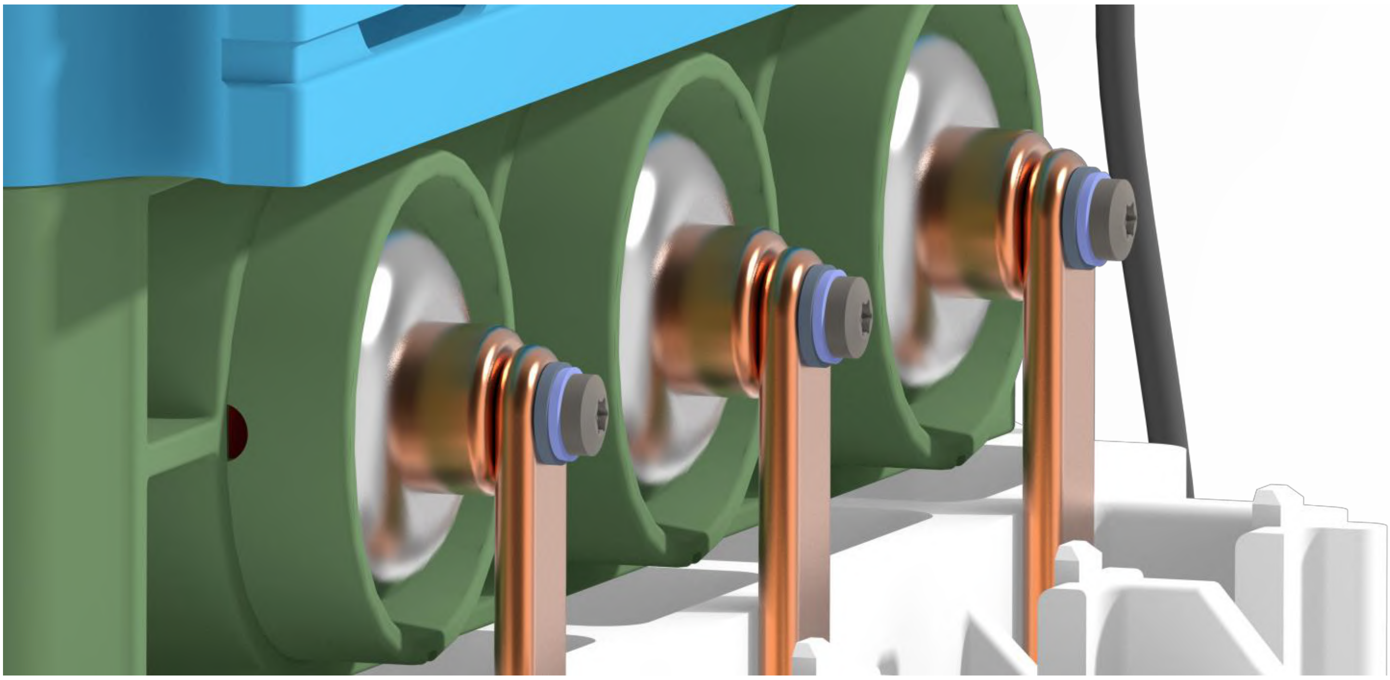

On-Load Tap-Changer with Surge Arresters

The development of a new surge arrester mounting solution

Master's thesis in Product Development

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MASTER'S THESIS 2024

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Abstract

Hitachi Energy are advancing the world's energy systems to be more sustainable, flexible and secure by offering solutions for distributing electricity over large distances. A key component in the electrical grid are transformers and their transformation of electrical energy between voltage levels. An important component of the transformer is the On-Load Tap-Changer (OLTC). It makes it possible to ensure a sufficiently stable voltage level on the power grid, by alternating the number of turns in the transformer winding. Quality assurance and safety is of essence since transformer failures can have huge consequences, therefore a safety device so-called surge arrester can be used to protect the OLTC from over-voltages from the grid that may occur and direct them to ground.

However, another tap-changer model in Hitachi Energy's product range lacks this feature due to space limitations within the tap-changer compartment. The aim with this thesis is to make a concept design with surge arresters for the model that does not have this feature yet.

During the project, a problem definition was stated and a prestudy performed in combination with the establishment of a requirements specification to find a solution to the problem. An iterative process of concept generation, design reviews and concept selection methods was done to end up with a final design. The final design was then 3D-printed to demonstrate the solution.

The final design consists of three holders that holds the surge arresters in place, the surge arresters has been modified with a groove and new connectors that connects the surge arresters electrically through connection plates to the diverter switch. This concept fulfils all requirements and wishes that has been possible to evaluate during the thesis and serves as a foundation for future work for Hitachi Energy.

Acknowledgments

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List of Acronyms

ABB	ASEA Brown Boweri
ASEA	Allmänna Svenska Elektriska Aktiebolaget
BBC	Brown Boweri & Cie
BIL	Basic Insulation Level
BOM	Bill Of Material
CAD	Computer Aided Design
DETC	De-Energized Tap Changer
FMEA	Failure Modes and Effects Analysis
HVDC	High Voltage Direct Current
OEM	Original Equipment Manufacturers
OLTC	On-Load Tap-Changer
RPN	Risk Priority Number
SMC	Sheet Moulding Compound

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1
Introduction

1.1 Background

Hitachi Energy's roots traces back to the late 1800s when the two electrical engineering firms, Allmänna Svenska Elektriska Aktiebolaget (ASEA) and Brown Boweri & Cie (BBC) were born during Europe's industrial revolution. After pioneering advancements in electrical power transmission, rail and industrail technologies both firms merged in 1988 to create ASEA Brown Boweri (ABB). During the following three decades, ABB continued to develop industry-leading power and automation technologies. In 2020, Hitachi and ABB's Power Grids' business joined forces to establish yet a new global leader in cutting-edge digital technologies, Hitachi Energy are now advancing the world's energy system to be more sustainable, flexible and secure [1].

1.1.1 Tap-changer

A key component in the electrical grid are transformers and their transformation of electrical energy between voltage levels. An important component of the transformer is the tap-changer. It makes it possible to ensure a sufficiently stable voltage level on the power grid, by alternating the number of turns in the transformer winding and thereby changing the turns ratio in the transformer. There are two types of tap-changers, an On-Load Tap-Changer (OLTC), see Figure 1.1 and a De-Energized Tap-Changer (DETC), see Figure 1.2.

Figure 1.1: Hitachi Energy model VUCL of type OLTC [2].

Figure 1.2: Hitachi Energy DETC [3].

As the name suggests, the OLTC operates under load as the transformer is energized and the DETC can only be operated while the transformer is de-energized. The OLTC can be divided into two primary designs, the diverter design and a non diverter design. For higher voltages and power the diverter design is used. It has a diverter switch, see Figure 1.3 where the switching arc may occur in oil or in a vacuum bottle and a separate tap selector, see Figure 1.4. Arcing in vacuum reduces the need for tap-changer maintenance greatly and opens up for use of more environmentally friendly insulating fluids compared to conventional tap-changers where the arcing occurs in oil [4][5]. The non diverter switch design is used for lower voltage ratings and combines the function of the tap selector and diverter switch into a single so-called selector switch or arcing tap switch [6].

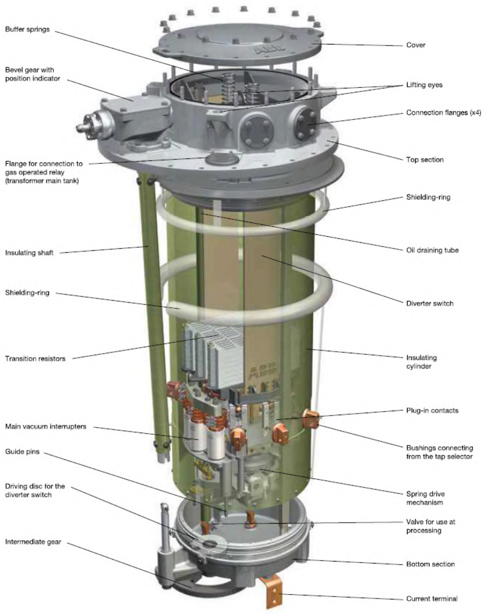

Figure 1.3: Hitachi Energy OLTC Diverter switch [7].

Figure 1.4: Hitachi Energy Tap selectors size C, ||| and F [7].

The switching principal used for the OLTC is of the type "make before brake", meaning that another tap is already selected before breaking contact with the load carrying tap. The position where two taps are connected at the same time is referred to as the "bridging position", the circulating current is limited by an impedance in this position and the switching operation from one tap to another happens very quick at roughly 50 ms to avoid heat buildup from the circulating current through the impedance [8]. The purpose with the "make before brake" switching principal is transferring load from one tap to another without interrupting the power transmission [6].

1.1.2 Surge arrester

A Surge arrester is a protective device, designed to restrict atmospheric and switching over-voltages by either discharging or redirecting the surge currents to ground. It is an essential component for increasing reliability of electricity networks, with many applications such as Air insulated substations and gas insulated substation equipment, AC and DC traction systems, High Voltage Direct Current (HVDC) protection and protection of transmission lines etc. and important for this thesis, tap changers [9][10].

The numbers of surge arresters inside of a OLTC varies depending on how they are connected and how many phases there are. The minimum amount of surge arresters corresponds to the number of protected phases, or in special cases number of forced current split paths [11]. The number of surge arresters could also be two times the number of protected phases if the surge arresters are connected to ground directly instead of over the diverter switch.

The surge arresters inside of the VUCL, see Figure 1.5 is made out of zinc oxide blocks stacked under pressure from a spring inside of a composite tube. It protects the diverter switch from atmospheric and switching overvoltages as mentioned previously and in addition also transient overvoltage that can occur in the transformer winding [11].

