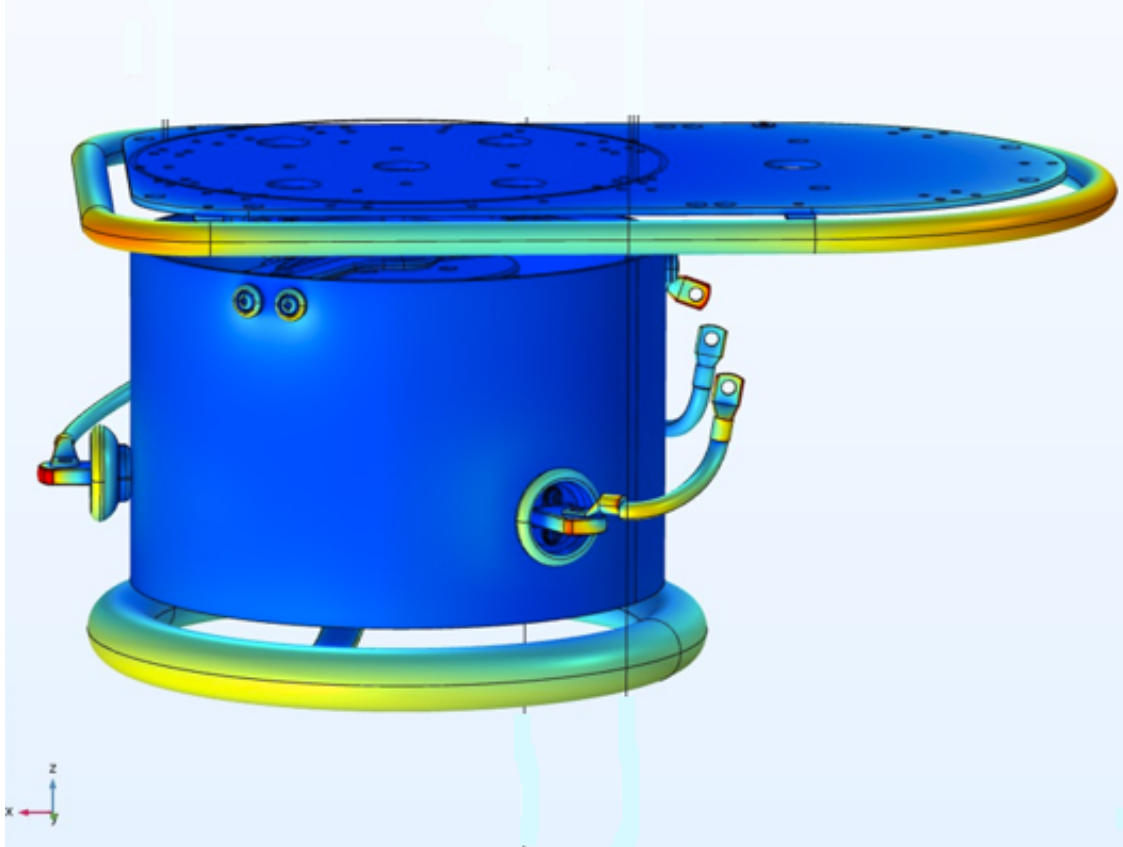




**CHALMERS**  
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# Dielectric Evaluation of Tap-changer

Master's thesis in Electric Power Engineering

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DEPARTMENT OF ELECTRICAL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2023

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MASTER'S THESIS 2023

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Gothenburg, Sweden 2023

Dielectric Evaluation of Tap-changer  
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Cover: Tie-in resistor simulated in COMSOL showing electric field distributions on the surface for BIL 750 [kV].

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Dielectric Evaluation of Tap-changer  
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## Abstract

Tap-changers are electro-mechanical devices typically inbuilt into power transformers used for voltage regulations in power systems. They operate under extreme electrical stresses and must be reliable to ensure un-interrupted power flow and voltage stability in the power system. Thus, according to the recent statistics, around 30% of failures of transformers in Europe are caused by failures in tap-changers.

The functionality and lifetime of a tap changer is directly affected by the ability of its insulating materials to withstand high voltages between the elements providing necessary clearances. The latter are defined by the geometry of the internal structures and the intensity of the electric field related directly to the magnitudes of voltage differentials. The traditional methods of tap-changer dielectric analysis have used a combination of rules of thumb that usually leads to oversizing of the insulating system. A more accurate approach to the high-voltage design is to use simulation tools to compute the electric field stresses on and in the components of tap-changers.

The aim of the present work is to perform the dielectric analysis of parts of tap-changers designed at the Tap-changer department of Hitachi Energy in Ludvika. Two types of tap-changers have been considered for the study. The mechanical models of the tap-changers have been provided by the department and used for setting up dielectric simulations in COMSOL Multiphysics software.

Since a tap-changer has a very complex geometry consisting of hundreds of parts in different sizes and shapes, which make the simulations challenging and time consuming, possibilities for simplifications of geometrical shapes of certain elements (different types of screws, various kinds of contacts and jumpers, etc.) have been evaluated. The results of electric field simulations of most critical parts are presented in this report. Furthermore, the calculated results have been evaluated against internal dielectric design rules of Hitachi Energy and necessary modifications have been introduced to fulfill the requirements. In additions, the sources of errors in the simulations have been considered focusing on possible errors in the original mechanical models, errors introduced while importing of the models into COMSOL Multiphysics as well as errors due to improper meshing of elements' geometries. It has been found that among the mentioned errors, meshing errors and the errors in the mechanical models have had a significant impact on the simulation results. The conducted simulations have resulted in an improved designs of the tap-changer that fulfills the dielectric requirements. A prototype of the device has been manufactured and sent to a high-voltage lab for dielectric testing.



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# 1

## Introduction

### 1.1 Background

Modern-day society is highly dependent on electrical power and the demand for a reliable supply of electricity is increasing every day and this trend will continue in the near future as well. Power systems in countries are made of many power-generation points, power distribution parts as well as transmission systems between power generations and consumptions [3]. Power transformers are primarily used for changing the voltage levels in transmission and distribution systems. The output voltages of transformers are determined based on input voltages by the ration of secondary to primary turns [4].

There will be voltage sag in any power source when the load current increases. Moreover, power systems are featured with high impedance of long power lines which together with load variations may lead to voltage variations in the power network. This can cause malfunctioning of equipment connected to the power grid. Furthermore, the increase of power demand in the existing network can also cause higher voltage sag and power quality issues as well as more complicated voltage regulations [5]. Hence, the power network voltage fluctuates for different reasons that can lead to additional losses and stability issues in power network [4].

In order to guarantee the power quality and also up to some extent stability in the power network a technical solution is needed to compensate for this voltage sag. One solution is using transformers, equipped with tap changers that can adjust the voltage ratio by changing the turns ratio of the transformers to regulate the secondary voltage to required levels [4] [5]. Power transformers are the most critical parts of electrical power systems and the reliability of transformers, and all its parts are crucial in order to ensure the availability of power systems. It is not only because transformers are fundamental equipment for operationality of power systems but also, they are the large capital investment in electrical power system. Furthermore, it is also time consuming and highly costly to repair and replace a power transformer. Electromechanical tap changers are the major cause of transformers' failure [1]. Almost 30% of all failures in substation transformers in Europe are caused by failure in electromechanical tap changers. About 22% of failures lead to fire or explosion are attributed by tap changers. Although over the years the failures caused by tap changers have decreased, it is still an obvious indication that tap changers play an important role in power transformer reliability and power system availability [4]. It is essential to analyze the insulating characteristic in the design of electrical and electronic circuits in high voltage applications in order to prevent the deterioration

of the dielectric properties of insulating materials [2]. The dielectric materials in tap changer are under constant stress of thousands of volts. The lifetime of tap changer is also affected by withstand strength of these insulating materials in high voltage. It should be considered that the insulation issue of dielectric materials can happen gradually and over time and it might not be an immediate problem for the device [6]. Therefore, it is essential to evaluate and analysis the dielectric feature of insulating materials to avoid potential failure in the power system.

There are different designs and variations of tap changers, the first variation is between off-load tap changer or de-energized tap changer (DETC) and on-load tap changer (OLTC or LTC) [4]. The focus in this study is on dielectric analysis of on-load tap changer.

## 1.2 Aim of the thesis

The aim of the master thesis is to evaluate different parts of the tap-changer from the dielectric perspective and to suggest improvements in the existing solutions to increase quality and competitiveness as well as ensure a more robust design and simplified assembly process.

## 1.3 Objectives

- Investigation of the new design, the tie-in switch for tap selector F to be used with tap selector III. It needs to be evaluated with three different BILs (Basic Insulation Level) of 380kV, 750kV and 1050kV to transformer tank and bottom. The below will be studied:
  1. How is the dielectric performance of new design tie-in resistor unit?
  2. Can the new design pass the requirements regarding electric field? And suggestions for improvement of the design from dielectric perspective.
- Investigation of jumpers used for connecting the tap-changer to the transformer for tap selector C. The present tap selector was made to carry a maximum current of 400A. As the design of selector C has been updated a new jumper for tap selector C is needed to comply with it. The selector C design has been updated to carry a maximum current of 600A and following that the jumper needs to be updated. The jumper should work even if there is only one cable come from regulating winding. It means the jumper needs to be able to carry a maximum current of 1200A. The below will be studied:
  1. Dielectrical evaluation of the new geometry with Comsol simulations in particular between jumpers and upper conductors and other possible risk areas. The evaluations need to be performed with caps and without caps. If the caps have to be used and do not fit the jumpers, it is allowed to change the jumpers.

2. Making a selection table for the type of jumpers and the number of needed jumpers for each type.

## **1.4 Limitations**

Mechanical design of parts of the tap-changer is out of the scope of the thesis.



# 2

## Theoretical background and implementation of tap changers

### 2.1 Tap-changers: operation principles and main components

The output voltage of transformer is changing by the input voltage or by the number of turns in the windings. Tap changer switches are an external means to adjust voltage and are used to change the turn ratio in between windings in a transformer. The traditional tap changers regulate the bus voltage that is closest to power transformer and is not able to compensate for voltage drop or deviation out in the distribution network. Tap changers can usually regulate up to  $-/+15\%$  of line voltage depending on their switching types [7]. There are different types of tap changers, de-energized tap-changer and on-load tap-changer [8].

De-energized tap-changer (DETC) is able only to change tap connections and do voltage regulations while the transformer windings are isolated as switches are not designed to interrupt high voltage electrical loads. The transformer needs to be first deenergized to adjust the tap position and after that the transformer is put into operation again. DETC application is mostly where the tap position needs to be changed rarely. DETC is usually mounted inside the transformer tank [8] [4].

On-load tap-changers (OLTC) can regulate voltage while the transformer is energized and is under load without interruption of the load. OLTCs are designed to change the tap position several times a day in order to adjust the voltage according to the load variations [9]. The focus in this study has been on OLTC which designed and manufactured by Hitachi Energy AB.

#### 2.1.1 On-Load Tap-Changer (OLTC)

Depending on how the contacts are selected and switched, there are two types of OLTC to be considered. One is the selector switch type, and another is the diverter switch type. In the selector switch type, tap selection and load switching occurs at the same time which can be used for more compact and cost-efficient products but in the applications with lower voltage, lower current and lower Basic Insulation Level (BIL). It is normally used for transformers up to 100 MVA [4][7].

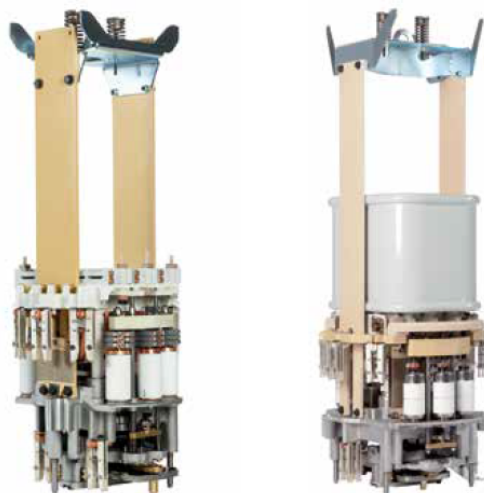
In the diverter switch type, there are two separate sections, the diverter switch section, and the tap selector section. The function of diverter switch section is to break the current in one tap and lead it to another tap. The function of tap selector

is only to choose which tap is the next tap to be connected without switching the current on.

### 2.1.2 Diverter Switch

Tap-changers used in high-power transformers have high current as well as high recovery voltage. Therefore, there will be high formation of ionic debris in the contact gap when a high current is interrupted by the contacts. With considering of higher recovery voltage, there is a need to increase considerably the gap between the fixed contacts in the case of having high power transformers. The fixed contact gap is increased in order to increase the effective arcing gap. Hence, as arcing takes place at all the fixed contacts, all gaps between the contacts must be increased and it causes the tap-changer to be bigger in dimension and goes up quickly in size. It becomes necessary to increase all the intercontact gaps in order to increase the arcing distance although there is no arcing everywhere. For the purpose of having a more compact design, the actual current switching part as well as arcing are removed to another part. It is a separate housing called diverter switch, with the necessary arcing gap. In this way the multiple arcing gaps of the selector switch will be eliminated, and it leads to a tighter packing of the fixed contacts [22].

One disadvantage of having the diverter switch is that it is more complex than the selector switch. It is only one switch that performs all the necessary actions to complete a tapchange in the selector switch. Whereas in the diverter switch concept, the function of tap selection and switching the current, which needs to be done simultaneously, are performed in two different compartments. Therefore, it is necessary in the diverter switch concept to synchronize the movement of tap selector and diverter switch. Loss of synchronism for any reason will lead to failure [10] [22](22)(10). The two types of diverter switch designed by Hitachi Energy are VUCG and VUCL. Type VUCL has higher power capacity [10].



**Figure 2.1:** Diverter switch, VUCG and VUCL (from left to right) [10].

### 2.1.3 Tap Selector

It is a device used in conjunction with a diverter switch to carry current but not to switch the current.

