          | 3     | Simple                   | 3     | <5                        | 3     | High              | 3     | 3-40 years                | 3     | low            | 3     |
| Medium (Moderate)                  | 2     | Periodical          | 2     | moderate                 | 2     | 5-10                      | 2     | Medium            | 2     | 20 years                  | 2     | Moderate       | 2     |
| Low (Complex)                      | 1     | Frequent            | 1     | Complex                  | 1     | >10                       | 1     | Low               | 1     | <20 years                 | 1     | High           | 1     |
| H - Endurance to harsh environment |       | I - Safe testing    |       | J - Degree of fulfilment |       |                           |       |                   |       |                           |       |                |       |
| Operating temperature              | Value | Safety level        | Value | Satisfactory level       | Value |                           |       |                   |       |                           |       |                |       |
| -60 to +60 deg                     | 3     | Risk free           | 3     | High                     | 3     |                           |       |                   |       |                           |       |                |       |
| -40 deg to +40 deg                 | 2     | Basic               | 2     | Moderate                 | 2     |                           |       |                   |       |                           |       |                |       |
| -20 deg to +30 deg                 | 1     | Unsafe              | 1     | Low                      | 1     |                           |       |                   |       |                           |       |                |       |

# H Kesselring Matrix

| Criteria:                           | Alternatives |           |        |      |             |      |       |           |       |   |           |   |    |
|-------------------------------------|--------------|-----------|--------|------|-------------|------|-------|-----------|-------|---|-----------|---|----|
|                                     | w            | Ideal     |        |      | Plug & Play |      |       | T-MechTap |       |   | T-ElecTap |   |    |
|                                     |              | v         | t      |      | v           | t    |       | v         | t     |   | v         | t |    |
| Name:                               |              |           |        |      |             |      |       |           |       |   |           |   |    |
| A (Manufacturability)               | 10           | 3         | 30,00  | 2    | 20          | 2    | 20    | 2         | 20    | 2 | 20        | 2 | 20 |
| B (Maintanability)                  | 7            | 3         | 21,00  | 2    | 14          | 2    | 14    | 2         | 14    | 1 | 7         | 1 | 7  |
| C (Design Complexity)               | 3            | 3         | 9,00   | 2    | 6           | 1    | 3     | 1         | 3     | 1 | 3         | 1 | 3  |
| D (Production Complexity)           | 3            | 3         | 9,00   | 3    | 9           | 2    | 6     | 1         | 3     | 1 | 3         | 1 | 3  |
| E (Scalability)                     | 9            | 3         | 27,00  | 3    | 27          | 3    | 27    | 3         | 27    | 3 | 27        | 3 | 27 |
| F (Degree of Reliability)           | 13           | 3         | 39,00  | 2    | 26          | 2    | 26    | 2         | 26    | 1 | 13        | 1 | 13 |
| G (Cost-material & manufacturing)   | 11           | 3         | 33,00  | 2    | 22          | 2    | 22    | 2         | 22    | 1 | 11        | 1 | 11 |
| H (endurance to harsh environments) | 11           | 3         | 33,00  | 2    | 22          | 2    | 22    | 2         | 22    | 1 | 11        | 1 | 11 |
| I (Safe Testing)                    | 16           | 3         | 48,00  | 3    | 48          | 3    | 48    | 3         | 48    | 2 | 32        | 2 | 32 |
| J (Degree of Fulfilment)            | 17           | 3         | 48,00  | 1    | 17          | 2    | 34    | 2         | 34    | 2 | 34        | 2 | 34 |
| T (Total weighed value)             |              | 30        | 297,00 | 22   | 211         | 21   | 222   | 15        | 161   |   |           |   |    |
| T / Tideal                          |              | 1,00      | 1,00   | 0,73 | 0,71        | 0,70 | 0,75  | 0,50      | 0,54  |   |           |   |    |
| Mean                                |              | 3,00      | 29,70  | 2,20 | 21,10       | 2,10 | 22,20 | 1,50      | 16,10 |   |           |   |    |
| Std                                 |              | 0,00      | 10,56  | 0,48 | 7,90        | 0,36 | 9,24  | 0,60      | 9,72  |   |           |   |    |
| Median                              |              | 3         | 32     | 2    | 21          | 2    | 22    | 1         | 12    |   |           |   |    |
| Number of weak points               |              | 0         |        | 1    |             | 1    |       | 6         |       |   |           |   |    |
| Ranking                             |              |           | 1      | 3    |             | 2    |       | 4         |       |   |           |   |    |
| Desicion                            |              | T-MechTap |        |      |             |      |       |           |       |   |           |   |    |