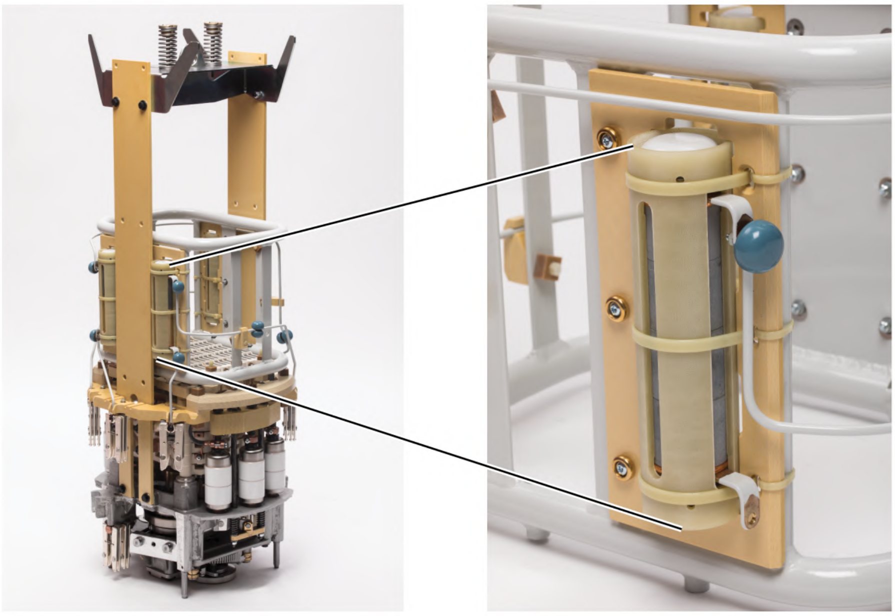

Figure 1.5: Surge arresters mounted inside Hitachi Energy's VUCL [11].

1.2 Problem identification

The OLTC is the only moving part inside of the transformer, subjected to mechanical, electric and thermal stresses simultaneously. The result of this is that tap changers are historically the main reasons of transformer failures [6], it is therefore crucial with quality assurance and constant OLTC design improvements to reduce the risk of failures.

To protect the OLTC from over-voltages from the network, surge arresters can be used. These devices consists of zinc-oxide blocks and are designed to protect electric equipment by limiting over-voltages that may occur or direct them to ground. The Hitachi Energy tap-changer model VUCL has been designed to be equipped with surge arresters placed inside the tap-changer compartment. However, another OLTC model in Hitachi Energy's product range lacks this feature due to space limitations within the diverter switch compartment, the OLTC model in question is not disclosed due to confidentiality reasons.
With that said, the task is to find a possible solution for how to mount the existing surge arresters to the tap-changer model that does not have this feature yet.

1.3 Aim

The aim with this thesis is to make a concept design of a surge arrester mounting solution for Hitachi Energy's OLTC model that does not have this feature yet. The final concept design should reuse as much as possible of the current surge arrester assembly and parts for cost saving and maintain the function and performance of the current solution.

1.4 Research questions

The following research questions will be used to guide the thesis to answer important questions.

- What are the key aspects when designing and mounting surge arresters?
- How does the mechanical, electrical and thermal stresses affect the mounting of the surge arrester and how is this designed for?
- What new factors are introduced with a new mounting location and how does these affect the surge arrester?
- Can the VUCL surge arrester assembly be used for external mounting outside the diverter switch?

1.5 Deliverables

The following items will be delivered by the end of the project.

- **Requirement specification**
  A detailed list describing the requirements with evaluation method and reference.

- **Concept designs**
  Concept design proposals including 3D CAD models. The final concept designs will be verified using evaluation methods stated in the requirement specification.

- **Cost analysis**
  A simple cost analysis including assembly, manufacturing, material and tooling costs will be carried out for the final concepts.

- **Physical prototype**
  A 3D-printed prototype will be manufactured in 1:1 scale for demonstration and to perform assembly testing.

1.6 Limitations

- For cost reasons and to reduce complexity of the task, it is desired to utilise the existing sub-assembly or components from the existing surge arrester.
- The surge arrester will still be mounted inside of the transformer tank, although it can be externally mounted from the tap changer.
- The installation of the surge arrester assembly should require no modification of the existing tap changers, major modification would require redo of general product type tests. Threaded holes and brackets are not considered major modification.
- Electrical simulations will be conducted by employees at Hitachi Energy.
- Already established specifications, requirements and regulations by Hitachi Energy will be taken into consideration and adhered to. This could for example be lists of materials approved for use in transformer oil or regulations on electric insulation levels.

1.7 Outline of report

The report has begun with a brief background about Hitachi Energy and basic knowledge about tap-changers and surge arresters that will aid the understanding of the problem at hand, which is explained more thoroughly in the problem identification chapter, followed by aim, research questions, deliverables and limitations as they serve to give more information about the overall approach of the project. This is followed by the method chapter, describing the overall process for how the problem will be solved as well as the stages more in-depth. The results chapters covers findings from the prestudy, the requirement specification, concept generation and selection phases and the final design, including requirement fulfilment, prototype, FMEA and a simple cost analysis.

2
Method

2.1 Overall process

This chapter aims to describe the processes used to conduct this project. The process is described below through a process diagram, see Figure 2.1 and is inspired by Ulrich and Eppingers approach in the book Product design and development [12].

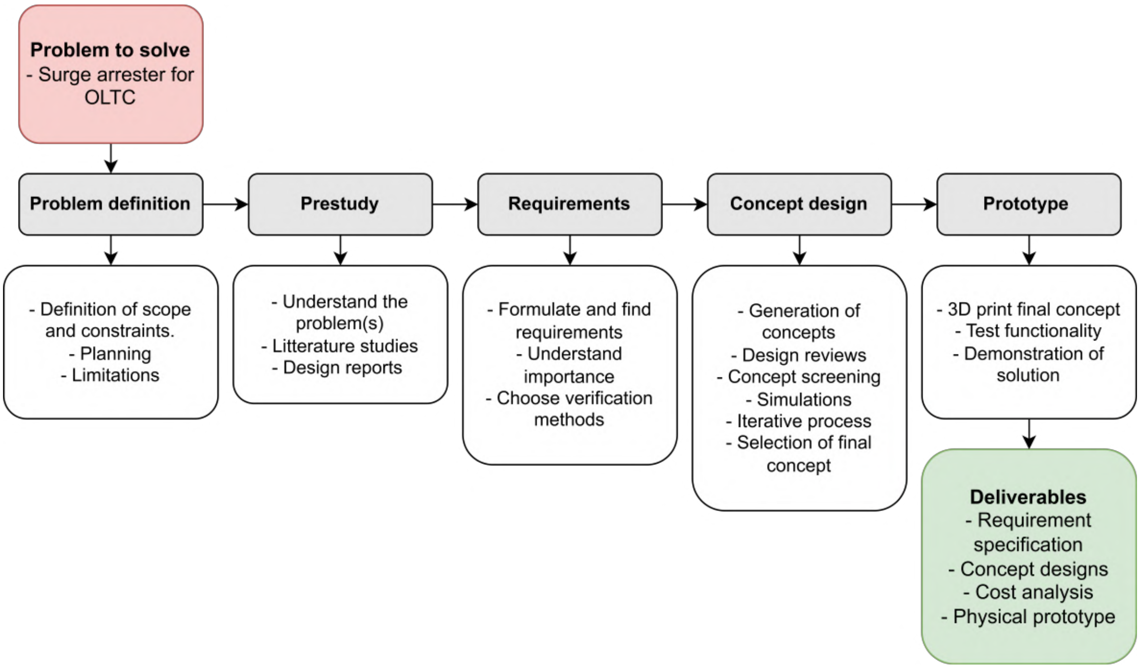

Figure 2.1: Flowchart of the process for solving the problem.

The project began with definition of scope, constraints and limitations. A plan was also made together with the supervisors at Hitachi Energy regarding support and resources from the company.

A deeper understanding of the problem(s) were thereafter achieved by doing a literature study on tap-changers and surge arresters as well as reviewing internal design reports.

The requirements for the solution was set during the next stage. The requirement specification will be used for methodical screening in the concept design phase. Technical requirements regarding performance and type testing was obtained from the

VUCL model that is equipped with surge arresters. The rest of the requirements were formulated through information from the literature study and discussions with the team at Hitachi Energy.

The purpose with the concept design phase was to end up with one final concept. This was achieved through an iterative process between idea generation and screening, where the most promising concepts were refined and the others screened out. The screening consisted of design reviews with Hitachi Energy and simulations, both mechanical and electrical.

The final concept will be manufactured through 3D printing in a 1:1 scale to demonstrate the solution and to perform the assembly process with a real tap changer to gain more knowledge about the final concept strengths and weaknesses.

2.2 Problem definition

Hitachi Energy wants to equip one of their OLTC models with an already existing surge arrester assembly from the VUCL tap changer model. The same mounting solution can however not be used due to space constraints caused by a different diverter switch housing design.

The problem to be solved is to find a new mounting solution for the surge arrester assembly that fit the OLTC model that is currently without this feature.

2.3 Prestudy

Information gathering was needed to better understand the problem and to be able to answer the research questions stated in Section 1.4.
The prestudy began with reading internal design reports about surge arresters and relevant tap-changers. Additional information was obtained through discussions with supervisors and the team at Hitachi Energy . Hands on experience was gained through a one-day internship at the assembly line for diverter switches where the assembly process of both conventional and vacuum type diverter switches was observed as well as mounting and connection of surge arrester to a VUCL diverter switch. Another important source of information was the already available CAD models of the OLTC and surge arrester. These sources combined laid the foundation for formulating the requirements and generate concept ideas.

2.4 Requirements

Ulrich and Eppinger describes "Specification" as something that *"spell out in precise, measurable detail what the product has to do"*, page 92 [12]. The requirements list helps identifying and display requirements and constraints, whom are important to consider through the development and reflection process. The requirement specification is also an important source of information for the concept selection methods.
A needs list was first created as a basis for the requirement specification. The needs list was filled with needs found from the prestudy-phase and categorised with number, subject, description and importance. Since the purpose of the needs list was to gather possible aspects of interest for the requirement specification it was more important with speed rather than accuracy.

The requirement specification was then created with the needs list as basis but broken down into it's constituent parts. The requirements specification specifies the requirement value and weight in case of wishes, evaluation method and criteria reference.
Needs of interest were further categorised with metric number, subject, description, justification, evaluation method, importance, unit and requirement value.

The following evaluation methods were set:

- **CAD**
  Requirements regarding mounting, material properties, dimensions and numbers of parts was set to be evaluated with CAD models. The built-in measuring tool and possibility to assemble and test fit concepts to already existing CAD models in Hitachi Energy's database made this evaluation method efficient.