Tap selectors have fixed contacts and moving contacts. The fixed contacts are installed around the central shaft and the moving contacts are installed on the central shaft. The moving contacts are operated by the central shaft and are connected to the diverter switch by paper insulated copper conductors. The moving contacts can have one contact arm or more contact arms in parallel depending on the load current. The moving contacts slide on the fixed contacts in order to make contact. The tap selector types for VUC range of tap-changers are C, III and F which have different values of maximum rated through-currents and maximum impulse test voltages.

Tap-selector C has 1500 [A] and 350 [kV], tap-selector III has 2400 [A] and 550 [kV], and also tap-selector F has 3000 [A] and 550 [kV] as max. rated through-current and max impulse test voltage respectively [10] [17].



**Figure 2.2:** Tap selector, size C, size III and size F respectively [10].

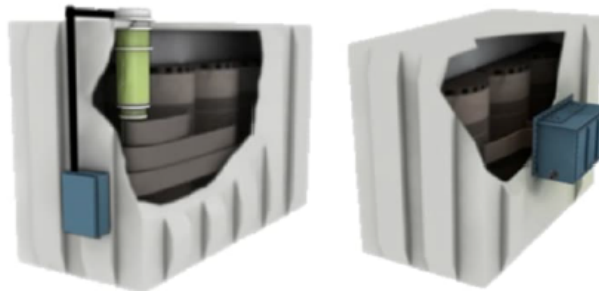
### 2.1.4 Change-over Selector

It is a device designed to carry current but not enable switching it. The device is used in conjunction with the tap selector or selector switch to make it possible for its contacts and the connection taps to be used more than once when moving from one extreme to the others [7] [17].

Change-over selectors connect or disconnect the main winding to the regulating winding. The regulating range of OLTCs can be almost doubled by using a tap winding in conjunction with a change-over selector [7] [17].

### 2.1.5 Tap-changer Placements

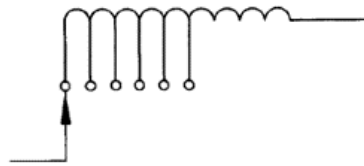
OLTCs are placed inside the transformer tank called in-tank types and the ones placed outside of the transformer tank in a separate compartment called on-tank. The in-tank types are used for higher voltages and power and the on-tank types are used for lower voltages and power [7].



**Figure 2.3:** In-tank type (left) and on-tank type (right) tap-changer [7].

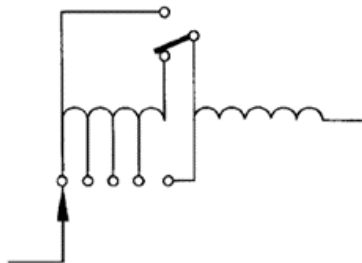
### 2.1.6 Type of Regulations

There are three types of regulation for tap selector: linear (L), plus/minus (R) and coarse/fine (D) switching. Linear switching has a simple design with low losses, and the regulating range is equal to the voltage of the tapped winding which gives a maximum regulating range of 10%. Change-over selector is not used for linear switching [7].



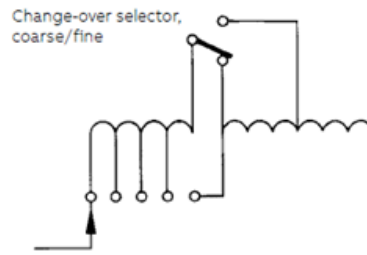
**Figure 2.4:** Linear switching [10]

Plus/minus switching uses a change-over selector to connect the main winding to two ends of the regulating winding and give the possibility of additive and subtractive regulation. It can increase the regulating range to twice the voltage of the tapped winding which gives the maximum regulating range of  $\pm 15\%$ . By reversing the magnetic flux generated by regulating winding, the voltage can be regulated [10].



**Figure 2.5:** Plus/minus switching [10]

Coarse/fine switching is connected to the change-over selector to increase the regulating range to twice the voltage of the tapped winding by connecting and disconnecting coarse winding. It can give the maximum regulating range of more than  $\pm 15\%$  [10].



**Figure 2.6:** Coarse/fine switching [10]

### 2.1.7 Type of Connections between Tap-changer and Transformer

There are different types of connection between tap changer and transformer. It is needed only one unit of OLTC (one three-phase tap-changer) for a star-connected winding arrangement and the transformer neutral point is connected in OLTC. Three-phase delta connections can need two or three units of OLTC depending on the type of delta connection.

### 2.1.8 Current conducting components in tap selector

There are different parts that conduct current in a tap selector and need to be dimensioned for maximum nominal current. Connections is a general name that is used for different conductors in tap selector. In order to conduct between the fine selector and the change-over selector, a flexible lead is usually used.

Fixed contacts are the type of contact that are installed on the cylinder shell. Fixed contacts conduct the incoming current from the transformer winding to the sliding contacts. Sliding contacts are mounted to conduct the current from the fixed conductors to the ring conductors. They are always connected to the ring conductors. Sliding contacts switch between a number of fixed contacts in circular direction around the central shaft.

Current collector rings are the ones that are installed around the central shaft. They conduct the current from the sliding contacts to the diverter switch.

### 2.1.9 Tie-in Resistor

Tie-in resistors are used to control the open circuit voltage of the change-over selector. The regulating winding is disconnected electrically from the main winding in a short time, during the operation of the change-over selector. This momentary disconnection causes the whole change-over selector to be floating and be exposed to high capacitively charged voltages. This capacitive voltage of winding can be determined by the voltage of, and the capacitances to, the surrounding windings or tank wall or the core. For some winding layout, voltages and capacitances, these capacitive voltages will reach the levels that are too high for the change-over selector. In a case of a successful breaking of the capacitive current, it will be followed by an

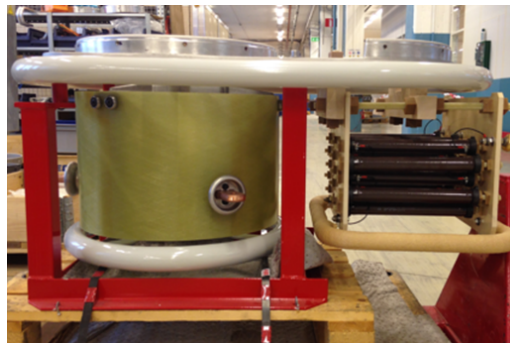
audible sound due to the generation and extinction of an arc between the contacts of change-over selector.

In case that the capacitive current cannot be broken by the change-over selector, the regulating winding will be short circuited. Here, there is a need to use potential controlling resistors, which is called tie-in resistor to limit the transient voltage between the contactors of the change-over selector. Depending on the tap selector types, the maximum permitted recovery voltage needs to be selected and then the tie-in resistor will be dimensioned accordingly [10][20][21].

Tie-in resistors are connected between the middle of the regulating winding and the connection point on the bottom of the diverter switch housing. It means the tie-in resistor is always included in the circuit and a current go through it which will generate heat and losses. The continuously dissipated power in the resistor must be taken into consideration at the calculation of no-load losses of the transformers [10][20][21].

If the power dissipation in the resistor is higher than acceptable level, a disconnecter called tie-in resistor switch should be used in the circuit to avoid high losses as well as overheating [10][20][21].

Tie-in resistors are usually mounted separately under the tap selector. In the case of having a tie-in resistor switch, there is no sufficient place for it under the tap selector [10][20][21].



**Figure 2.7:** Tie-in unit (resistor and switch) [21]

### 2.1.10 Different Designs of OLTC

OLTCs can be divided into two categories. The first category is with a diverter switch and tap selector that are placed inside two separate housings (UC and VUC types). The second category is comprised of only one housing where a selector switch and change-over selector are placed inside it (UZ, UB and VUB types) [12].

There are also two main technologies used in OLTC, Traditional technology and Vacuum technology. In traditional technology which is also called conventional on-load tap-changers, arc quenching in oil is used (UZ, UB and UC types).

In vacuum technology, arc quenching in separate interrupters is used (VUB, VUC and VRLTC types) [7].

Tap-changers use a motor-drive mechanism for operations which is placed on the outside of the transformer. The motor-drive mechanism connected to the tap-changers by the drive shaft and bevel gears [7].

Here are some short descriptions of each design:

- **Type UZ**

It is a conventional type, on-load tap-changer and has two different types: UZE and UZF. The selector and switching mechanism are combined. The tap-changer and all its equipment are contained in a single compartment and ready to install on the outside of the transformer tank. The motor-drive mechanism is attached to the outside of the transformer [13].

OLTC, UZ type has a range of up to 145 [kV] and power of 110 [MVA] [13].

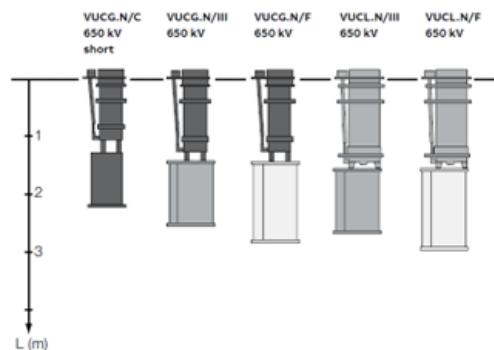
- **Type UBB and VUBB**

They are designed to install inside of the transformer tank, and it is cost-efficient and compact. There are both conventional type which is UBB and vacuum type which is VUBB. The motor-drive mechanism is installed on the outside of the transformer tank and connected to the OLTC by drive shafts and bevel gear. The UBB is primarily designed for small and medium-sized transformers with a maximum number of 27 tap positions. VUBB is intended for transformers up to 100 [MVA] with maximum number of 19 tap positions [14].

- **Type UC**

It is an on-load tap-changer which comes in many different types with a rating suitable for most applications. The vacuum types in UC families are VUCG and VUCL and the conventional types that operate with arc quenching in oil. In this family are UCG, UCL, UCD and UCC.

The VUCG type is suitable for transformers up to 800 [MVA] with a current rating of 1800 [A] and BIL rating of 1050 [kV]. It is smaller than VUCL type. The VUCL is the largest vacuum type of UC family, and it has been designed for transformers up to 2300 [MVA] with a current rating of 1600 [A] and BIL rating of 1175 [kV].

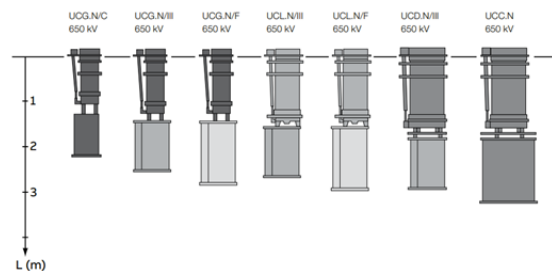


**Figure 2.8:** Tap-changer types, VUCG and VUCL [10]

The smallest in the UC family is the UCG model. It has been designed for transformers up to 500 [MVA] with a current rating of 600 [A] and the BIL rating of 1050 [kV] [15].

The mid-size in the UC types is the UCL model and is suitable for transformers up to 850 [MVA] with a current rating of 925 [A] and the BIL rating of 1175 [kV] [15].

The large size in the UC types are the UCC and the UCD models. They are suitable for the most demanding requirements with a current rating of 1600 [A] and the BIL rating of 1050 [kV] [15].



**Figure 2.9:** Tap-changers type, UC [10]

- **Type VRLTC**

The VRLTC is vacuum reactance load tap changer which is an on-load tap-changer for either automatic or manual control. It is a three-phase tap-changer and can be configured in linear, plus/minus and coarse/fine arrangements. The maximum number of positions is 35 with regulating winding sections of 8 effective positions. It covers up to a range of 72.5 [kV] with a current rating of 2000 [A] and the BIL rating of 200 [kV] [7][16].



**Figure 2.10:** Tap-changer type, VRLTC [16]

The VRLTC is driven and controlled using digital technology. It consists of three major components: the tap changing components, the driving components, and the decision making/monitoring components. The tap changing

components are contained in an oil-filled steel tank. The deriving and decision-making components are contained in a separate steel air compartment installed below the oil-field tank with a drive shaft connecting it to the tap-changer [16]. Tap Logic Monitoring system (TLMS) is installed in the motor compartment which is responsible for monitoring and control of the entire system [16].

### 2.1.11 Design tests requirement for OLTC

There are type tests that need to be performed on a sample of tap-changer after the final development of the product according to IEC 60214-1 and IEEE C57.131 [10][11].

- **Contact temperature rise test**

The test is performed for contacts which carry current continuously and are opened and closed or being moved during a time at their service life time or maintenance. The temperature test values should not exceed the values given in standard IEC 60214-1.

- **Switching test**

Breaking capacity tests and service duty cycle tests are included in switching tests. The most demanding conditions that the OLTC is rated for must be considered. Refer to IEC 60214-1 to find out the most difficult conditions of switching test for resistor or reactor on-load tap-changer as well as vacuum-type and non-vacuum-type tap-changers.

- **Short-circuit current**

The test is performed for all contacts that carry current continuously and the duration of short-circuit current is 2 [s] (+-10%).

- **Transition impedance**

The test is performed with 1.5 times the maximum rated through-current at the relevant rated step voltage to meet the overload requirements according to IEC 60214-1:2014 part 4.3. Tap-changers shall not restrict emergency loading of the transformer as described in IEC 60214-1:2014 part 4.3.

- **Mechanical tests**

Mechanical tests which include Simulation of transformer drying procedure, Mechanical endurance test, Sequence test, Operation under maximum allowable static pressure as well as Pressure and vacuum tests need to be performed in accordance with IEC 60214-1:2014.

- **Dielectric test**

The focus has been made in this study on the dielectric calculations of tap-changers to be able to analyze it and if necessary to modify the design before the dielectric test of the product.

On-load tap-changer test is performed in clean transformer oil or in a test tank that is filled with clean oil. The test voltages need to be according to the appropriate values stated in IEC 60214-1. There are different types of voltage which are applied on OLTC. The test voltage types are as follows, lightning impulse test, switching impulse test, chopped wave lightning impulse test and applied voltage test that duration of this test is 60 [s] and it is performed as described in IEC 60060-1. Moreover, measurement of partial discharges should be done according to the requirements [11].

There is a recommendation for testing sequence that starts with lightning impulse test and then follows with chopped wave lightning test, switching impulse test and lastly applied voltage test [11].

The dielectric tests need to be performed for different distances in order to prov the insulation levels for the distances according to IEC 60214-1. This has been described in more detail in section 2.1.12.