# I Requirement Specification

| Project: Dual Taps on Transformer Bushings                |             |                   | Requirement specification Bushing Adapter |              |                           |                             |
|---|-------------|-------------------|---|--------------|---------------------------|-----------------------------|
| Date created: 4/7 - 2025                                  |             |                   |   |              |                           |                             |
| Date modified: 10/7-2025                                  |             |                   |   |              |                           |                             |
| Criteria  | Targetvalue | Unit              | D/W                                       | Ranking(1-5) | Verification              | Comments                    |
| <b>1. Electrical Requirements</b>                         |             |                   |   |              |                           |                             |
| 1.1 Maximum System Voltage                                | upto 1100   | kV                | D   | 4            | Simulation/Test           |                             |
| 1.2 Operating Frequency                                   | 50 or 60    | Hz                | D   | 5            | Simulation/Test           |                             |
| 1.3 AC withstand voltage (60sec @60Hz) and (72 sec @50Hz) | 20          | kV                | D   | 5            | Simulation/Test           | According to IEC 60137      |
| <b>2. Mechanical Requirements</b>                         |             |                   |   |              |                           |                             |
| 2.1 Interface match with IEEE bushing taps                | Yes         | Binary            | D   | 5            | Fitment check             | According to IEEE C57.19.00 |
| 2.2 Operating force                                       | <40         | N                 | W   | 4            | Measure                   |                             |
| 2.3 Switching life  | <500        | Cycles            | W   | 4            | Analysis/test             |                             |
| 2.4 Locking at position                                   | Yes         | Binary            | D   | 5            | Physical test             |                             |
| 2.5 Consistent functionality                              | Yes         | Binary            | D   | 5            | Function test             |                             |
| <b>3. Environmental and Durability</b>                    |             |                   |   |              |                           |                             |
| 3.1 Operating temperature                                 | -50 - +100  | °C                | D   | 5            | Simulate/testing          |                             |
| 3.2 Ingress protection                                    | IP65/IP67   | IP classification | D   | 5            | IP test                   | According to IEC 60529      |
| 3.4 Corrosion resistance                                  | CX-high     | -                 | D   | 5            | weathering/age test       | According to ISO 12944-9    |
| 3.5 Pressure range  | 1.1         | MPa               | D   | 5            | pressure test             | According to IEC 61462      |
| 3.6 Bending resistance                                    | 1000        | N                 | D   | 4            | Simulation/bending test   | According to IEC 60137      |
| 3.7 Vibration withstand                                   | class 4M4   | -                 | D   | 3            | Simulation / Seismic test | According to IEC 60721-3-4  |
| <b>4. Safety and Protection</b>                           |             |                   |   |              |                           |                             |
| 4.1 Enclosed live parts with grounded cover               | Yes         | Binary            | D   | 5            | Check                     |                             |
| 4.2 Mechanical lock to prevent switching under service    | Yes         | Binary            | D   | 5            | Functional test           |                             |
| 4.3 Position labels "ONLINE"/"OFFLINE"                    | Yes         | Binary            | D   | 5            | Visual Inspection         |                             |
| 4.4 Operating instruction label                           | Yes         | Binary            | D   | 5            | Visual Inspection         |                             |
| 4.5 Warning label in Cover                                | Yes         | Binary            | D   | 5            | Visual Inspection         |                             |
| 4.6 CE Marking  | No          | Binary            | D   | 5            | Visual Inspection         |                             |
| <b>5. Material properties</b>                             |             |                   |   |              |                           |                             |
| 5.1 Insulating material to isolate the conducting parts   | tbd         | tbd               | D   | 5            | Granta edupack            |                             |
| 5.2 Internal components withstands high temperatures      | Yes         | Binary            | D   | 5            | Validate                  |                             |
| <b>7. Design</b>  |             |                   |   |              |                           |                             |
| 7.1 Feasible for manufacturing                            | Yes         | Binary            | D   | 5            | Consultation              |                             |
| 7.2 Steps to assemble                                     | ≤10         | Steps             | W   | 3            | Consultation              |                             |
| 7.3 Weight total  | ≤5          | Kg                | W   | 3            | Measure                   |                             |
| 7.4 Optional to use                                       | Yes         | Binary            | W   | 3            | Validate                  |                             |
| 7.6 Bushing performance unaffected                        | Yes         | Binary            | D   | 5            | Validate                  | According to IEC 60137      |
| 7.7 PD Free   | Yes         | Binary            | D   | 5            | Validate                  | According to IEC 60270      |
| <b>7. Optional Features</b>                               |             |                   |   |              |                           |                             |
| 7.1 Replaceable internal components                       | Yes         | Binary            | D   | 3            | Question                  |                             |
| 7.2 Modular compatibility for different bushings          | Yes         | Binary            | W   | 3            | Validate                  |                             |
| <b>8. Miscellaneous</b>                                   |             |                   |   |              |                           |                             |
| 8.1 Applicable to HE's internal requirements              | Yes         | Binary            | D   | 5            | Consultation              |                             |
| 8.2 Applicable to IEEE regulations                        | Yes         | Binary            | D   | 5            | Consultation              | According to IEEE C57.19.00 |
| 8.3 Applicable to IEC regulation                          | Yes         | Binary            | W   | 5            | Consultation              | According to IEC 60137      |
| 8.4 Cost  | Secret      | SEK               | D   | 2            | Cost computation          |                             |