- **Simulation**
  Simulations are quicker and cheaper alternative to real life testing, it is therefore preferred to run multiple simulations on the concepts and making sure they pass as part of the screening process and before performing any sort of real life testing and validation.

- **Type test**
  Physical observations in the form of type test are performed as the final check to make sure that the tap changer passes critical scenarios without failure, for example dielectric type tests, mechanical vibration and endurance type testing.

- **Written information**
  Material specifications and regulations etc. was found or could be found through internal documents, supplier documents and other written sources.

2.5 Concept generation overview

After the requirements had been specified, concepts could be generated. The plan was to have an iterative process with generation of concepts and design reviews with Hitachi Energy. The design reviews served as a time for discussion and reflection which often led to identification of improvements and opportunities. The concept generation was done in two stages, see Figure 2.2 and each stage will also be described in more detail below. The generation phases were separated by design reviews where the discussed improvements and opportunities were applied in the following concept generation phase. The final concept generation stage will be explained in section 2.8.

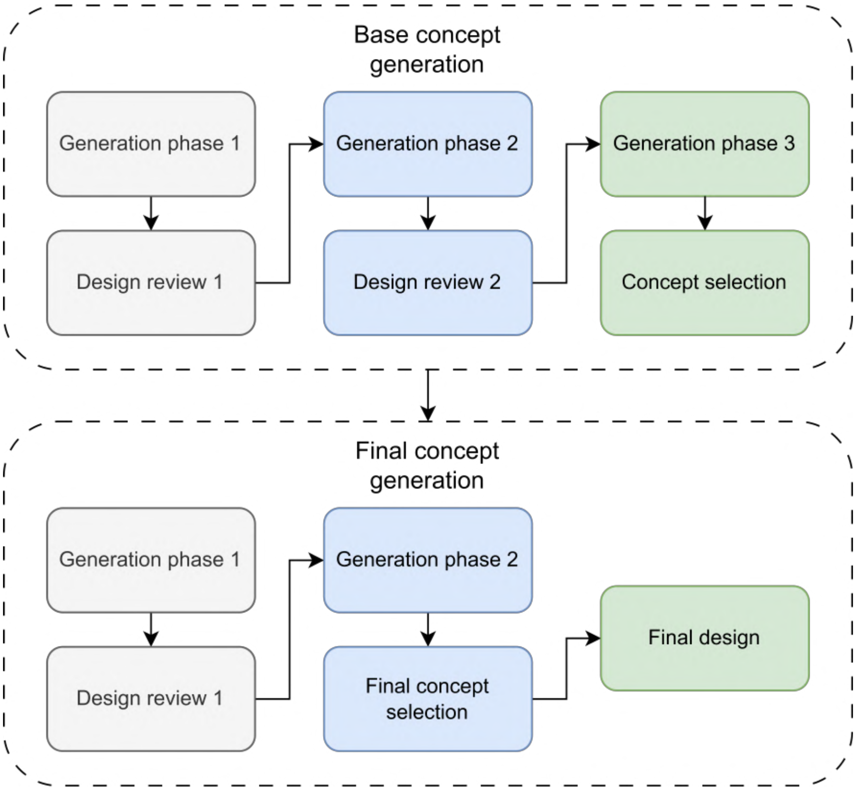

Figure 2.2: Flowchart of the concept generation approach.

2.5.1 CAD models

The concepts were made in PTC Creo Parametric, a 3D CAD system [13]. Base models for tap changers and the VUCL surge arrester assembly was provided by Hitachi Energy. The concepts were made in CAD since it enables fast editing of models with a comprehensive visual representation of the concepts. The CAD models were also used for mechanical and electrical simulation, it was therefore efficient to make the concepts directly in a compatible format with the simulation software.

2.6 Base concept generation

2.6.1 Phase 1

The focus for the first phase was to have a wide scope of concepts with the goal of capturing different types of solutions. Detail was not as important as variety in this phase since the goal was to find out from the design reviews what general type of solution could be the most promising and elaborate further on them in the upcoming phases. Another thought with presenting a variety of solutions at the design review was that it created an environment to think outside of the box and therefore not exclude any possible solutions.

2.6.2 Phase 2

Phase two consisted of redesigning and improving promising ideas from the first phase with input regarding what might work and important aspects to consider from the design review. New concepts were also created from combinations of concepts from phase 1 with input from the previous design reviews of how these concepts could be combined. The level of detail was kept on the same low level as in phase 1 to be able to output as many ideas as possible in a short period of time. The objective for the following design review was to verify and discuss if the ideas from the previous design review would be any promising in concept-state.

2.6.3 Phase 3

The focus for the third and final phase was to apply the feedback from the second design review. This meant improving the promising concepts concepts and increasing the level of detail before proceeding to the concept selection. A higher level of detail than previous phases was preferred since the chance of finding issues with concepts are greater in that case.

2.7 Concept selection

"Concept selection is an iterative process closely related to concept generation and testing. The concept screening and scoring methods help the team refine and improve the concepts, leading to one or more promising concepts upon which further testing and development activities will be focused." [12].

The funnel type approach in Figure 2.3 was used, the concept screening was mainly done through design reviews, concept scoring will be explained below and the concept testing was done with the prototype.

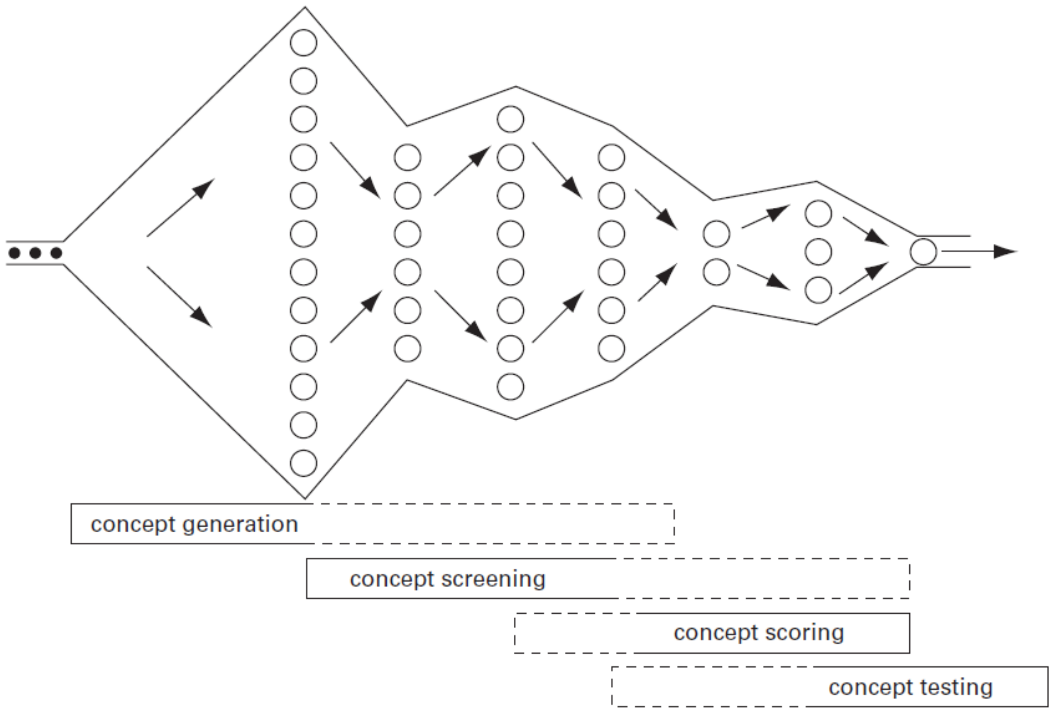

Figure 2.3: Illustration of the concept development process by Ulrich and Eppinger [12].

2.7.1 Concept scoring matrix

A concept scoring strategy inspired by Ulrich and Eppinger was used. The strategy helps identifying promising concepts quickly by eliminating the less suitable ones by comparing them to each other based on needs and requirements. The relative importance of each selection criteria is reflected by a weight and the score for each concept is the sum of the weighted rating [12]. The highest scoring concept was further developed.

The following steps are explaining the approach to setting up a scoring matrix, inspired by Ulrich and Eppingers approach[12].

Step 1: Prepare the selection matrix

- The concepts to be analysed are entered in the top of the matrix.
- The selection criteria are entered, typically from the customer needs.
- Weights are added to each selection criteria, so that the total allocates 100%.

Step 2: Rate the concepts

- Rate the concepts performance for each selection criteria on a scale of 1 to 5 where:
  - 1: Much worse than average
  - 2: Worse than average
  - 3: Average
  - 4: Better than average
  - 5: Much better than average

Step 3: Rank the concepts

- The weighted scores are calculated by multiplying the raw scores by the criteria weights
- The total score for each concept is the sum of the weighted scores
- Each concept is given a rank, highest amount of points is rank 1.

The concept that comes out on top with the highest weighted score will be investigated further with simulation and further development. If the concept ranked as number one from the concept scoring does not pass the simulation test after further development, then the concept ranked as second would be chosen instead for further development and simulation. This method was used to avoid spending time on simulation of concepts that would not be chosen as the final concept in the end, see Table 2.1 for illustration of the matrix.

Table 2.1: An empty concept scoring matrix.

		Concept									
		Concept 1		Concept 2		Concept 3		Concept 4		Concept 5	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Criteria 1	XX %										
Criteria 2	XX %										
Criteria 3	XX %										
Criteria 4	XX %										
Criteria 5	XX %										
Criteria 6	XX %										
Criteria 7	XX %										
Criteria 8	XX %										
Criteria 9	XX %										
Criteria 10	XX %										
Criteria 11	XX %										
Criteria 12	XX %										
	Total Score Rank	0	0	0	0	0	0	0	0	0	0
	Continue?										

2.7.1.1 Weights

The weights were derived from a criteria comparison matrix. Each criteria was listed both vertically and horizontally, this enables comparison between all criteria. Each horizontal criteria is compared with all vertical criteria, if the horizontal is more important, it gets a "1", if the vertical criteria is more important, it gets a "0". All points are then added together for the horizontal criteria and finally the share of total points was calculated for each criteria, which shows the importance, weight, of the criteria in relation to each other, see Table 2.2 for illustration of the matrix.

Table 2.2: An empty Weight matrix.