The transformer or regulating winding which is connected to OLTC determines the dielectric requirement of OLTC [11].

It is the responsibility of transformer manufacturers to select an OLTC with the right insulation level as well as considering the appropriate insulation level of the leads connected between the winding of the transformer and the OLTC [11].

■ Note:

Dielectrics are insulating materials or very poor conductors of electric current. When dielectric materials are placed in an electric field, no current or very low current can flow through them.

In a material when an electromotive force is strong enough to cause the electric charge movement, the current begins flowing in the material. This movement of charge is carried by the existing electors in the materials. There are some materials, like metals such as copper, aluminum etc. that have many free electrons to transfer electric charges and have a low resistance to the flow of charge which make the metals good conductor. The physical structure of insulating materials makes them perform the opposite way as the conductive materials perform. In insulating materials, electrons cannot move easily and freely and this is the cause that they are not able to carry charge effectively through the insulating materials. It should be remarked that it is always possible to apply a sufficiently high voltage to insulating materials and force them to conduct.

The insulation breakdown of insulating materials can be described as a sudden change in the resistance of the insulation due to the applied voltage and electrical potential differences. It means that the applied voltage can break down the insulation properties of the materials. The dielectric breakdown of materials is a complex physical phenomenon and different materials require different applied voltages and different levels of electric field to make the dielectric breakdown of material happen. Insulating materials need a very high

voltage field to allow the electrical current to flow unlike metals and other conductors that have free electrons without needing to be placed in any electric field.

The electrons are energized in the insulator once the electric field is sufficient, and the electrons get enough energy to cross the bandgap and move into the conduction band. There is now a sharp increase in the conductivity of the insulating material. This transformation of electrons from bandgap into the conduction band is called dielectric breakdown and the electric field necessary to start the breakdown is called breakdown strength or dielectric strength. Hence, dielectric breakdown is the result of electrical potential differences which lead to a sudden increase in the conductivity of an insulator [19].

### 2.1.12 Selection of OLTC

The tap-changer should be chosen in a way to fulfill the requirements of the applications as well as be able to satisfy the basic conditions. It is the responsibility of the transformer manufacturer to make sure the correct selection has been made for a fully assembled tap-changer for a given transformer.

The basic conditions that should be fulfilled (if applicable) by the tap-changer are as follow:

- **Frequency**

The designs and tests of OLTCs according to IEC 60214-1 or IEEE Std C57.131 are suitable for use in both 50 [Hz] and 60 [Hz] systems. It should be consulted with the tap-changer manufacturer in case of using in applications with other frequencies (like application in railways with frequency of 16 2/3 Hz).

- **Currents**

There are three parameters to be considered as defined in IEC 60214-1 or IEEE Std C57.131-2012 which is Rated through-current for OLTCs, Overload current and short circuit current. It is not a requirement that the OLTC operate under short-circuit conditions and the OLTC is not capable to switch the short-circuit current.

- **Rated Step Voltage**

It is the highest permissible voltage between terminals that intended to be connected to successive taps of the transformer for each value of rated through-current [17]. Therefore, the rated step voltage is a function of the rated through current . The maximum permitted step voltage needs to be lower than switching capacity and the electrical strength of the diverter switch [10].

The tap-changer should have a rated step voltage of at least equal to the highest step voltage of the tapped winding considering that the applied voltage on the transformer does not exceed the limitations defined in IEC 60076-1

or IEEE Std C57.12.00. The tap-changer should have a higher rated step voltage in case the tap-changer is frequently in operation at a higher applied transformer voltage.

Moreover, transformers with variable flux can have different values of step voltages and through currents in each tap position. It causes the tap-changer to get different stresses in different tap positions which influences the selection of the tap-changer.

Furthermore, in the case of transformers with regulating windings that have a different number of turns between taps, it is necessary to evaluate all the different positions to find the most severe condition. The selection of OLTC with regards to the breaking and dielectric stresses needs to be according to the most severe condition [18].

It is responsibility of the transformer manufacture to provide the tap-changer manufacture with data such as step voltage in each tap position, number of turns between every tap and all other relevant technical data in order to make an accurate choice of OLTC.

- **Breaking Capacity**

The highest tap current and the voltage per step of the transformer are required to be within the values of the rated-through current and the relevant step voltage of the tap-changer in order to fulfill the braking capacity requirement [18].

- **Insulation levels**

Insulation levels are values of the impulse and applied voltages to earth, and where applicable between phases, and between the parts where insulation is needed with regards to its ability to withstand the electric stresses.

The following voltage values need to be checked on all tap positions of the transformer against the tap-changer values in accordance with IEC 60214-1 or IEEE Std C57.131.

- Power-frequency operating voltages on the tap-changer in service (PF).
- AC voltages on the tap-changer during tests on the transformer ( $U_m$ ).
- Impulse voltages on the tap-changer during tests on the transformer.

Impulse voltages are lightning impulse (LI), switching impulse and chopped lightning impulse voltages. Among the above-mentioned impulse voltages, it is only the lightning impulse voltage that has been considered for dielectric calculations with COMSOL. The others should be evaluated by tests [18].(18)

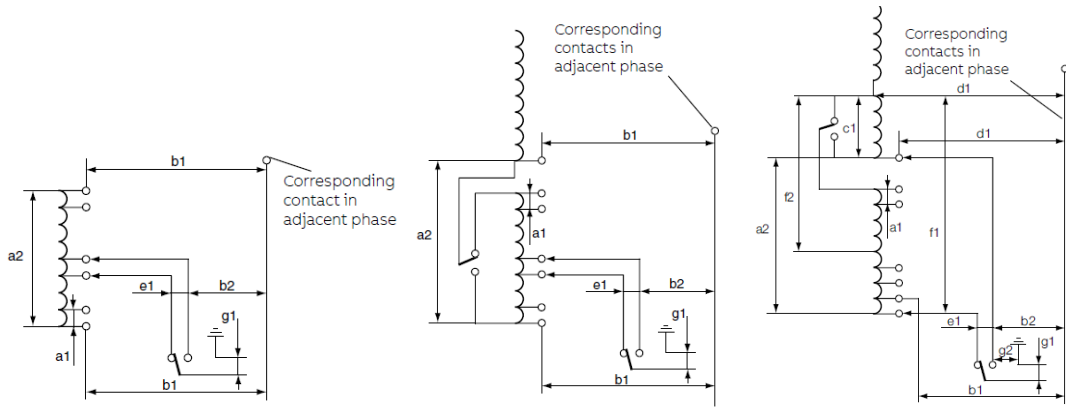
It should be noted that in networks switching operation can cause very fast transient over-voltages which can result in very fast oscillating over-voltage stresses on the tap-changer. These stresses are not taken into account by the switching impulse test of the transformer, and they have to be considered when selecting the lightning impulse level of the tap-changer [10][17].

The partial discharge (PD) level of tap-changers needs to be according to the requirements for the power transformer.

A standardized lightning impulse voltage has a shape of 1.2/50 [ $\mu s$ ]. The power

frequency test voltage (Pf) has a duration of 60 [s]. The insulation levels are identified as impulse withstand voltage and power frequency withstand voltage.

The insulation levels between different parts as shown in figure 2.10 for different regulations need to be measured. It depends on the types of tap-changers, there are different approved values for different parts and also different types of withstand voltages which stated in Hitachi Energy technical guides for each tap-changer model. The focus has been made in this thesis on OLTC, type VUCG and the insulation levels in (g1) and (a2) refer to figure 2.10 [10].



**Figure 2.11:** Insulation level in different distances for different regulations [10]

The definitions of different insulation parts according to the Hitachi Energy guideline in [10] shown in figure 2.11 are as below:

- (a1): between any electrically adjacent contacts in the tap selector which is not connected.
- (a2): between the ends of the fine regulating winding (across the range). For coarse/fine switching in minus position, this means between the freely oscillating end of the coarse winding and any end of the fine winding.
- (b1): between not connected taps of different phases in the fine selector.
- (b2): Between open contacts of different phases in the diverter switch.
- (c1): Between ends of the coarse winding in coarse/fine switching.
- (d1): Between taps of different phases in the coarse selector (coarse/fine switching).
- (e1): Between pre-selected tap and connected tap of one phase in the diverter switch and in the tap selector.
- (f1): Between any end of the coarse winding and connected tap.
- (f2): Between any end of the coarse winding and the middle of the fine winding.
- (g1): Connected tap to earth.
- (g2): Pre-selected tap to earth.

Insulation levels to earth (g1) for lighting impulse (LI) levels and also power frequency (Pf) levels correspond to the different values of  $U_m$  are as stated in table 2.1 [10].

**Table 2.1:** Insulation levels.

LI [kV]	Pf [kV]	$U_m$ [kV]
380	150	72.5 <sup>1)</sup>
750	325	170
1050	460	300

1) 72.5 [kV] is the value in IEC but Hitacchi Energy consider 76 [kV] as the insulation level for  $U_m$ .

- **Number of tap positions**

When the tap range increases, the voltage regulation range also increases. It should be considered that there is a risk of over voltage when operating or testing at minimum winding positions. Hence, necessary measures need to be taken to limit the over voltage [18].

- **Change-over selection recovery voltage**

Recovery voltage is the power frequency voltage that appears across the change-over selector contacts during contact separation. When change-over selectors operate, the tap winding will be disconnected momentarily and there will be discharges between opening and closing contacts. This can result in dielectric stresses and the formation of gases which make it necessary to take precautionary measurements to avoid it. Limiting devices like tie-in resistor need to be used to control the recovery voltage in case it is higher than the recovery voltage withstand level specified by manufacturers [18].

- **Coarse/fine regulation**

There will be a high leakage inductance when changing from the end of the fine winding to the end of the coarse winding between the two windings in series opposition. It leads to extended arcing of the diverter or selector switch which is caused by a phase shift between the switched current and recovery voltage of the diverter or selector switch.

The rated characteristics of an OLTC are Rated through current, Maximum rated through current, Rated step voltage, Maximum rated step voltage, Rated frequency and Rated insulation level.

## 2.2 Requirements and Limitations for Electric Field Strength

The dielectric limits for tap changers are according to the internal document of Hitachi Energy. Tables 2.2 and 2.3 show the electric field limits for bare electrodes and for insulator materials.

For epoxy coated electrodes the  $U_{long}$  limits are doubled.

Moreover, in the case of insulator materials, it is only the tangential component of the electric field ( $E_t$ ) on the surface at the voltage  $U_{1min}$  that should be checked in pure oil.

**Table 2.2:** Electric field limitations for electrodes.

Applied voltage [kV]	Electric field limits [kV/mm]
$U_{Long}$	$\alpha$
$U_{Pf}$ or $U_{1min}$	$\alpha\alpha$
$U_{LI}$	$\alpha\alpha\alpha$

**Table 2.3:** Electric field limitations for materials.

Applied voltage [kV]	Electric field limits [kV/mm]
$U_{Pf}$ or $U_{1min}$	$\beta$

Table 2.4 shows the distance to the ground that needs to be considered for the case of insulation level to earth (g1).

**Table 2.4:** Distance to the ground considered for different BILs.

BIL [kV]	Distance to the ground [mm]
380	$\gamma$
750	$\gamma\gamma$
1050	$\gamma\gamma\gamma$



# 3

## Methods

### 3.1 Modelling Approach

#### 3.1.1 Electric Field Study in COMSOL

Comsol Multiphysics is a Finite Element Analysis (FEA) software that numerically solves partial differential equations. The changes of a system are mostly described by differential equations rather than its state over space and time. It is partial differential equations (PDE) that describe the changes in more than one independent variable. Engineers and scientists can use PDEs to describe the law of physics by solving the PDEs in a mathematical model to predict the outcome of an experiment and have a better understanding of the process which described by the mathematical models. An approximation of equations is used for most geometries and problems based on different types of discretization since PDEs cannot be solved for them with analytical methods. The discretization methods approximate the PDEs with numerical model equations in order to be solved with numerical methods. So, these numerical method solutions are an approximation of the real solutions to PDEs. The method used to compute such approximations is called finite element analysis methods (FEA) [23].

Geometries are subdivided into smaller elements. The accuracy that can be obtained from FEA methods is directly related to the element sizes. A finer mesh gives more accurate results, but it leads also to a greater computation time. Therefore, there is a trade-off between accuracy and computation time [23].

#### 3.1.2 Electric Field

The electric field caused by stationary charges is electrostatics. Electrostatics as the physic has been chosen in COMSOL Multiphysics since it has Poisson's equation built in, which is used for computing of electric field in dielectric materials.

The mathematical model of electrostatics in free spaces is formed of the below equations which specify the divergence and curl of the electric field.

$$\nabla V = \frac{\rho_v}{\epsilon_0} \quad [V/m^2] \quad (3.1)$$

Where,

$\rho_v$  is a space charge density,

E is the electric field,

$\epsilon_0$  is a constant, permittivity of free space.

Equation 3.1 establishes that in electrostatics, the space charge density acts as volume source and the static electric field is solenoidal if the volume charge density  $\rho_v$  is zero. It means, the field contains no sources, or it sinks without the presence of a volume charge density. Equation 3.1 is not enough since there is an additional requirement, which is equation 3.2 [23].

$$\nabla V \times E = 0 \quad (3.2)$$

Equation 3.2 is Maxwell's equation implies that a static electric field is irrotational and it has no net circulation (Curl free). Moreover, an irrotational field is also a conservative field which can be represented as the gradient of a scalar field as below that leads to the definition of electric potential [V] [23]:

$$E = -\nabla V \quad [V/m] \quad (3.3)$$

The negative sign in equation 3.3 is an old convention to express that the potential increases against the direction of the electric field. The application of Equation 3.1 is limited to being used in free space and it is not applicable in dielectric materials. In order to make it applicable for dielectric materials, equation 3.1 needs to be modified to contain the effect of polarization. Therefore, another field quantity, which is called electric displacement field (D) has been defined as [23]:

$$D = \varepsilon_0 \varepsilon_r E = \varepsilon E \quad [C/m^2] \quad (3.4)$$

In order to measure how much the bound charges in a material become polarized in an electric field  $\varepsilon$  is defined as permittivity of medium. As seen in equation 3.4, vector D contains electric field due to both free charges as well as the displacement of bound charges.