# J Bill of Materials (BOM)

| Product - T-MechTap |                  |                   |                       |              |                     |                       |                          |                              |                                |                               |                  |
|---------------------|------------------|-------------------|-----------------------|--------------|---------------------|-----------------------|--------------------------|------------------------------|--------------------------------|-------------------------------|------------------|
| Part                | Part Type        | Material          | Type of manufacturing | Weight (kg)  | Material Cost (SEK) | Time to Machine (min) | Manufacturing Cost (SEK) | Manufacturing Overhead (SEK) | Total Manufacturing Cost (SEK) | Miscellaneous Cost (SEK)      | Total Cost (SEK) |
| Centre housing      | product specific | Aluminum          | Machining             | 1.540        | 53.900              | 60.000                | 314.000                  | 471.000                      | 838.900                        | 296.310                       | 1135.210         |
| Glide Platform      | product specific | PEEK              | Machining             | 0.054        | 40.500              | 20.000                | 104.667                  | 157.000                      | 302.167                        | 409.950                       | 702.117          |
| Slider              | product specific | PTFE-glass filled | Machining             | 0.278        | 38.920              | 30.000                | 157.000                  | 235.500                      | 431.420                        | 584.363                       | 1015.783         |
| Socket Screw        | product specific | Brass             | Machining             | 0.038        | 2.888               | 10.000                | 52.333                   | 78.500                       | 133.721                        | 46.947                        | 180.668          |
| Contact Pin         | product specific | Brass             | Machining             | 0.190        | 14.440              | 18.000                | 94.200                   | 141.300                      | 249.940                        | 88.201                        | 338.141          |
| Cam                 | product specific | PEEK              | Machining             | 0.001        | 0.750               | 10.000                | 52.333                   | 78.500                       | 131.583                        | 46.092                        | 177.675          |
| Lever               | product specific | GRP               | Molding               | 3.285        | 0.000               | 0.000                 | 0.000                    | 0.000                        | 0.000                          | 1.314                         | 4.599            |
| Insulating Flange   | product specific | PEEK              | Machining             | 0.007        | 5.250               | 5.000                 | 26.167                   | 39.250                       | 70.667                         | 24.995                        | 95.663           |
| Online flange       | product specific | Aluminum          | Machining             | 0.078        | 20.160              | 20.000                | 104.667                  | 157.000                      | 281.827                        | 381.744                       | 663.571          |
| Insulating Flange   | product specific | PEEK              | Machining             | 0.038        | 2.888               | 10.000                | 52.333                   | 78.500                       | 133.721                        | 46.947                        | 180.668          |
| Online side         | product specific | Brass             | Machining             | 0.038        | 2.888               | 10.000                | 52.333                   | 78.500                       | 133.721                        | 46.947                        | 180.668          |
| Socket Screw        | product specific | Brass             | Machining             | 0.190        | 14.440              | 18.000                | 94.200                   | 141.300                      | 249.940                        | 88.201                        | 338.141          |
| Contact Spring      | Standard         | Copper            | Machining             | 0.019        | 1.444               | 10.000                | 52.333                   | 78.500                       | 132.277                        | 46.266                        | 178.543          |
| Washer              | Standard         | Steel             | -                     | -            | -                   | -                     | -                        | -                            | -                              | -                             | -                |
| Screw               | Standard         | Steel             | -                     | -            | -                   | -                     | -                        | -                            | -                              | -                             | -                |
| Online cover        | Standard         | Aluminum          | Machining             | 0.600        | 21.000              | 5.000                 | 26.167                   | 39.250                       | 86.417                         | 31.296                        | 117.713          |