	Criteria 1	Criteria 2	Criteria 3	Criteria 4	Criteria 5	Criteria 6	Criteria 7	Criteria 8	Criteria 9	Criteria 10	Criteria 11	Criteria 12	Sum of points	Share of total points in % (Weight)	Ranking
Criteria 1															
Criteria 2															
Criteria 3															
Criteria 4															
Criteria 5															
Criteria 6															
Criteria 7															
Criteria 8															
Criteria 9															
Criteria 10															
Criteria 11															
Criteria 12															

2.8 Final concept generation

2.8.1 Detailed design

The highest ranking concept from the previous concept selection was further developed. The same approach using a design review between phases was used for the final concept generation as well.

2.8.2 Phase 1

New concept ideas based on the highest ranking concepts were generated. The general mounting location was still used but with different approaches on fastening of the surge arresters. This was done so that the different alternatives could be examined at the following design review, advantages and disadvantages with each alternative and possibilities for new designs were discussed.

2.8.3 Phase 2

The purpose with the second and last phase of final concept generation was to implement new ideas from the previous design review.

2.9 Final concept selection

2.9.1 Final concept scoring

The previous concept scoring matrix was used as basis, see Table 2.1, selection criteria yielding the same score across all concepts were then removed and the criteria weight recalculated in the weight matrix, see Table 2.2. The scoring matrix was redone in this fashion to make the differences between the more similar concept greater and the results easier to interpret.

2.9.2 Simulation

Electrical and mechanical simulations is part of the last steps in the concept selection process and was done on the final detailed concept in an iterative fashion since the mechanical aspects such as material and dimensions can affect electrical aspects, most importantly the Basic Insulation Level (BIL).

Electrical simulation

The electrical simulations were planned to be carried out in COMSOL Multiphysics [14] by Hitachi Energy. The final concept need to pass the electrical simulation. The most important parameter is the BIL-level which must higher than the advertised rated voltage level of the OLTC including safety factors.

Mechanical simulation

Static structural simulations were performed in Creo Parametrics built in simulation software [13]. The purpose with the mechanical simulations was to confirm that the solution for mounting and fastening of the surge arrester can handle the static forces but also impacts according to type tests.

2.10 Final design

The final modifications and refinements were done to the CAD-models as well as choosing suitable hardware and other articles needed for the assembly. This was done as preparation for both the cost analysis and prototype.

2.10.1 Prototype

The final design was made into a prototype by 3D-printing. This made it possible to demonstrate the final concept in reality and perform assembly testing.

2.10.2 FMEA

Failure Modes and Effects Analysis (FMEA) is a tool for improving product design through a structured process of investigating and quantifying possible risks associated with a design. Actions to minimise the risks can then be implemented to create a safer and more reliable solution [15].

The main component of the FMEA is the Risk Priority Number (RPN), it reflects the potential severity, likelihood of occurrence and likelihood of detection for each risk. The risk with highest RPN number is in the greatest need of attention and actions to minimise the potential harm associated with the risk.

2.10.3 Cost analysis

A simple cost analysis was conducted covering assembly, manufacturing, material and tooling costs. The simple analysis puts the final designs costs in perspective to the corresponding costs for the existing solutions in percentage, this is done to avoid disclosing actual figures due to confidentiality reasons. All costs are an estimation based on findings from the prestudy phase and should only be seen as a approximation to get an idea of how the final design ranks against the already existing solutions.

3
Results

This chapter will provide the results of this project. The results will be presented and explained thoroughly in the same order as they were described in chapter 2. Beginning with stating the final problem definition, moving on to presenting the requirements, concept generation results, concept selection and in the end, the final concept.

3.1 Problem definition

A general finding from further discussions with Hitachi Energy regarding the problem definition was that the solution needs to match or exceed the long service life of a OLTC and that it is preferred if one solution can fit all versions of the OLTC in questions, different arrangements of shielding rings outside the diverter switch housing being the most prominent difference.

With that taken into consideration, the problem definition was finalised as "*Develop a new mounting solution for fitting VUCL surge arresters to another OLTC model, the solution should fit most versions of said OLTC while retaining the performance and long service life of the VUCL installation.*"

The OLTC model that is planned to be equipped with this feature is not disclosed due to confidentiality concerns.
To ensure that the new mounting solution would retain the performance and long service life of the VUCL's mounting solutions, some key aspects were identified as:

- **Mechanical loads**
  The new solution should be able to support the weight of the surge arresters without risk of failure.
- **Electrical distances**
  The new solution should not introduce any critical dielectric distances.
- **Material compatibility**
  Used material should be compatible with the surrounding environment, i.e. heat and transformer oil.
- **Protection function**
  The surge arresters should function as intended to protect the diverter switch in case of over-voltages.

3.2 Prestudy

The topics of most interest for the prestudy were the key aspects identified during the problem formulation, these were therefore studied and the results are presented below, in-depth information can not be disclosed due to confidentiality concerns. Nonetheless, the prestudy phase gave a lot of valuable information for the understanding of the problem.

3.2.1 Mechanical loads

The most demanding requirement for the mechanical load is a vibration type test, where the mounting solution would need to be subjected to dynamic forces of 4g from different directions under 12 hours.

3.2.2 Dielectric distances

A critical dielectric distance is the minimum distance at which an electric arc, or electrical flashover does not occur between difference voltage potentials. There is no rule or fixed distances that will result in enough electrical distance between surfaces, since the distance depends on many parameters such as material, insulating fluid, voltage levels and potential differences etc. Therefore simulation is needed to determine critical dielectric distances.

3.2.3 Material compatibility

3.2.3.1 Vapour phase

Vapour phase is a drying process used to drive moisture out of an object. This is done by isolating the object at high temperatures, above 100 °C and in vacuum for a few days. This might have influence on material properties and will therefore need to be checked accordingly.

3.2.3.2 Oil compatibility test

Since the OLTC is submerged in transformer oil, it is important that the materials used are compatible with the transformer oil. To test the compatibility of a material and transformer oil, the material is exposed to the oil at a certain temperature under a fixed amount of days. The ratio of material to oil is higher than it is in the planned use case. Properties of either the material or the oil can then be measured from which a difference calculated from before and after the test, a material or oil has passed if the difference is within predefined limits.

3.2.4 Electric protection function

The in-depth information can not be disclosed due to confidentiality reasons. But the protection function, i.e. diverting overvoltages to ground, of the surge arresters will remain as long as critical electric distances are not introduced in combination with a similar mounting environment as the VUCL surge arrester is mounted in.

3.2.5 Findings from CAD models

3.2.5.1 VUCL

The prestudy began with analysing the mounting solution for the VUCL, as can be seen in Figure 3.1.

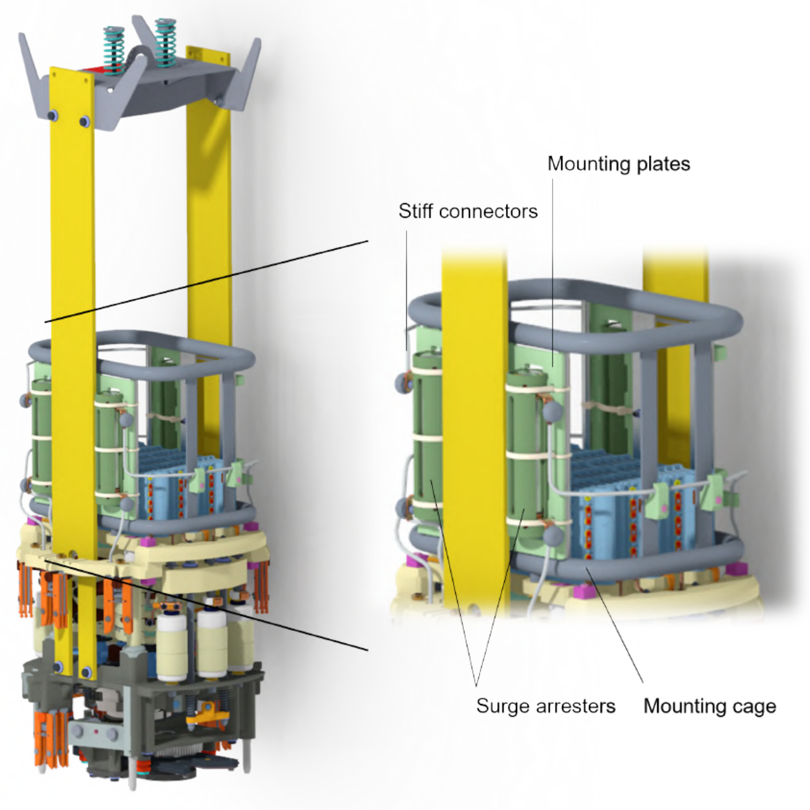

Figure 3.1: Hitachi Energy VUCL with surge arresters mounted on the diverter switch.

The topics of interest were primarily:

- How are the surge arresters mounted?
- What benefits does this mounting solution have?
- What drawbacks does this mounting solution have?
- How are the surge arresters connected electrically?

How the surge arresters are mounted

The surge arresters are each mounted to a composite plate with three cable ties. The purpose with the cable ties is only to keep the surge arresters from moving horizontally, the majority of the weight is carried by the cut out in the plate. The plates are then secured to a steel cage by three screws and three cable ties. The cage is fastened to the diverter switch with four screws.

Benefits with the mounting solution

- **Serviceability**
  If needed, the possibility of inspection and replacement of the surge arresters is easily performed since the diverter switch can be lifted out of the housing and transformer tank at site. Inspection is then easy thanks to the arrangement and space around the surge arresters. Disassembly requires no special tools and can be performed without further disassembly of the diverter switch itself.

- **Assembly** The surge arresters are easy to install at the production line thanks to easy access. In addition it does not interfere with assembly for other Original Equipment Manufacturers (OEM) manufacturers such as Hitachi Energy Transformers since the outside of the OLTC stays the same, regardless if it is equipped with surge arresters or not.

Drawbacks with the mounting solution

The main drawback with the mounting solution is that it only fits the VUCL model, and a similar concept with minor changes can not be used due to problems with BIL-levels in the OLTC of interest for this thesis. Another drawback is regarding the electrical connection, it can be challenging to install the mechanically stiff conductor due to a high number of sharp bends in some of them.

Electrical connection

The surge arresters are connected over the diverter switch, from one side of the plug-in contact to the corresponding one on the other side. This is done with mechanically stiff conductors, six in total. The conductors are attached to the surge arresters with a screw connection, where the screw head is covered with a shielding ring for covering sharp edges and distributing the electrical field.