From equations 3.1 and 3.4, we have equation 3.5 [23].

$$-\nabla \cdot (\varepsilon \nabla V) = \rho_v \quad [C/m^3] \quad (3.5)$$

This equation is the one that is solved in COMSOL Multiphysics for the electrostatics physics module for the given geometry and materials to compute the electrostatic potential and field.

## 3.2 Study Cases

The dielectric simulations are done according to IEC 60214-1 and Hitachi Energy manual for VUC (1ZSC000562-AAX EN, REV.3) with consideration of a new tap-changer and clean transformer oil with temperature of 30°C according to IEC 60296,2012-02. The withstand voltage value of the oil is higher than 40 [kV]/2.5 [mm].

Dielectric simulations have been performed with COMSOL Multiphysics for two different study cases as described in section 3.2.1.

### 3.2.1 Different Study Cases

- Case A, Tie-in resistor switch for selector F used with tap selector III:  
The purpose of the calculations is to assess whether the designed product can fulfill the requirements regarding the insulation level for distance (g1) to the surrounding transformer walls (ground) for different basic insulation levels.
- Case B, Tap selector C with jumpers:  
The purpose of the calculations is to assess whether the tap-changer VUCC with different regulation types can fulfill the requirements regarding the insulation level for distance (a2) as described in part 2.1.12 (insulation level).

### 3.2.2 Applied voltages in different study Cases

There are three types of voltage that are applied in dielectric calculations in COMSOL as listed below. There are more in detailed explanations of them in part 2.1.12 Selection of OLTCs. The calculation has been done for three insulation levels, BIL 380 [kV], BIL 750 [kV], and BIL 1050 [kV].

- $U_{Long}$  = Continues voltage during max rated allowed operation (rms).
- $U_{1min}$  or  $U_{Pf}$  = Rated short duration power frequency withstands voltage (rms).
- $U_{LI}$  or  $U_{1.2/50}$  = Rated lightning impulse withstand voltage (peak).

■ For case A (Tie-in resistor switch for selector F used with tap selector III):

**Table 3.1:** Basic Insulation levels according to IEC.

BIL [kV]	$U_{Long}$ [kV]	$U_{1min}$ or $U_{Pf}$ [kV]	$U_{LI}$ [kV]	Distance to ground [mm]
380	76/sqrt (3)	150	380	$\gamma$
750	170/sqrt (3)	325	750	$\gamma\gamma$
1050	300/sqrt (3)	460	1050	$\gamma\gamma\gamma$

$$E_{abcm\max}(U_{long}) = E_{Calculated} \times U_{long} < \alpha \quad [kV/mm] \quad (3.6)$$

$$E_{abcm\max}(U_{1min}) = E_{Calculated} \times U_{1min} < \alpha\alpha \quad [kV/mm]$$

$$E_{abcm\max}(U_{LI}) = E_{Calculated} \times U_{LI} < \alpha\alpha\alpha \quad [kV/mm]$$

■ For Case B, Tap selector C with jumpers:

The applied voltages are in different levels depending on the regulation types of tap-selector C, number of tap positions and the number of loops between the taps. Referring to table 6 and 14 for distance (a2) in Hitachi Energy technical guide maximum withstand voltages for different regulation taps can be found.

The calculations have been done for the tap-selectors with 27 taps (7D), 31 taps (8D) and 35 taps (9D) for distance (a2). The regulation types that have been considered are plus/minus switching (R) and coarse/fine switching (D).

The withstand voltages for tap-changer VUCG with tap selector C shown in table 3.2.

**Table 3.2:** Basic Insulation levels for tap selector C

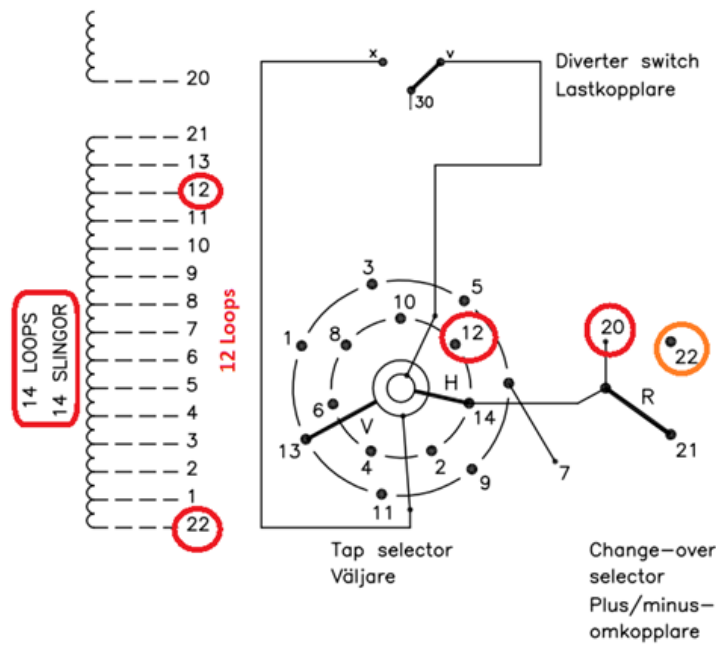
No. of positions	Regulation type	$U_{Long}$ [kV]	$U_{Pf}$ [kV]	$U_{LI}$ [kV]
16-27 (7D)	D, R	35	140	350
28-31 (8D)	D, R	35	120	290
32-35 (9D)	D, R	35	95	250

The above table is extracted from table 6 and table 14 in Hitachi Energy manual for VUC (1ZSC000562-AAX EN, REV.3).

The applied voltages for the dielectric calculations are also depending on the number of tap loops and the positions of the taps which can be found in the connection diagrams of each type of Hitachi Energy tap-changer.

For tap-changer 7D and regulation type R, the applied voltages can be calculated by referring to Connection diagram for VUCGR/C to find the ratio between the max possible loop to the total loop of the tap selector for tap-changer VUCGR/C.

The total number of loops as specified on the drawing and can be seen from figure 3.1 is 14 loops. And the max possible number of tap loops is between tap 12 and tap 20 when tap 20 is connected to tap 22. So, there are 12 loops here between tap 22 and tap 12 as shown in figure 3.1.



**Figure 3.1:** Tap-changer VUCGR/C, 7D, regulation type R showing the max number of tap loops

The higher loops between two taps near each other means the higher impedance and also higher voltage differences between the two taps.

And the applied voltages defined as follow:

$$U_{Long} = 35 \text{ [kV]} \times (\text{No. of max possible loops} / \text{No. of total loops}) = 35 \times (12/14) = 30 \text{ [kV]}$$

$$U_{1min} \text{ or } U_{Pf} = 140 \text{ [kV]} \times (\text{No. of max possible loops} / \text{No. of total loops}) = 140 \times (12/14) = 120 \text{ [kV]}$$

$$U_{LI} = 350 \text{ [kV]} \times (\text{No. of max possible loops} / \text{No. of total loops}) = 350 \times (12/14) \approx 300 \text{ [kV]}$$

The above calculations have been done for all the three different number of tap positions (7D, 8D and 9D) and each for different regulation types (R and D). The higher voltage has been chosen in each case and shown in table 3.3.

**Table 3.3:** Calculated applied voltage levels for tap selector C

No. of positions	Regulation type	$U_{Long}$ [kV]	$U_{Pf}$ [kV]	$U_{LI}$ [kV]
27 (7D)	D, R	32.3	129.4	323
31 (8D)	D, R	32.6	112	271
35 (9D)	D, R	31.2	85	223

### 3.3 Implementation of the models

Geometry models of tap-changers were first built in a software named Creo Parametric and then imported into COMSOL Multiphysics. It is a complex geometry with more than 500 parts [6].

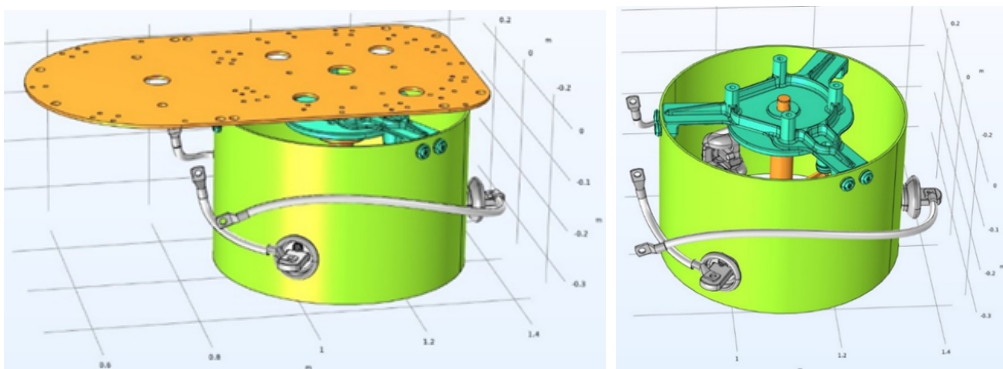
Electric potentials and dielectric properties are defined to address the electric stress problem and then iterative simulations have been run to display the results of computations in terms of both amplitudes, and the pattern of the electric field strength. Then, the dielectric stresses results have been compared with Hitachi Energy internal dielectric design rules that come from the dielectric stress information that have been derived from the long history with building tap-changers at Hitachi Energy to accurately predict the functionality of the products as well as the operational life of the tap-changers [6].

#### 3.3.1 Geometry and Material

##### 3.3.1.1 Study Case A

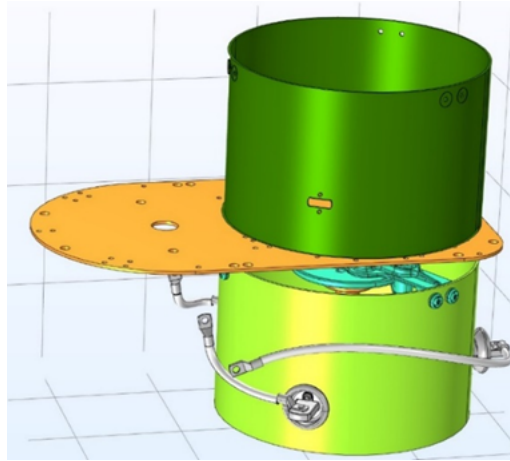
The geometry that imported into COMSOL Multiphysics is as shown in figure 3.2 for study case A, which is Tie-in resistor for selector F used with tap selector III. It is only the bottom plate of tap selector III that has been used to do dielectric evaluation with the conjunction of the tie-in resistor for selector F.

Figure 3.2 shows also the tie-in resistor without the bottom plate for tap selector III.



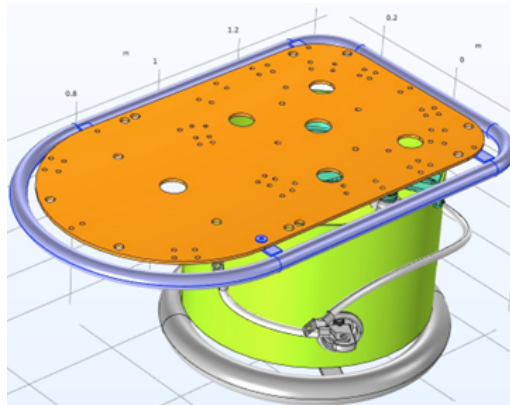
**Figure 3.2:** Geometry for study case A, Tie-in resistor for selector F. The left one is with the bottom plate for tap selector III and the right one is without the bottom plate.

Additionally, as shown in figure 3.3 a metal cylinder has been used on top of the bottom plate for tap selector III to simulate conductors and all the electric potential parts above the bottom plate, which can affect the results.



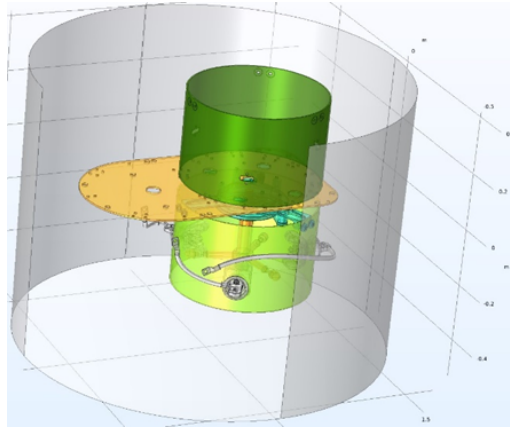
**Figure 3.3:** Geometry for study case A, with a metal cylinder on top of the bottom plate.

Moreover, in some cases the simulations have been done with two shielding rings as shown in figure 3.4 to control the electric field strength and keep it in the accepted limit. One shielding ring is around the bottom plate and another shielding ring mounted around insulating cylinder.



**Figure 3.4:** Geometry for study case A, with two shielding rings.

Furthermore, as it can be seen in figure 3.5 that the transformer tank has been depicted with a big cylinder, which the whole geometry (the tap-changer) is placed inside of it. The minimum distance between the metal parts and the transformer walls and bottom varies in different simulations, depending on the BIL (Basic Insulation Level) that the simulation has been done for it, according to table 2.4. Thus, it is only the cylinder, which depicts the transformer tank will have different sizes in the three simulations of case A and the rest of the geometry will be the same.



**Figure 3.5:** Geometry for study case A, with transformer tank.

- **Material**

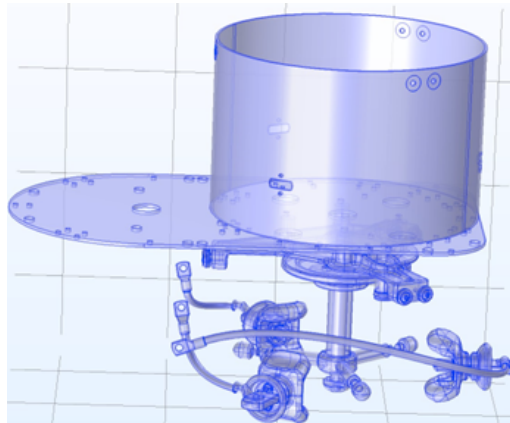
It is shown in table 3.4 the materials used in the models imported into COMSOL, study case A (Tie-in resistor switch for selector F used with tap selector III) together with their characteristics.