| Offline Flange      | product specific | Aluminum          | Machining             | 0.623        | 21.805              | 18.000                | 94.200                   | 141.300                      | 257.305                        | 91.147                        | 348.452          |
| Insulating Flange   | product specific | PEEK              | Machining             | 0.008        | 6.000               | 5.000                 | 26.167                   | 39.250                       | 71.417                         | 25.296                        | 96.713           |
| Insulating Flange   | product specific | PEEK              | Machining             | 0.008        | 6.000               | 5.000                 | 26.167                   | 39.250                       | 71.417                         | 25.296                        | 96.713           |
| Offline cover       | product specific | Aluminum + Epoxy  | Machining             | 0.830        | 29.050              | 8.000                 | 41.867                   | 62.800                       | 133.717                        | 48.253                        | 181.970          |
| Intermediate Flange | product specific | Aluminum          | Machining             | 0.524        | 18.340              | 15.000                | 76.500                   | 117.750                      | 214.590                        | 290.614                       | 505.204          |
| Insulating Flange   | product specific | PEEK              | Machining             | 0.011        | 8.250               | 5.000                 | 26.167                   | 39.250                       | 76.024                         | 26.196                        | 98.883           |
| Guide Pin           | product specific | Brass             | Machining             | 0.018        | 1.388               | 15.000                | 76.500                   | 117.750                      | 197.618                        | 69.235                        | 266.853          |
| Socket screw        | product specific | Brass             | Machining             | 0.019        | 1.444               | 10.000                | 52.333                   | 78.500                       | 132.277                        | 46.389                        | 178.647          |
| Contact spring      | Standard         | Copper            | -                     | -            | -                   | -                     | -                        | -                            | -                              | -                             | -                |
| Washer              | Standard         | Steel             | -                     | -            | -                   | -                     | -                        | -                            | -                              | -                             | -                |
| Screw               | Standard         | Steel             | -                     | -            | -                   | -                     | -                        | -                            | -                              | -                             | -                |
| <b>Total</b>        |                  |                   |                       | <b>5.390</b> | <b>305.020</b>      |                       | <b>1495.733</b>          | <b>2245.100</b>              | <b>4046.853</b>                | <b>1431.650</b>               | <b>5478.503</b>  |
|                     |                  |                   |                       |              |                     |                       |                          | <b>Assembly</b>              | <b>15.000</b>                  | <b>Miscellaneous cost</b>     | <b>49.500</b>    |
|                     |                  |                   |                       |              |                     |                       |                          | <b>15.000</b>                | <b>33.000</b>                  | <b>Cost of one T-Mech Tap</b> | <b>5581.003</b>  |

| Year                | 0        | 1          | 2          | 3           | 4           | 5          | 6           | 7           | 8           | 9           | 10       |
|---------------------|----------|------------|------------|-------------|-------------|------------|-------------|-------------|-------------|-------------|----------|
| Profit/loss         | 8400     | 8400       | 8400       | 8400        | 8400        | 8400       | 8400        | 4480        | 4480        | 4480        | 4480     |
| No. of units sold   | -3500000 | 420000     | 420000     | 420000      | 420000      | 420000     | 3360000     | 7168000     | 14336000    | 28672000    | 57344000 |
| Discount rate       | -3500000 | 347107.438 | 631104.433 | 1147462.605 | 2086295.645 | 3793264.81 | 6687649.803 | 12159726.91 | 22108594.39 | 49177905.25 |          |
| Present value (SEK) |          |            |            |             |             |            |             |             |             |             |          |
| <b>NPV</b>          |          |            |            |             |             |            |             |             |             |             |          |

| Category                   | Value (SEK) |
|----------------------------|-------------|
| Development Cost           | 2500000     |
| Marketing and support cost | 1000000     |

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