3.2.5.2 OLTC

This is the OLTC of interest for the thesis. The purpose with the analysis of these CAD models was to investigate possible areas of both the diverter switch housing, Figure 3.2 and diverter switch, Figure 3.3 where the surge arresters could possibly be mounted.

Figure 3.2: The OLTC Diverter switch housing.

The locations of interest for a solution were concluded to be between the top shielding ring, marked in Figure 3.2, and the casting for the bottom section of the housing.

Through discussions with Hitachi Energy, it was clear that the top section of the diverter switch housing is not suitable to use since it is grounded, which means that critical dielectric distances will be introduced due to the high voltage potential difference. The area underneath the diverter switch housing was also ruled out since the Tap selector uses all that available space in some combinations of variants. The locations of interest for a solution were concluded to be between the top shielding ring, light grey in Figure 3.2, and the casting for the bottom section of the housing. This part of the housing has some interesting areas for mounting, the casting could for example be modified with drilled and tapped holes for mounting of the surge arresters as well as the possibility to utilise the contacts for the tap selector. For nomenclature, please see Figure 1.3.

The OLTC diverter switch itself was also investigated, see Figure 3.3. It was concluded that there is not enough space between the diverter switch and the bottom section of the housing to mount the surge arresters below the diverter switch. This mounting location would also subject the surge arrester to metallic debris from contact wear during diverter switch operation, which is preferably avoided since the electrical protection function over time is unknown in an environment with larger amounts of metallic debris than usual. The same reasoning with distance to the top section as for the housing applies here, the critical dielectrical distance is exceeded if the surge arresters would be placed standing or laying down on top of the resistor packs, which would have been the most obvious solution, and very similar to that in the VUCL, see Figure 3.1.

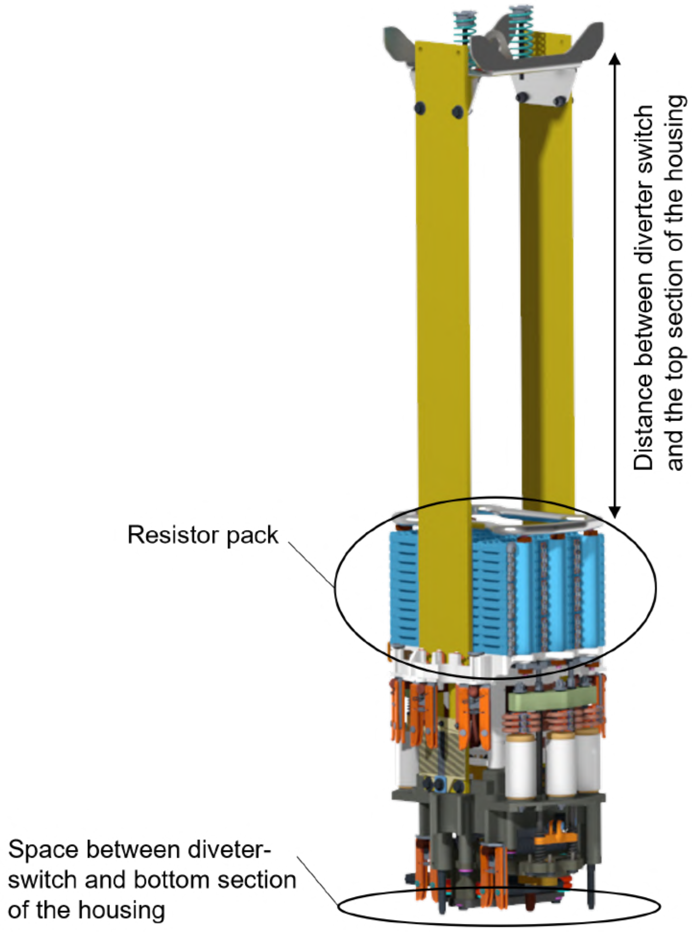

Figure 3.3: The OLTC Diverter switch.

3.2.5.3 Surge arrester

Figure 3.4 shows the surge arrester without the mounting plate and cable ties. The most important factor to consider while developing a new mounting solution is the size of the surge arrester, it measures 229.5 mm tall and 60 mm in diameter, excluding the connection tabs. The mass is about 2,8 kg. From discussion with Hitachi Energy, it was found that it is possible to re-design the connection tabs or create entirely new connection points for more placement and mounting freedom. The outside of the housing can also be modified, as long as the structural integrity is kept.

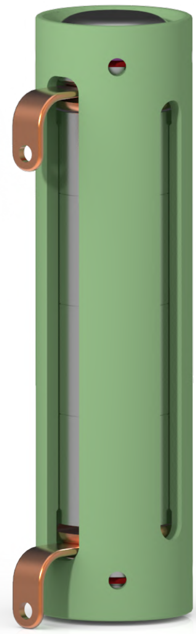

Figure 3.4: The base surge arrester model.

3.2.6 Prestudy conclusion

The prestudy gave valuable information about the OLTC and surge arrester. Requirements about mechanical loads and dielectric distances were found. Findings were also done regarding material compatibility in vapour phase and oil compatibility. This information was important for the requirement specification and concept generation and selection phases. The analysis of the existing solution for the VUCL OLTC model gave a deeper understanding of the surge arrester mounting solution including benefits and drawbacks with the solution and the electrical connection. The OLTC to be equipped with surge arresters was also studied, both the outside of the OLTC diverter switch housing, see Figure 3.2 and the OLTC diverter switch itself, see Figure 3.3. The primary topic of interest were to find and investigate possible areas where the surge arresters could be mounted and reject locations where it is obvious that installation would not work. Two main areas of interest were found as mounting locations as can be seen in Figure 3.2. The surge arrester was also studied, aside from size and weight, an important finding was that the connection points can be redesigned for more mounting freedom.

3.3 Requirements

3.3.1 Needs list

The final needs list can be seen in Table 3.1. The needs were obtained through findings in the prestudy phase, see section 3.2 and through discussions with Hitachi Energy. The importance level of the needs were also derived from discussions with Hitachi Energy. The scale is 1 to 5, where 1 corresponds to an not so important need and 5 means that the need is very important to fulfil. The purpose with the needs list was to find and organise the needs that the final concept aims to fulfil and also to serve as a basis for the requirements specification.

Table 3.1: The needs list.

No.	Subject	Need	Importance
1	Performance	The surge arrester fulfills the electric protecting function on the correct voltage levels	5
2	Performance	Surge arrester performance is not affected by mounting environment	5
3	Performance	Mounting components fulfills requirements on mechanical loads	5
4	Performance	Mounting location does not introduce critical dielectric distances	5
5	Availability	The same mounting solution should fit all three types of tap selectors (C, III, F)	3
6	Installation	Installation of surge arresters should not require major modification of the existing tap changers (threaded holes ok)	4
7	Installation	Installation should be possible to perform for existing units at site	2
8	Material	Materials used are compatible with surronding oil and temperature changes over at least 30 years	5
9	Material	Reuse as much as possible of the current surge arrester assembly and parts for cost saving	3
10	Regulations	Internal and external requirements and regulations should be adhered to	5
11	Type test	The solution should be designed to pass the mechanical vibration test "1ZSC028354_Test specification of mechanical vibration test on VUCL Sugre arresters"	5
12	Type test	The solution should be designed to pass the dielectrical type test "1ZSC028341_Test specification of dielectric type test on VUCL with surge arresters"	5
13	Type test	The solution should be designed to pass the mechanical endurance test "1ZSC028688_Test specification - Mechanical endurance test on VUCL with surge arresters"	5
14	Visual	Apperence of the solution should look robust and fit the apperance of the OLTC	2

3.3.2 Requirements specification

The requirements list is essentially the needs list broken down into it's constituent parts and can be seen in Table 3.2.

Table 3.2: The requirements specification.

#	Criteria	Requirement value	Req/ Wish	Weight	Evaluation Method	Reference
	Performance					
R1	Mounting components fulfills requirements on mechanical loads	> 4g	R		Simulation	R&D
R2	Mounting location does not introduce critical dielectric distances		R		Simulation	R&D
R3	Surge arrester performance is not affected by mounting environment		R		Simulation	R&D
R4	The surge arrester system fulfills the protecting function on the correct voltage levels		R		Theoretical	R&D
	Type test					
R5	The solution should be designed to pass the dielectrical type test "1ZSC028341_Test specification of dielectric type test on VUCL with surge arresters"		R		Type test	Standard
R6	The solution should be designed to pass the mechanical endurance test "1ZSC028688_Test specification - Mechanical endurance test on VUCL with surge arresters"		R		Type test	Standard
R7	The solution should be designed to pass the mechanical vibration test "1ZSC028354_Test specification of mechanical vibration test on VUCL Sugre arresters"		R		Type test	Standard
	Assembly					
R8	Few special tools for assembly and maintenance/inspection	< 5 tools	R		CAD	Manufacturing
		< 2 tools	W	4		
R9	Minimal interaction needed from other OEM business	< 10 operations	R		CAD	Manufacturing
		< 2 operations	W	3		
R10	Number of different parts should be limited	< 20 parts	R		CAD	Manufacturing
		< 5 parts	W	3		
R11	Should fit all three types of Hitachi Energy tap selectors (C, III, F)		R		CAD	Manufacturing
R12	The installation of surge arresters requires ____ modification of the existing OLTC	< Major*	R		CAD	Manufacturing
		< Minor*	W	4		
	Material					
R13	Materials used are compatible with temperature changes from -40 to +115 °C over at least 30 years		R		Lists	Standard
R14	No use of forbidden or non-qualified materials		R		Lists	Standard
R15	Reuse as much as possible of the current surge arrester assembly and parts	> 50% in weight	R		Lists	Product planning
		> 75% in weight	W	3	Lists	
R16	Reuse materiels with known vapour phase compatibility	> 75% of total weight	R		Lists	Product planning
		100% of total weight	W	4	Lists	
R17	Reuse materials with known oil compatibility	> 75% of total weight	R		Lists	Product planning
		100% of total weight	W	4	Lists	
R18	Use materials compatible with different types of oils and esters	> 25% of total weight	R		OEM info	Product planning
		75% of total weight	W	3		
	Regulations					
R19	The solution should adhere to internal and external requirements and regulations		R		Examination	Standards
	Maintenance					
R20	Inspection interval	> interval of OLTC	R		Endurance Type test	Customer
		> 2 * interval of OLTC	W	4		
R21	Maintenance	> interval of OLTC	R		Endurance Type test	Customer
		> 2 * interval of OLTC	W	4		

The criteria are divided into six categories, Performance, Type test, Assembly, Material, Regulations and Maintenance for an easy overview. The performance and type test criteria must all be fulfilled with evaluation methods simulation and type tests, failure of fulfilment could lead to damaged equipment and expensive faults.