**Table 3.4:** Property of materials

Domain	Relative Permittivity
Paper	5
Oil	2.2
Insulating cylinder	6.3

It should be noted that the tap-changer is placed in a transformer tank which is filled with oil.

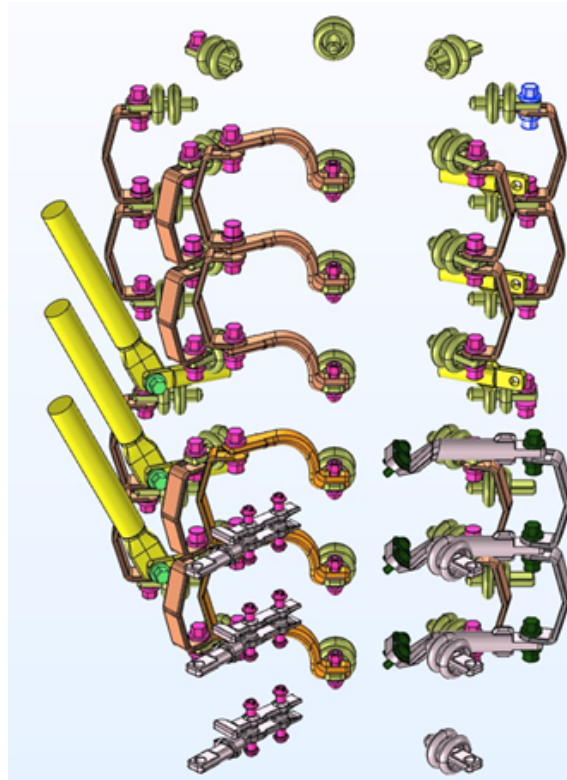
And the rest are metal parts, which have been considered as boundaries in COMSOL as shown in figure 3.6.



**Figure 3.6:** Geometry for study case A, selection of the boundaries.

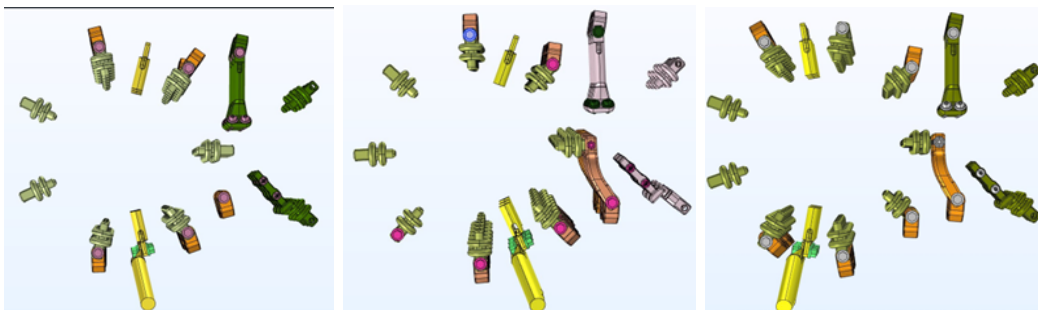
### 3.3.1.2 Study Case B

The study has been done for tap selector C with three different number of tap positions, with 27 taps (7D), 31 taps (8D) and 35 taps (9D). It is shown in figure 3.7 a general view as an example for an imported tap selector C with jumpers into COMSOL for the geometry 8D (31 taps).



**Figure 3.7:** Study case B, tap selector C, 8D.

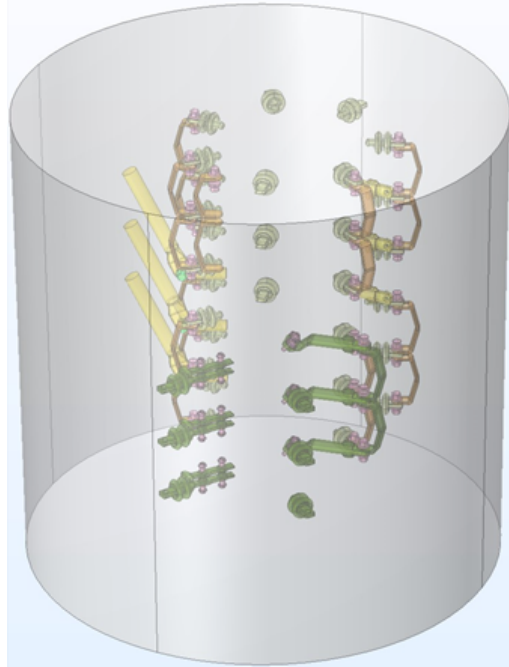
So, there are three different geometries that were imported into COMSOL Multiphysics, each in a separate file. Figure 3.8 shows the top view of each geometry for 7D, 8D and 9D from left to right respectively.



**Figure 3.8:** Geometry for study case B, tap selector C for 7D, 8D and 9D.

Furthermore, as it can be seen in figure 3.9, the transformer tank has been depicted with a big cylinder, which the whole geometry (the tap-changer) is placed inside of

it. The minimum distance between the metal parts and the transformer walls and bottom is the same in all the different simulations.



**Figure 3.9:** Geometry for study case B, with the transformer tank.

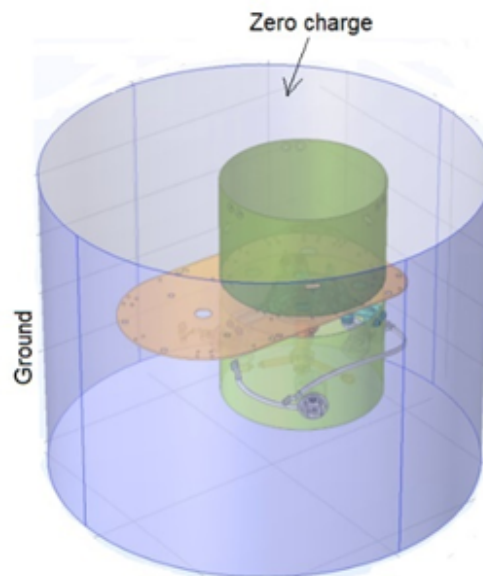
The tap-changer is placed in a transformer tank which is filled with oil. The rest are metal parts, which have been considered as boundaries in COMSOL.

The only domain defined in study case B is the oil in the transformer tank which has relative permittivity of 2.2.

#### 3.3.2 Electrostatics (es) Set up in COMSOL

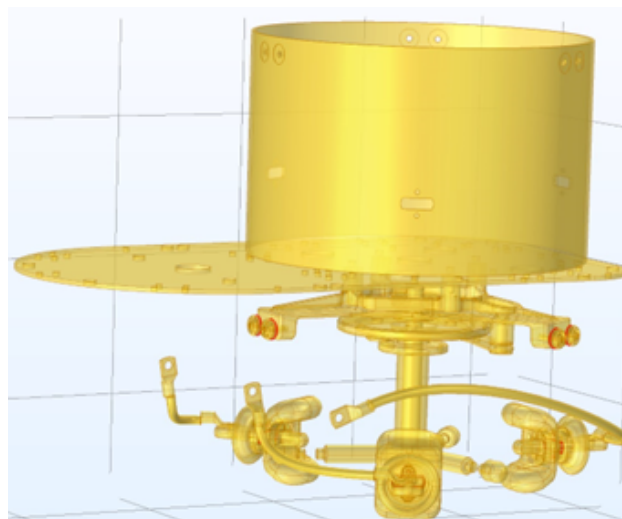
- **Study case A**

Initial values have been considered zero for all the models in COMSOL. The transformer cylinder walls, and bottom have been set to the ground potential and the top part of transformer tank has been set to zero charge as shown in figure 3.7.



**Figure 3.10:** Study case A, electrostatics.

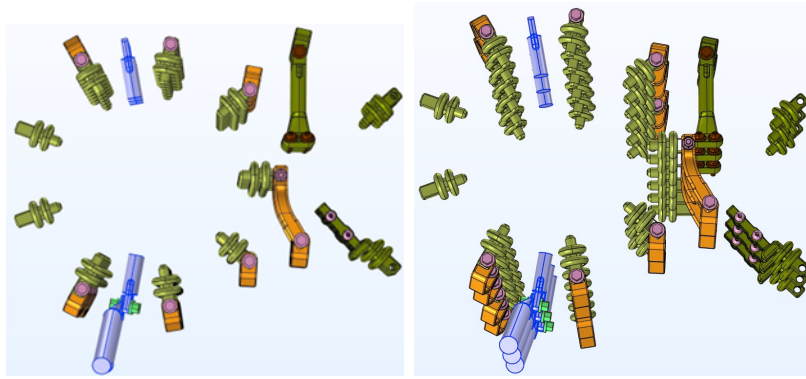
Electric potential of 1000 [V] have been applied to the rest of boundary parts as shown in figure 3.8. The computed electric field will be then multiplied by an appropriate factor depending on the potential levels and types as described in section 3.2.2 to get the actual electric field values.



**Figure 3.11:** Study case A, the parts that electric potential have been applied.

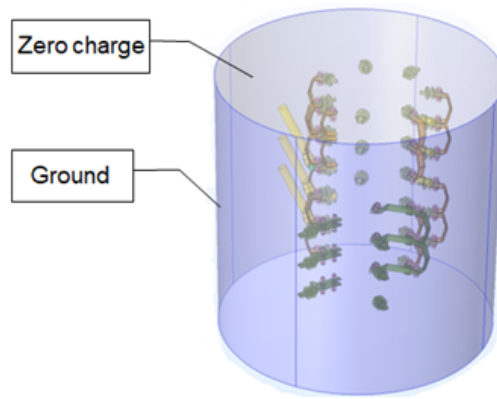
- **Study case B**

Initial values have been considered zero for all the models in COMSOL. The transformer cylinder walls, and bottom and the diverter switch contacts (the blue highlighted parts in figure 3.12) have been set to the ground as shown in figures 3.12 and 3.13.



**Figure 3.12:** Study case B, the blue highlighted contacts has been set to ground potential.

The top part of transformer tank has been set to zero charge is shown in figure 3.13.



**Figure 3.13:** Study case B, ground and zero charge parts.

Electric potential of 1000 [V] have been applied to the rest of boundaries. The computed electric field will be then multiplied by an appropriate factor depending on the potential levels and types as described in section 3.2.2 to get the actual magnitudes of the electric field strength.

#### 3.3.3 Mesh used in the simulations

The geometries for both study cases have been imported to COMSOL but due to importing process and mechanical drawing quality some parts of geometries intersect each other slightly and these overlaps caused errors in COMSOL. Free tetrahedral and free triangular mesh were used for the entire geometry for all the models in both study cases.

- **Study case A**

An overall view of meshing shown in figure 3.14. See table 3.5 for more information regarding meshing in different parts of the geometry.

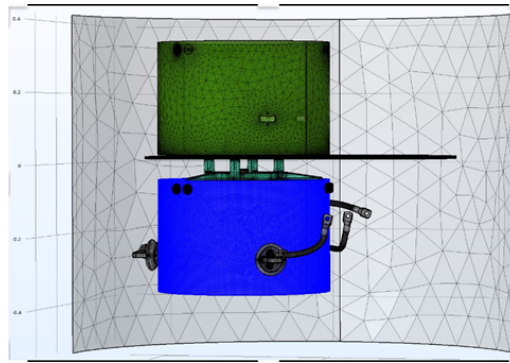


Figure 3.14: Study case A, General mesh view.

Table 3.5: Mesh, study case A, max. element size

Study case A	Domain	Max element Size [m]
		Insulating cylinder
	Paper	0.002
Study case A	Boundary	Max element Size [m]
	Screws	0.0008
	Shielding of contacts	0.0008
	Bottom plate for the tap Selector III	0.0008
	Shielding ring	0.002
	Transformer tank	fine
	The rest	0.008

Figure 3.15 shows the general mesh statistics of the geometry.

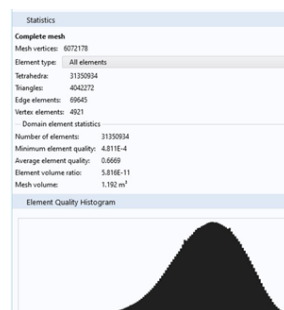
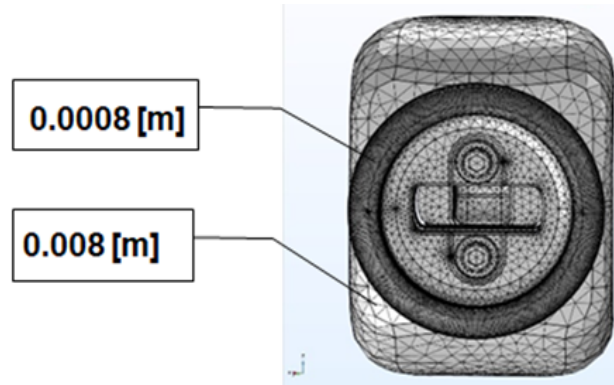


Figure 3.15: Study case A, mesh statistics.

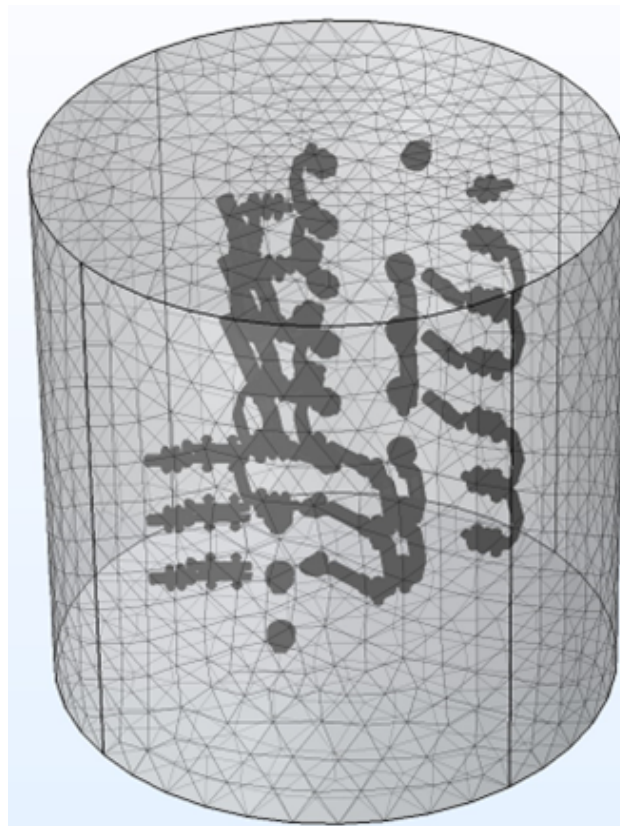
Figure 3.16 illustrates an example of meshing for a contact as well as its shielding.