The assembly category is the requirements and wishes on tooling, operations and parts for assembling the final concept and fitting it to the OLTC. These are quite self explanatory except R9 "Minimal interaction from other OEM business" and R12 "The installation of surge arresters requires Major/Minor modification of existing OLTC". Minimal interaction from other OEM business means that other original equipment manufacturers such as Hitachi Energy Transformers, who uses OLTC's in their transformers can be needed to, for example, disassemble and later reassemble parts of a surge arresters system during the installation process of a OLTC if the surge arresters are interfering in one step of the process. Regarding R12, Major modification means changes implemented so large that the type tests R5,6 and 7 will have to be redone, which is costly and time consuming. Minor modifications covers changes of the OLTC that can be implemented without having to redo all type tests such as drilling and tapping holes for mounting. If a modification is major or minor will be evaluated by an expert within the area.

For the material section, the most common evaluation method is information from lists, the main concern is that the material used must be compatible with the surrounding environment consisting of temperature changes and submersion in oil over the span of at least 30 years.
Regulations set either internally by Hitachi Energy, by customers or governments are crucial to follow. Non-compliance could lead to no sales and business of OLTC's equipped with surge arresters before the regulations are met.

Inspection and maintenance intervals is the duration of time between between an either visual or mechanical inspection, which could consist of measuring resistance or similar for a health check of the surge arresters. Maintenance interval is the time period between the need of replacing or performing maintenance to the surge arresters. In theory, the surge arresters should not need any inspection and maintenance, since they are rarely used and does not contain any moving parts, it would however be good practice to perform an inspection of the surge arresters if the opportunity arises, as a proactive safety measure.

3.4 Concept generation

Three phases of concept generation was done to end up with five concepts for the next stage, concept selection. This section will showcase the concepts in each phase and explain the thinking and reasoning behind them. The discussions about improvements and opportunities from the design reviews and how these were implemented in the following concept generation phase will also be covered.

3.4.1 Phase 1

3.4.1.1 Alternative 1

This concept utilises the complete surge arrester assembly used in the VUCL OLTC model, see Figure 3.1. The composite plates are stacked on top of each other as can be seen in Figure 3.5. They are stacked vertically on the long side of the plate so that the surge arrester assembly is as close to the cylindrical body of the OLTC as possible while also being compact in regards to height, keeping the highest point below the lower shielding ring. The concept aims to keep the footprint of the OLTC the same, seen from the top sections perspective, since mounting of the OLTC to the transformer tank will be difficult if the surge arresters sticks out further than the mounting flange of the top section. This concept does not interfere with the Tap selector contacts, see Figure 1.1 for cable routing to the tap selector.

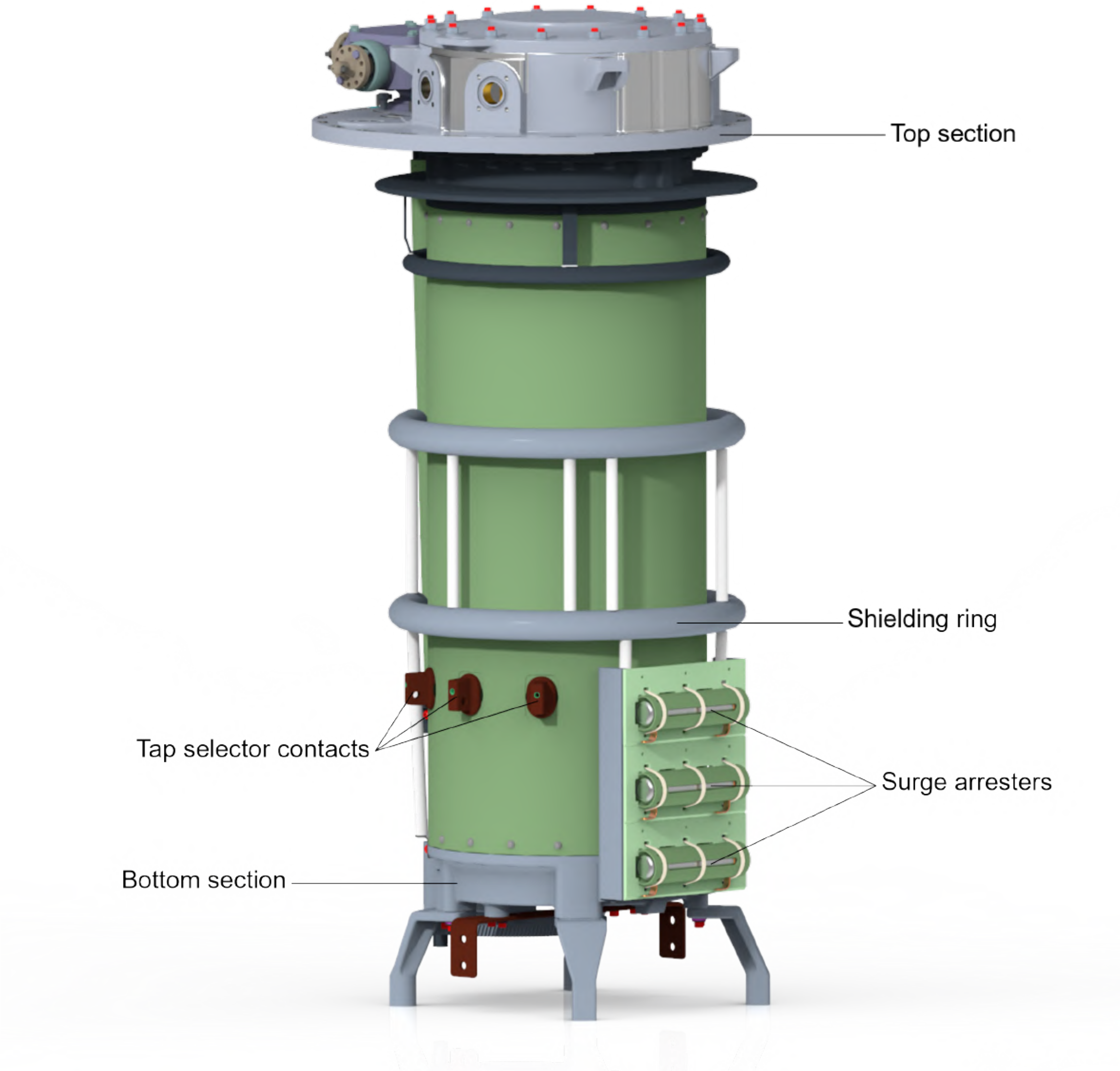

Figure 3.5: Concept "Alternative 1" mounted on OLTC.

The holder, "Alternative 1", is shown above in Figure 3.6. The thought behind the concept was to keep it simple but show the general idea of how the surge arresters could be mounted as basis for discussion at the design review. The concept is supposed to be mounted to the OLTC by drilling and threading holes in the casted bottom section of the OLTC and then use four screws to secure the holder to the OLTC.

Figure 3.6: Concept "Alternative 1".

Feedback from design review

The approach with drilling and tapping the casted bottom section could work since there is a lot of material in the bottom section. The main issue with this arrangement of the surge arresters is the connection to the OLTC. Each end of the surge arrester needs to be connected to a separate tap selector contact for the electrical protection function to work properly. This means that the arrangement of connectors from the surge arresters to corresponding tap selector contacts would be complicated and not ideal. Concept "Alternative 1" will not be developed further.

3.4.1.2 Alternative 2

This alternative is mounted in a similar position to "Alternative 1", the concepts are however different in the arrangement of the surge arresters as Figure 3.7 shows. As with "Alternative 1", the whole surge arrester assembly from the VUCL is utilised, but "Alternative 2" has a standing arrangement of surge arresters instead along the cylindrical body of the OLTC. This concept has a lower total height then "Alternative 1" but is a bit wider, so it has more interference with the tap selector contacts, see Figure 1.1 for cable routing. The same reasoning with foot print is applicable to this solution, hence the curve in the holder so that the surge arresters stay as close as possible to the body of the OLTC.