**Figure 3.16:** Study case A, meshing of contacts.

- **Study case B**

An overall view of meshing shown in figure 3.17. For more information regarding meshing in different parts of the geometry, see table 3.6. The mesh information is the same in all the three models.



**Figure 3.17:** Study case B, General mesh view.

**Table 3.6:** Mesh, study case B, max. element size

Study case B	Boundary	Max element Size [m]
	Screws	0.0003
	contacts	0.001
	Shielding cap	0.0005
	Jumper	0.002
	Transformer tank	fine

Figure 3.18 shows the general mesh statistics of the geometry.

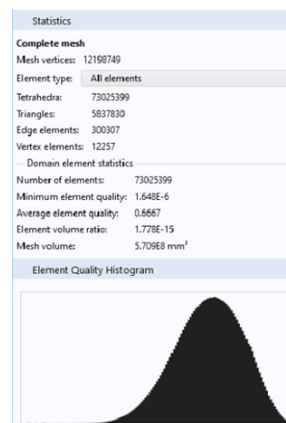
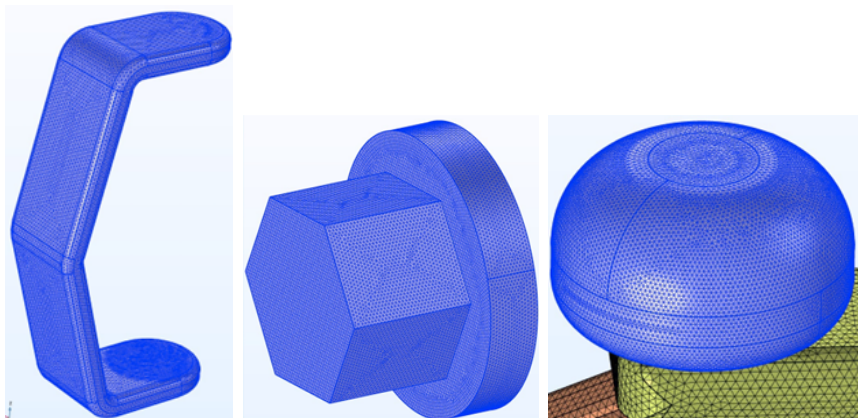
**Figure 3.18:** Study case B, mesh statistics.

Figure 3.19 illustrates some examples of meshing in different parts. They are jumper, screw and shielding cap from left to right respectively.

**Figure 3.19:** Study case B, meshing.



# 4

## Results

The results of simulations for both cases are presented in this part. These simulation results have been evaluated against Hitachi Energy internal dielectric design rules and criteria for accepted long-term and short-term creep and strike field magnitudes.

Many different parts have been studied, including screws of different types, various types of contacts and insulating parts. Additionally, different geometry configurations (with and without shielding rings and shielding caps) of tap-changers for two cases have been evaluated but here only the results of the most critical parts have been presented.

In the case that the electric field is not within the permitted limits, a proper measure has been taken to control the electric field strength in the critical area.

## 4.1 Case A (Tie-in resistor switch for selector F used with tap selector III)

The results for case A have been presented in three separate parts according to the BIL that simulation has been performed for it.

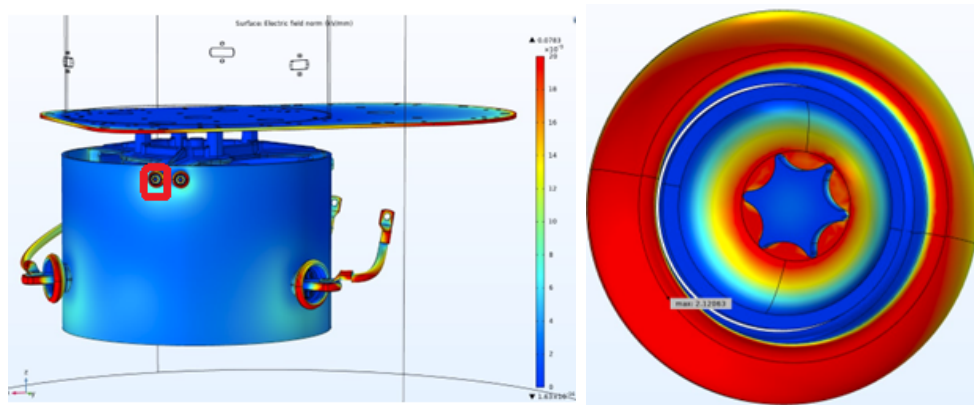
### 4.1.1 Results for BIL 380 [kV]

- Screws

The results for the red-marked screw shown in figure 4.1 have been presented here since the highest electric field stress is on this screw among other screws in the model. The results of computation shown in table 4.1 and can be seen the magnitude of the electric field for  $U_{Long}$  is higher than the accepted limit.

**Table 4.1:** Results for the screw shown in fig 4.1

Applied voltage [kV]	E-field results [kV/mm]	E-field limit [kV/mm]
$U_{Long}$	2.2	$\alpha$
$U_{Pf}$	7.3	$\alpha\alpha$
$U_{LI}$	18.4	$\alpha\alpha\alpha$

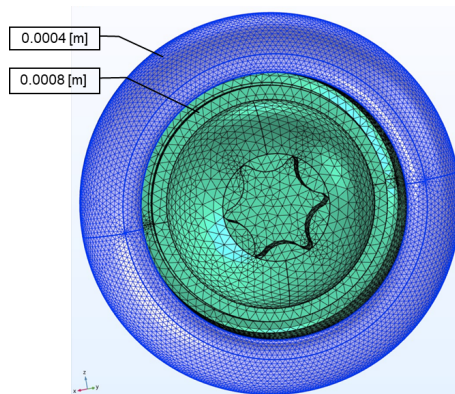


**Figure 4.1:** Result case A, BIL 380 [kV], Screws.

If the electric field magnitude is higher than the limited value, one solution is coating of the part in order to keep the electric field within the limit.

There might be also other reasons for getting higher electric field values than the accepted limit such as low quality imported model into COMSOL, poor or not good enough meshing of objects. They need to be checked before selecting a solution for controlling the field.

Some parts of screw in figure 4.1 has been simulated with a better meshing as shown in figure 4.2. The blue-marked surface has been meshed with the max element size of 0.0004 [m] while the whole surface area was 0.0008 [m] before.

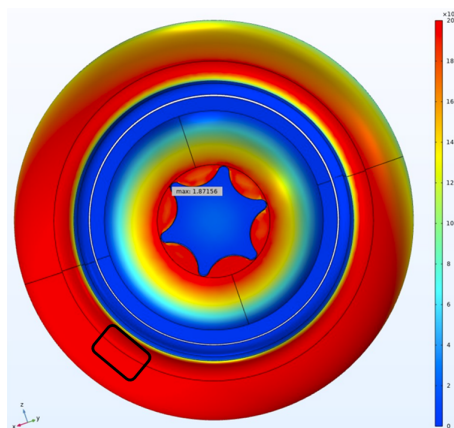


**Figure 4.2:** Better meshing for the screw shown in fig. 4.1

And the computation results with new meshing shown in figure 4.3 and table 4.2. The areas marked in figure 4.3 is the same area in figure 4.1 with the max magnitude of electric field. The electric field magnitude in the marked area is 1.4 [kV/mm] which is much lower than the previous case that was 2.2 [kV/mm].

**Table 4.2:** Results for the screw shown in fig 4.2.

Applied voltage [kV]	E-field results [kV/mm]	E-field limit [kV/mm]
$U_{Long}$	1.4	$\alpha$
$U_{Pf}$	5	$\alpha\alpha$
$U_{LI}$	12.5	$\alpha\alpha\alpha$

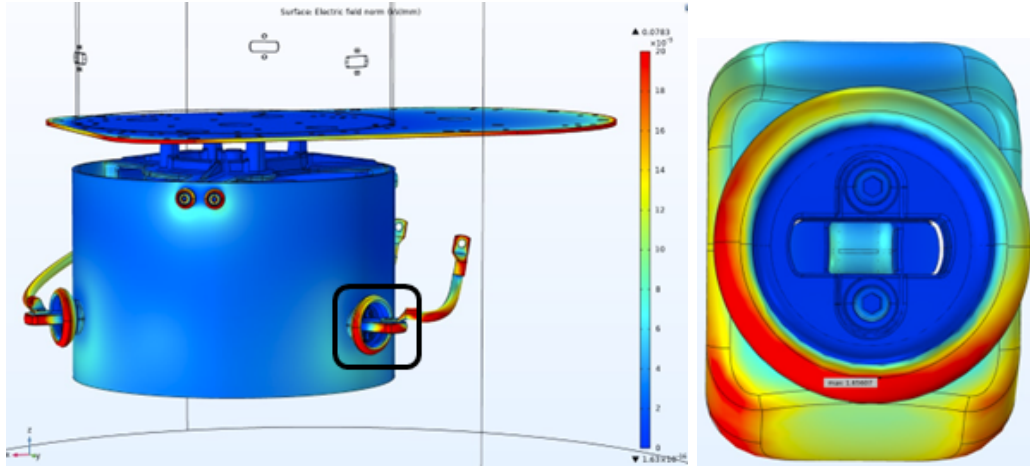


**Figure 4.3:** The result with meshing shown in fig. 4.2.

All the values for the electric field strength is within the accepted limit as shown in table 4.2 and no more action is needed to control the electric field strength for the screws.

- **Contacts**

The highest electric field stress on a contact for the tie-in switch is on the contact that has been marked in figure 4.4. So, the result of this contact is only presented here in table 4.3 and also illustrated in figure 4.4.



**Figure 4.4:** Result case A, BIL 380 [kV], Contacts.

**Table 4.3:** Results for the contact shown in fig 4.4.

Applied voltage [kV]	E-field results [kV/mm]	E-field limit [kV/mm]
$U_{Long}$	1.65	$\alpha$
$U_{Pf}$	5	$\alpha\alpha$
$U_{LI}$	14.4	$\alpha\alpha\alpha$

The results show that the electric field strength for all the contacts are in the permitted limit.

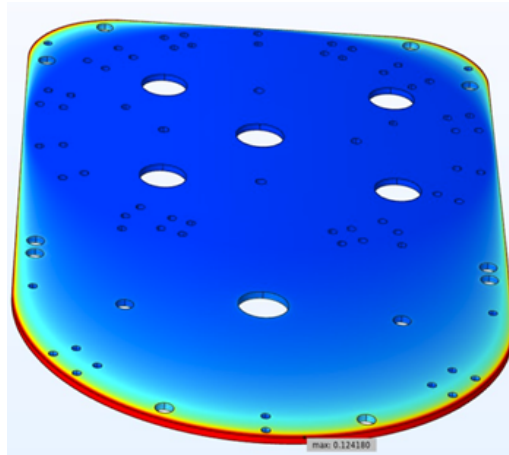
- **Bottom plate for tap selector III**

The bottom plate is the part tap selector III which tie-in resistor F is connected to it. The results has been presented in table 4.4 and also illustrated in figure 4.5. The magnitudes in table 4.4 are for the max point shown in figure 4.5.

**Table 4.4:** Results for the bottom plate (tap selector III).

Applied voltage [kV]	E-field results [kV/mm]	E-field limit [kV/mm]
$U_{Long}$	5.5	$\alpha$
$U_{Pf}$	18.7	$\alpha\alpha$
$U_{LI}$	47.2	$\alpha\alpha\alpha$

As can be seen from table 4.4, the electric field magnitudes for  $U_{Long}$ ,  $U_{Pf}$  as well as  $U_{LI}$  are much higher than the limits.



**Figure 4.5:** Result case A, BIL 380 [kV], Bottom plate for tap selector III.

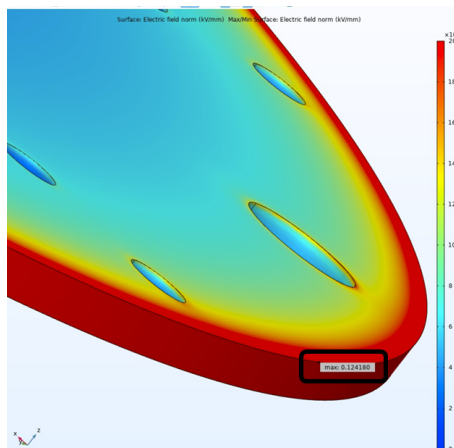
Possible causes of getting such high values for the electric fields has been investigated.

First, it has been noticed that the electric field magnitudes are much lower in the area around and very close to the max point shown in figure 4.5. It is not normal to have such a significant difference between the magnitudes of the electric fields for points, which are so close. The highest electric field around the max point in figure 4.5 shown in table 4.5.

**Table 4.5:** The highest E-field around the max point shown in figure 4.5.

Applied voltage [kV]	E-field results [kV/mm]	E-field limit [kV/mm]
$U_{Long}$	3.1	$\alpha$
$U_{Pf}$	10.5	$\alpha\alpha$
$U_{LI}$	26.6	$\alpha\alpha\alpha$

Figure 4.6 illustrates a closer look at the high stress parts of the bottom plate.