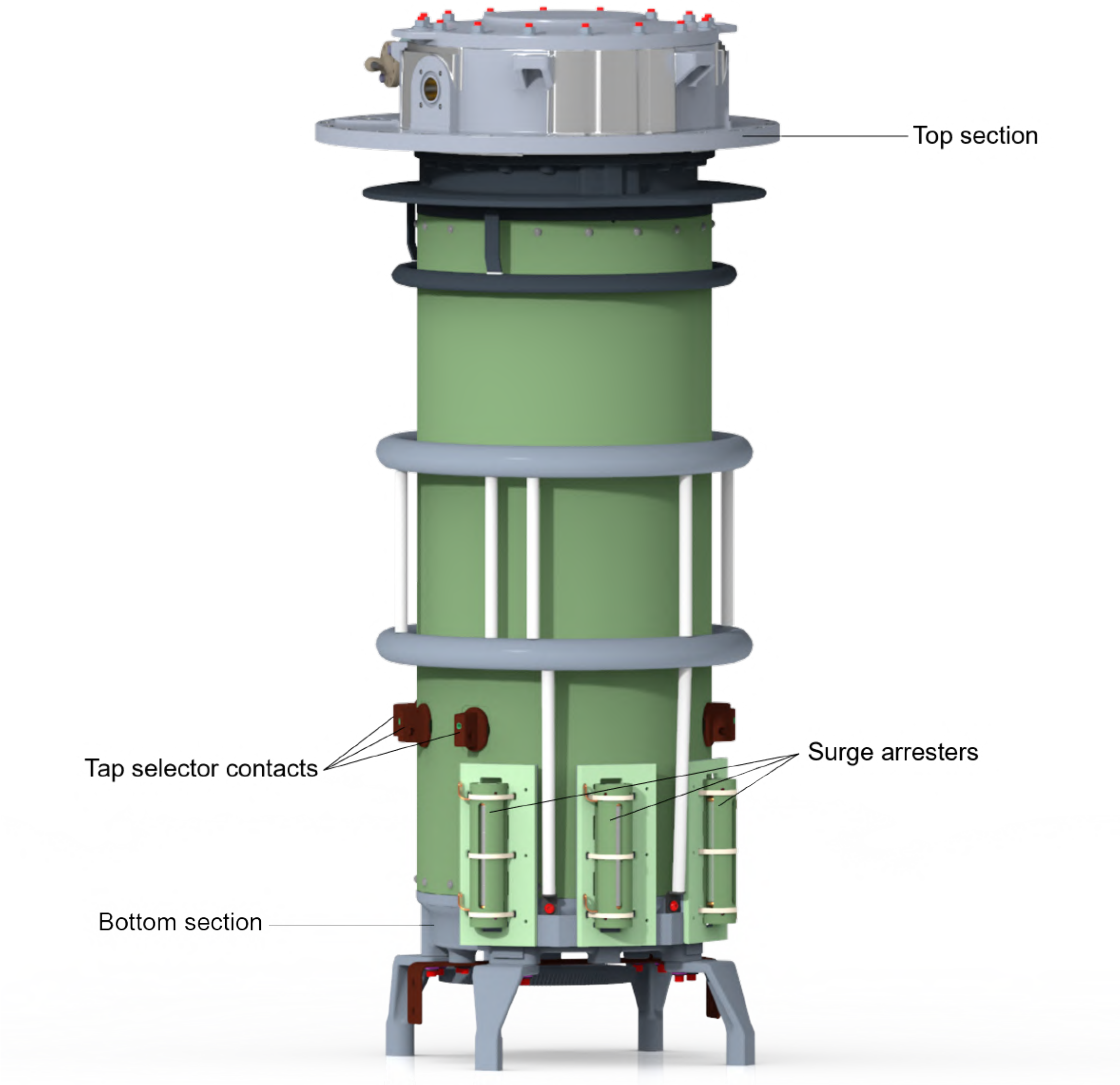

Figure 3.7: Concept "Alternative 2" mounted on OLTC.

The holder for "Alternative 2" is shown in Figure 3.8. The thought behind the concept was to keep it simple but show the general idea of how the surge arresters could be mounted as basis for discussion at the design review. The concept is supposed to be mounted to the OLTC by drilling and threading holes in the casted bottom section of the OLTC and then use four screws to secure the holder to the OLTC.

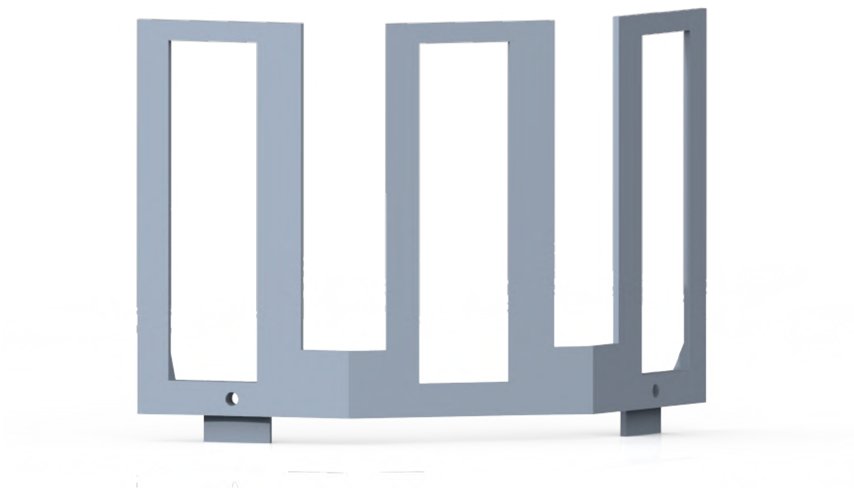

Figure 3.8: Concept "Alternative 2".

Feedback from design review
Similar feedback as with concept "Alternative 1", meaning that mounting to the bottom section would work by drilling and tapping the casting and then use screws to fasten it. The main issue being the routing of the cables in this case as well, even more troublesome for "Alternative 2" since it will require even longer connectors to reach the tap selector contacts on the right side in Figure 3.7. Concept "Alternative 2" will therefore not be developed further.

3.4.1.3 Alternative 3

This solution is a bit different from the two previous alternatives since it makes use of already existing holes in the legs as attachment points as can be seen in Figure 3.9. The whole assembly including composite plate is used for simplicity for this proof of concept. The surge arrester assemblies are stacked laying flat, resulting in the lowest height yet, but with a large protrusion outwards, extending beyond the footprint of the top section, which would result in difficulties mounting. Nevertheless, the concept worked great as discussion material at the design review.

Figure 3.9: Concept "Alternative 3" mounted on OLTC.

Figure 3.10 shows a close up of concept "Alternative 3". As with the previous concepts, the thought was to keep it simple and illustrate roughly how a solution could look. This solution would not require modification to the OLTC since existing holes are utilised with a nut and bolt fastening approach. The surge arresters are then stacked in the rack on top of each other, no fastening mechanism has been designed, deemed not necessary in this phase.

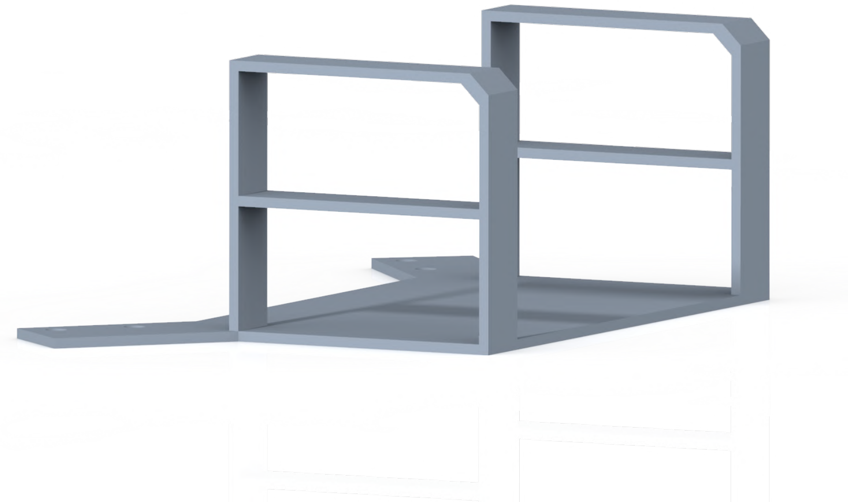

Figure 3.10: Concept "Alternative 3".

Conclusions from design review
As previously mentioned, this concept made for interesting discussions and findings at the design review. The result from the design review was that "Alternative 3" will be developed further.
The following updates and alternatives will be investigated in the next concept generation phase:
- Mount the holder on the opposite side of the tap changer, where the insulating shaft is, this could open up the opportunity for staying within the footprint of the top section, see Figure 1.1 for how the top section is not centred with the cylindrical body of the OLTC.
- Do not utilise the legs as mounting location, these are not always included depending on tap selector model.
- Make the holder smaller by excluding the VUCL surge arrester mounting plate, keep only the surge arrester itself.
- Investigate possibility to mount custom shielding ring, if it will be relevant in the future to avoid arcing.

3.4.1.4 Alternative 4

The idea with "Alternative 4" was to test something different from the other concepts. The surge arresters are placed higher up then previously, between the shielding rings. As shown in Figure 3.11, the surge arresters are not connected to the OLTC by a holder, this was due to uncertainties about if the placement would work since it is closer to the top section which is grounded, which might introduce critical dielectric distances, but the model was accurate enough to illustrate the general idea and serve as discussion material at the design review.

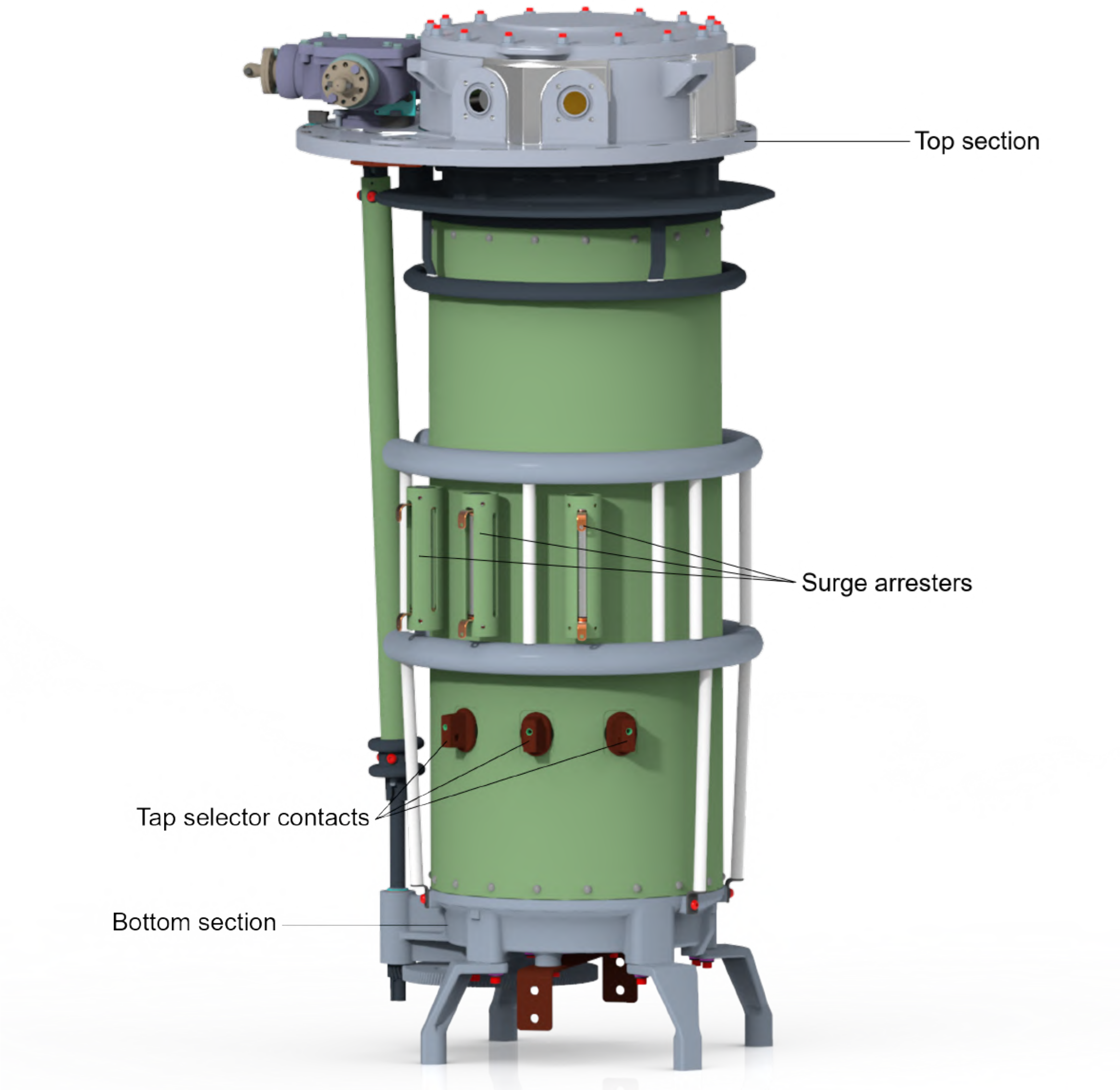

Figure 3.11: Concept "Alternative 4" mounted on OLTC.