**Figure 4.6:** Result case A, Bottom plate for tap selector III, critical area.

Furthermore, it can be observed from figure 4.6, that all the high electric stress points are whether on the edge or on the area very close to the edge of the

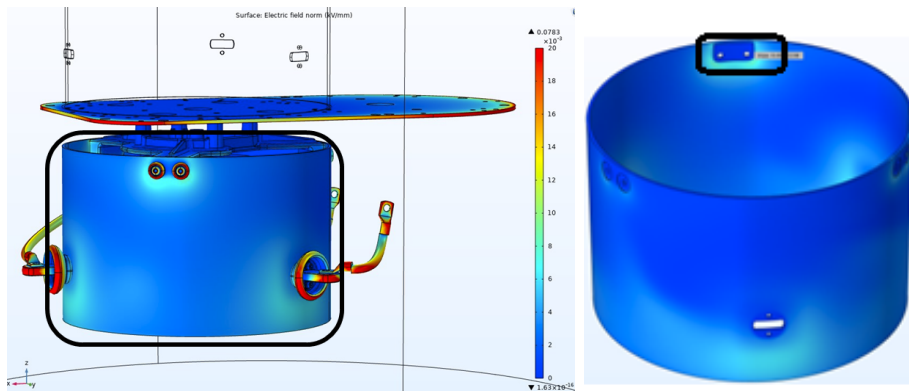
bottom plate. In reality the bottom plate does not have that sharp edges. In this case the imported mechanical model does not match the real component and it is the cause of high electric stress in the area.

- **Insulating cylinder**

For insulating material, the tangential component of electric field will be considered at  $U_{1min}$ . The tangential component of electric field is continuous across interface.

The maximum allowed tangential component of electric field  $E_t$  in any point needs to be less than the magnitude of the electric field calculated by taking into account of the creep distance in that point.

Figure 4.7 illustrates the simulation result for the insulating cylinder. The max electric field magnitude is 1.3 [kV/mm], which is less than  $\beta$  [kV/mm] as the accepted limit shown in table 2.3.



**Figure 4.7:** Result case A, BIL 380 [kV], Insulating Cylinder.

#### 4.1.2 Results for BIL 750 [kV]

The evaluations have been performed for four different cases, without shielding rings, with shielding rings and two different cases with only one shielding ring in order to study the effect of shielding rings. Here only the results for two cases, with shielding rings and without shielding rings have been presented.

The first part is the results when there is no shielding rings mounted and it is obvious from the results, presented here that the electric field strength in all the parts are higher than the accepted limits.

- **Screws**

The result of the screws marked in figure 4.8 presented in table 4.6 which is the same screw as in the one that evaluated in case BIL 380 [kV].

**Table 4.6:** The highest E-field on the screws shown in figure 4.8.

Applied voltage [kV]	E-field results [kV/mm]	E-field limit [kV/mm]
$U_{Long}$	6.8	$\alpha$
$U_{Pf}$	22.8	$\alpha\alpha$
$U_{LI}$	52.5	$\alpha\alpha\alpha$

The area which electric field is higher than the limits are highlighted on the both screws in figure 4.8, which is considerably big area.

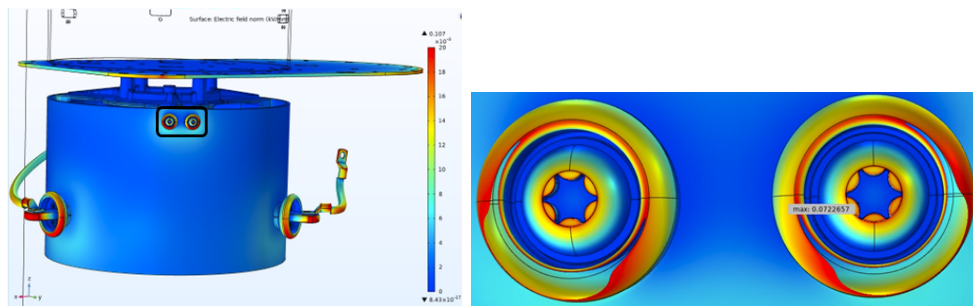
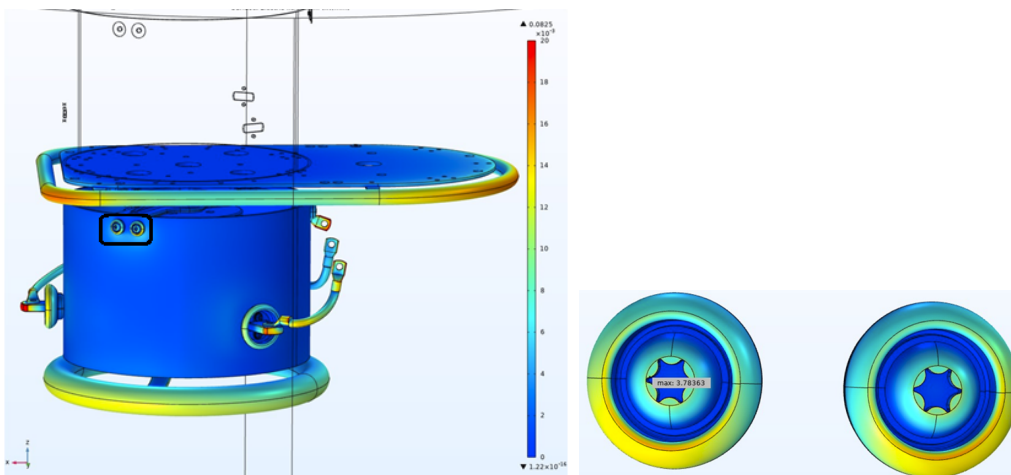
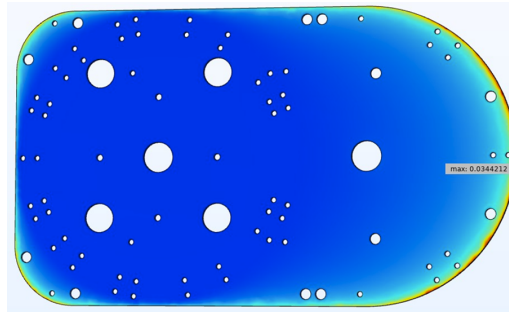
**Figure 4.8:** Result case A, with shielding rings, BIL 750 [kV] , Screws.

Figure 4.9 illustrates the results with the shielding rings. The electric field strength is now within the limits.

**Figure 4.9:** Result case A, BIL 750 [kV] , Screws.

- **Bottom plate for tap selector III**

The electric field strength is high even in the area that is not close to the edges of the bottom plate. The results illustrates in figure 4.10 and it is higher than the accepted levels.



**Figure 4.10:** Result case A, BIL 750 [kV], Bottom plate for tap selector III.

The magnitudes of max electric field for two cases, with and without the shielding rings shown in table 4.7. The values with the shielding rings is within the limits and are acceptable.

**Table 4.7:** E-field values with/without shielding rings for the bottom plate, BIL 750 [kV].

Applied voltage [kV]	without shielding rings [kV/mm]	with rings [kV/mm]
$U_{Long}$	3.4	1.8
$U_{Pf}$	11.2	5.9
$U_{LI}$	25.8	13.6

### 4.1.3 Results for BIL 1050 [kV]

The dielectric evaluation of the model has been performed only in one case, with both shielding rings. As it can be seen from the results the electric field stress is very high on all the parts even on the shielding rings. There is a need for necessary actions to be taken here to control the electric field stress on the component within the safe levels.

All the screws and the contacts will be coated. Moreover, thick paper insulation is wrapped around the shielding rings.

The results of the shielding rings have been only presented here.

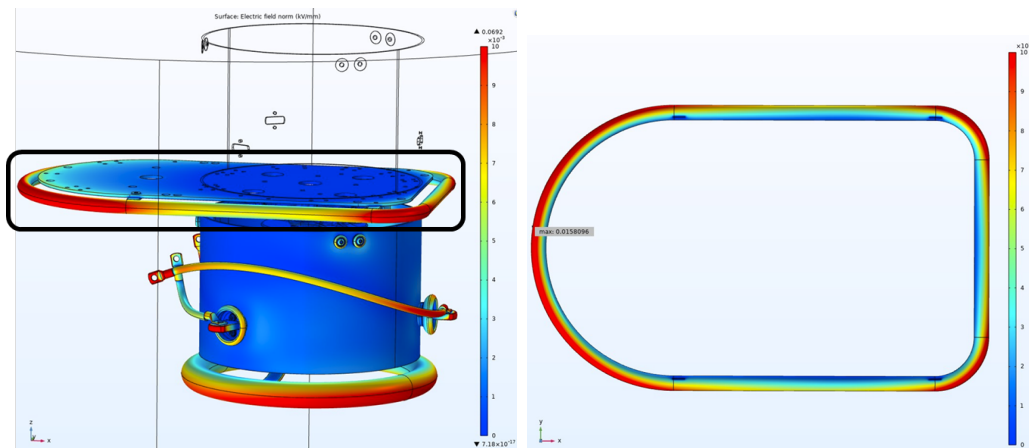
- **Shielding ring 1**

The results illustrated in figure 4.11 and the max magnitudes of electric field shown in table 4.8.

**Table 4.8:** The highest E-field on shielding ring 1.

Applied voltage [kV]	E-field results [kV/mm]	E-field limit [kV/mm]
$U_{Long}$	2.8	$\alpha$
$U_{Pf}$	7.3	$\alpha\alpha$
$U_{LI}$	16.6	$\alpha\alpha\alpha$

The shielding ring will be wrapped with insulating paper since the electric field is higher than the limit.



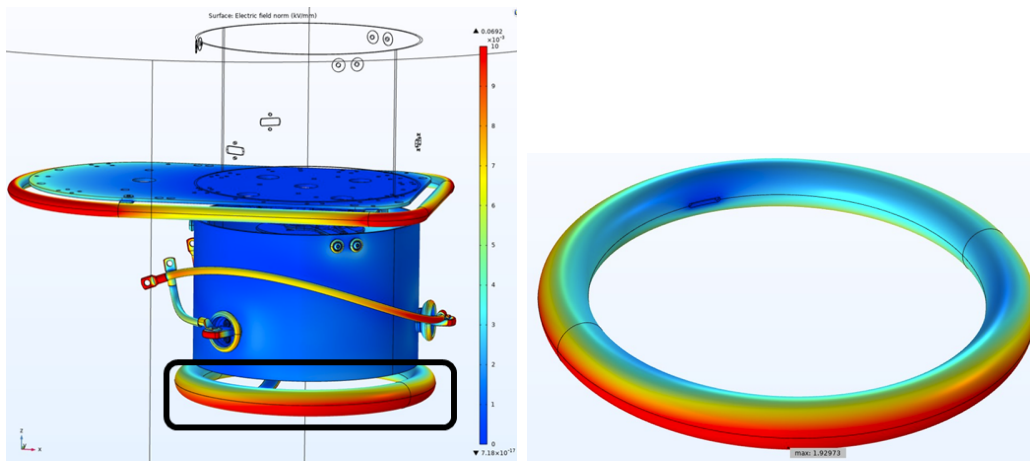
**Figure 4.11:** Result case A, BIL 1050 [kV], Shielding ring 1.

- **Shielding ring 2**

The results shown in table 4.9 for shielding ring 2. The magnitude for  $U_{long}$  is very close to the limit. the shielding ring here also will be wrapped with insulating paper.

**Table 4.9:** The highest E-field on shielding ring 2.

Applied voltage [kV]	E-field results [kV/mm]	E-field limit [kV/mm]
$U_{Long}$	1.95	$\alpha$
$U_{Pf}$	5.1	$\alpha\alpha$
$U_{LI}$	11.7	$\alpha\alpha\alpha$



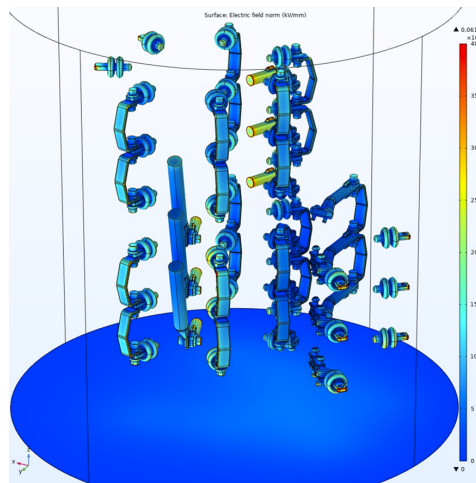
**Figure 4.12:** Result case A, BIL 1050 [kV], Shielding ring 2.

## 4.2 Case B (Tap selector C with jumpers)

The results for simulations in case B have been presented in three separate parts according to the number of tap positions 7D, 8D and 9D.

### 4.2.1 Results for 7D

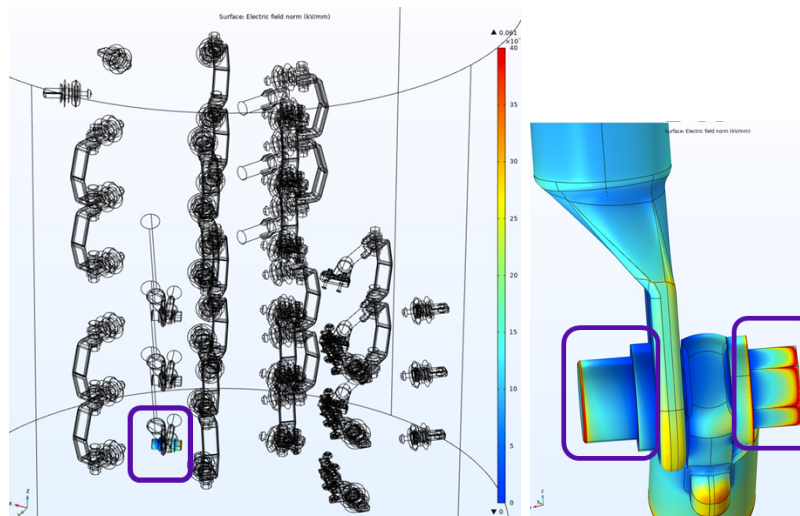
A general view of the result shown in figure 4.13. The electric field stress is within the acceptable limits on all the parts. Here only the results of a critical part has been presented.



**Figure 4.13:** Result case B, 7D, General view.

- **Screws**

Figure 4.14 shows the location of the selected screws in the component. The screws have a shorter distance to ground potential compared with other parts, hence the higher electric field stress.



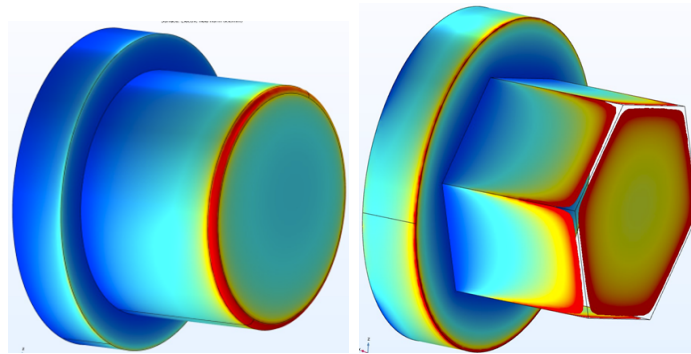
**Figure 4.14:** Result case B, 7D, Screw's location in the model.

It is shown in table 4.10 the max electric field magnitudes on the left screw shown in figure 4.15. As it can be seen from table 4.10, the values are close to the limit or slowly higher than the limit. According to the investigation that has been done, the mechanical model of the screw does not match perfectly with reality, the physical screw and also by taking into consideration of errors in meshing, we can conclude that the electric field magnitude is within the acceptable limit.

Regarding the right screw in figure 4.15, the max electric field is 3.5 [kV/mm]. It should be noted that the sharp shapes in the mechanical model that imported into COMSOL does not match the reality and the physical screw.

**Table 4.10:** The highest E-field on the left screw in figure 4.15.

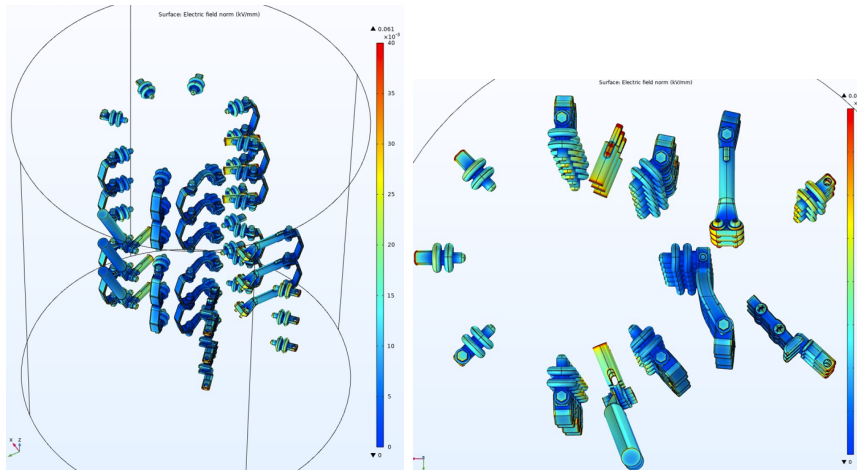
Applied voltage [kV]	E-field results [kV/mm]	E-field limit [kV/mm]
$U_{Long}$	2	$\alpha$
$U_{Pf}$	8.1	$\alpha\alpha$
$U_{LI}$	20	$\alpha\alpha\alpha$



**Figure 4.15:** Result case B, 7D, Screws.

## 4.2.2 Results for 8D

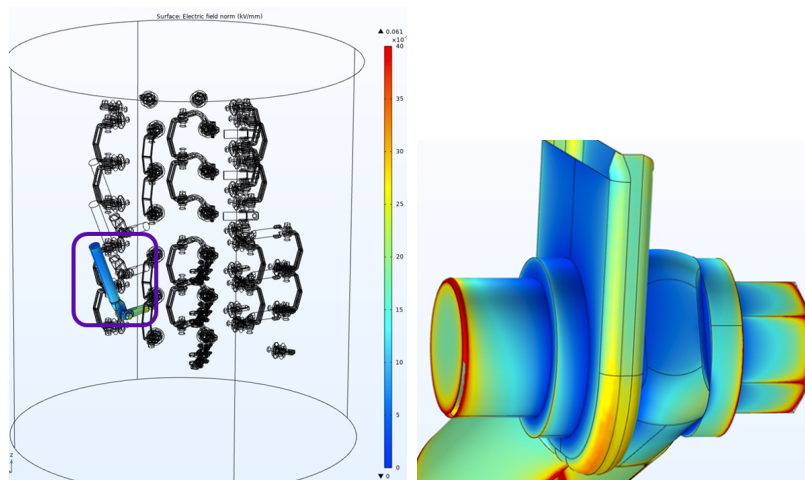
A general view of the result shown in figure 4.16. The electric field stress on some parts are higher than the limits. The simulations have been done for two cases, without and with shielding caps for the screws.



**Figure 4.16:** Result case B, 8D, General view.

- **Screws**

The location of the selected screws in the component is marked in figure 4.17. The electric field stress is higher here than other parts of the component. The screws have a shorter distance to ground potential compared with other parts.



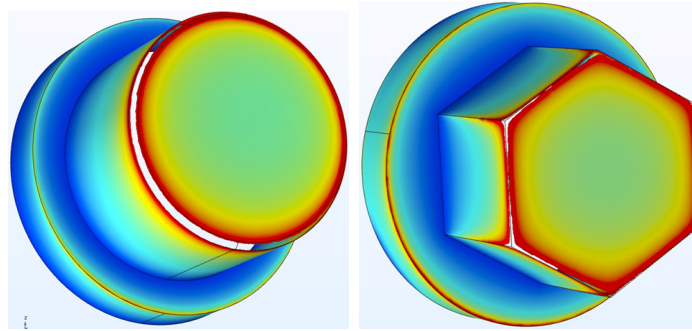
**Figure 4.17:** Result case B, 8D, Screw's location in the model.

It is shown in table 4.11 the max electric field magnitudes on the left screw shown in figure 4.18. As it can be seen from table 4.11, the value for  $U_{Long}$  is higher than the limit and the value for  $U_{Pf}$  is on the limit.

**Table 4.11:** The highest E-field on the left screw in figure 4.17.

Applied voltage [kV]	E-field results [kV/mm]	E-field limit [kV/mm]
$U_{Long}$	2.3	$\alpha$
$U_{Pf}$	8	$\alpha\alpha$
$U_{LI}$	19.5	$\alpha\alpha\alpha$

The highlighted area (white color) in figure 4.18, are the area with higher electric field values than accepted.

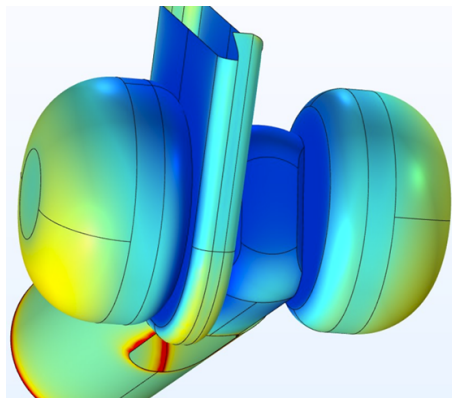
**Figure 4.18:** Result case B, 8D, Screws.

The simulation has been once again with shielding caps for the screws to have the electric field stress in the permitted limits. The max electric field magnitudes on the shielding caps have been shown in table 4.12.

**Table 4.12:** The highest E-field on shielding caps for the screws.

Applied voltage [kV]	E-field results [kV/mm]	E-field limit [kV/mm]
$U_{Long}$	0.9	$\alpha$
$U_{Pf}$	3	$\alpha\alpha$
$U_{LI}$	7.3	$\alpha\alpha\alpha$

The result of simulation illustrated in figure 4.19 and shown in table 4.12 confirm that the electric field stresses are within the limit.

**Figure 4.19:** Result case B, 8D, shielding caps for the screws.

### 4.2.3 Results for 9D

A general view of the result shown in figure 4.20. The electric field stress on some parts are higher than the limits. The simulations have been done for two cases, without and with shielding caps for the screws but here only the results without the shield caps will be presented.

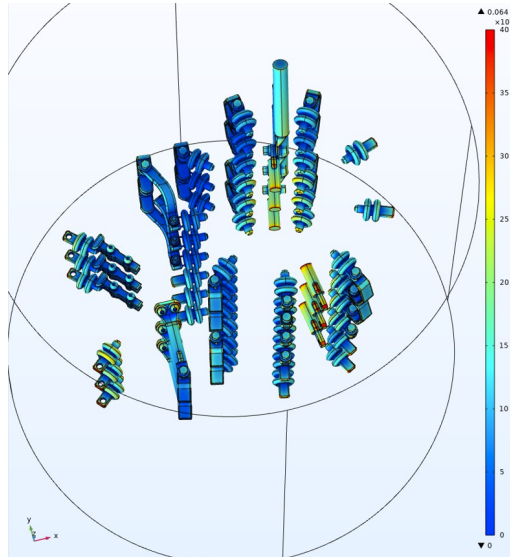


Figure 4.20: Result case B, 9D, General view.

- Screws

The location of the selected screws in the component is marked in figure 4.21. It is almost the same location or the same screws as the two previous cases for 7D and 8D.

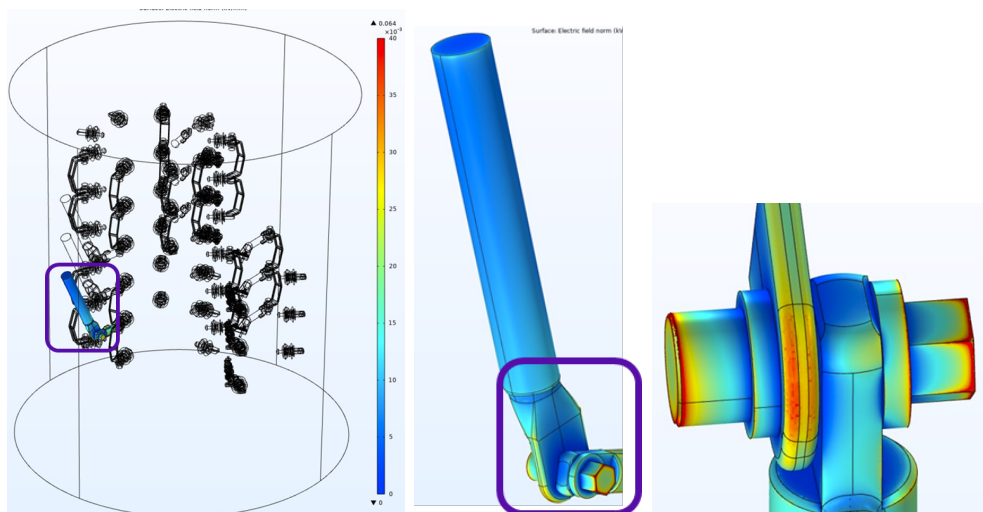


Figure 4.21: Result case B, 9D, Screw's location in the model.

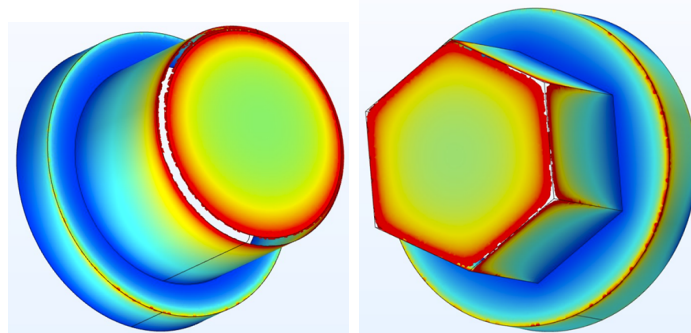
It is shown in table 4.12 the max electric field magnitudes on the left screw shown in figure 4.22. As it can be seen from table 4.13, the value for  $U_{Long}$  is higher than the limit and the value for  $U_{Pf}$  is close to the limit.

**Table 4.13:** The highest E-field on the left screw in figure 4.22.

Applied voltage [kV]	E-field results [kV/mm]	E-field limit [kV/mm]
$U_{Long}$	2.6	$\alpha$
$U_{Pf}$	7.1	$\alpha\alpha$
$U_{LI}$	18.7	$\alpha\alpha\alpha$

The highlighted area (white color) in figure 4.22, are the area with higher electric field values than accepted.

It can be noticed from the results that the electric field strength for  $U_{Long}$  on the screws in case 9D is higher than the same ones in case 8D and 7D. One reason can be due to more number of taps, the contacts and following that the screws are closer to each other. So. the screws that are close to the ground potential in case of 9D have shorter distance to ground than the same ones in case 7D.



**Figure 4.22:** Result case B, 8D, Screws.

The shielding caps are needed for the screws in the component in order to control the electric field.

# 5

## Conclusion

Tap-changers are complex and consist of many different small parts, which make the dielectric simulation of the component complicated and time consuming. There are many small surfaces like screws of various types. These small surfaces require smaller element size for meshing. If the element sizes are not small enough, it can be a cause of errors or not reliable results. The smaller element size in meshing means more time consuming both for meshing and also for the computations. Hence, there is a trade-off between accuracy of the results and the time required to compute.

It is important to know how much accuracy is needed in the results for that specific simulation and then meshing and computing time can be set accordingly.

Moreover, the parts that have no effect or less effect in the results can be removed from the mechanical model to save more time during meshing and also computing. Additionally, the parts that are not on focus in simulations can have lower mesh quality.

The results of simulations in COMSOL are affected directly by meshing and poor meshing causes the results with low reliability. Due to meshing or problems with the mechanical model the calculated results at a point might be significantly different with surrounding points.

The importance of geometry and the spacing between different parts is significant in dielectric simulation and evaluations.

It should be considered that there are errors in mechanical models, importing the model into COMSOL, meshing and calculations.

## 5.1 Case A (Tie-in switch unit from "selector F" to be used at tap selector III)

- **BIL 380 [kV]**

It is only the selector bottom that has higher E-field strength than accepted due to sharp edges in mechanical drawings. The rest is OK.

- **BIL 750 [kV]**

Both shielding rings needed in order to have the electric field strength in the accepted limit.

- **BIL 1050 [kV]**

The electric fields are higher than accepted limits with both shielding rings installed. Actions to take: Coating of the screws and the contacts and paper wrapping of the shielding rings.

## 5.2 Case B (Tap selector C with jumpers)

- **7D**

E-fields are mostly in accepted range and some parts around the accepted range which needs to be checked if the mechanical model is accurate enough.

- **8D**

The simulation has been performed with and without shielding caps. The electric field magnitudes are higher than accepted limits for some screws. The shielding caps are needed.

- **9D**

The electric field is higher than accepted limits for some screws and the shielding caps are needed.

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