Conclusions from design review
As suspected, the surge arresters are probably to close to the top section, introducing risk of flashovers. The general idea was however interesting, so a plan was made to move the surge arresters downwards and place them underneath the tap selector contact, in between the contacts and the bottom section. The surge arresters can then be connected between the tap selector contacts and the bottom section, six surge arresters are then needed to protect three phases since the connection is between the potential and ground instead of "over" the OLTC diverter switch like previous concepts.

3.4.1.5 Design review summary of phase 1

Concepts "Alternative 1" and "Alternative 2" will not be developed further due to both of them requiring troublesome electrical connection from a technical and practical point of view.

Concepts "Alternative 3" and "Alternative 4" will be developed further with the following updates.

Alternative 3
- Mount the holder on the opposite side of the tap changer, where the insulating shaft is, this could open up the opportunity for staying within the footprint of the top section, see Figure 1.1 for how the top section is not centred with the cylindrical body of the OLTC.
- Do not utilise the legs as mounting location, these are not always included depending on tap selector model.
- Make the holder smaller by excluding the VUCL surge arrester mounting plate, keep only the surge arrester itself.
- Investigate possibility to mount custom shielding ring, if it will be relevant in the future to avoid arcing.

Alternative 4
- Keep the same layout of the surge arresters but place them between the tap selector contacts and bottom section
- Six surge arresters are then needed instead of three, since the electrical connection will be between potential and ground instead of "over" the diverter switch.

New concept
Create a new concept where the surge arresters are mounted internally, below the resistor packs.

3.4.2 Phase 2

3.4.2.1 BackPack

The result after modifying concept "Alternative 3" can be seen in Figure 3.12.

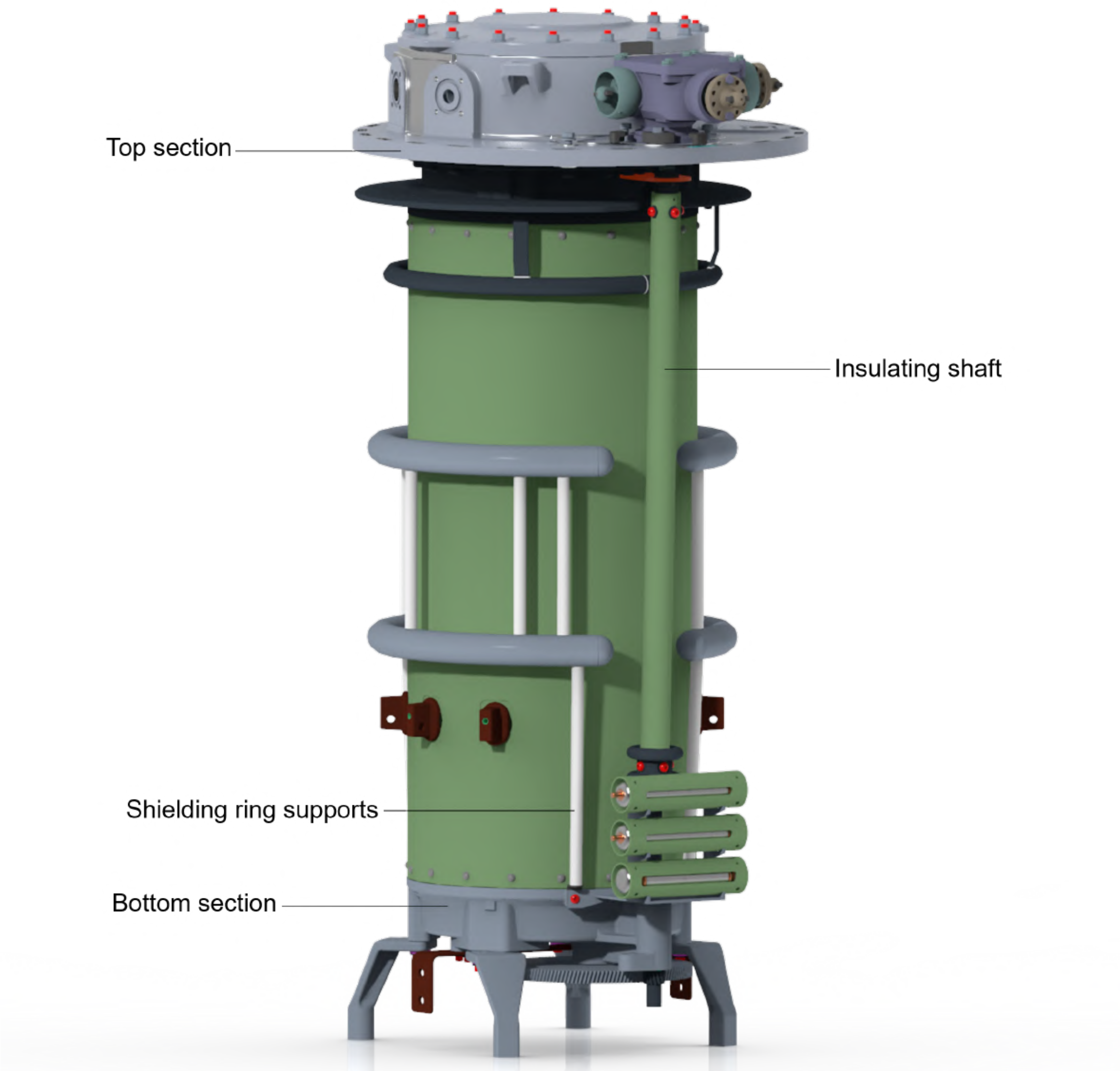

Figure 3.12: Concept "BackPack" mounted on OLTC.

The modifications were based on the discussion from the design review in the previous concept generation phase. The implemented changes were the following:
- The holder, Figure 3.13, was mounted on the opposite side of the OLTC, outside of the insulating shaft. This placed the surge arresters and holder inside of the top section's footprint which is preferred since mounting of the OLTC to the transformer tank will be easier if the OLTC can be lowered straight down into the transformer.
- The other implemented change from the design review was to exclude the mounting plates for the surge arresters, this aided the process of making the holder more compact.
- Since the legs used in "Alternative 3" is not always used, another solution was found, utilising the fastening points for the shielding ring supports. The bottom sections guide for the insulating shaft was used as support from underneath the holder for carrying the load of the surge arresters in the vertical direction.

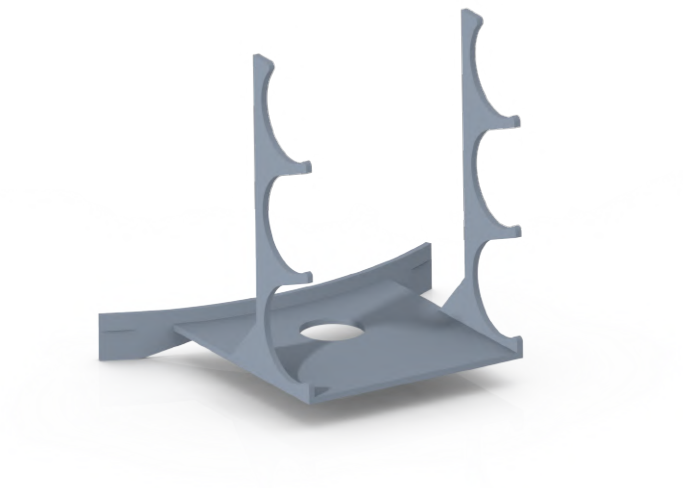

Figure 3.13: Close-up of concept "BackPack".

There are cut outs for each surge arrester at an angle to provide a secure fitment by reducing the risk of surge arresters "falling" out of the holder as can be seen in Figure 3.13. This concept lacks fixation of the surge arresters in vertical and side directions as well as rotation.

The standard surge arrester is modified with the connection points in the end instead of along the side, see Figure 1.5 for the standard surge arrester and Figure 3.14 for the modified variant that will be used in the upcoming concepts.

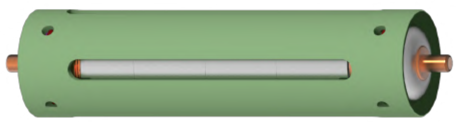

Figure 3.14: Modified surge arrester with new electrical connectors.

Conclusions from the design review

This concept will be developed further with fixation for rotation and movement of the surge arrester. A possible downside with this concept is that the electrical connection and routing would have to be done by the customer and or OEM.

3.4.2.2 Resistor Sandwich

This is a new concept idea from the first phase design review. Instead of mounting the surge arresters on the outside of the OLTC as in previous concepts, the surge arresters are mounted on the inside, on the diverter switch.

The surge arresters are placed horizontally underneath the resistor plates as can be seen in Figure 3.15. This solution has some advantages being on the inside of the OLTC, the first one being that the electrical connection is simple since the surge arresters can be connected directly to the plug in contacts, only requiring a short and simple connector. Another advantage being that it can be completely assembled at the diverter switch assembly station, requiring no interaction from other OEM's or customers.

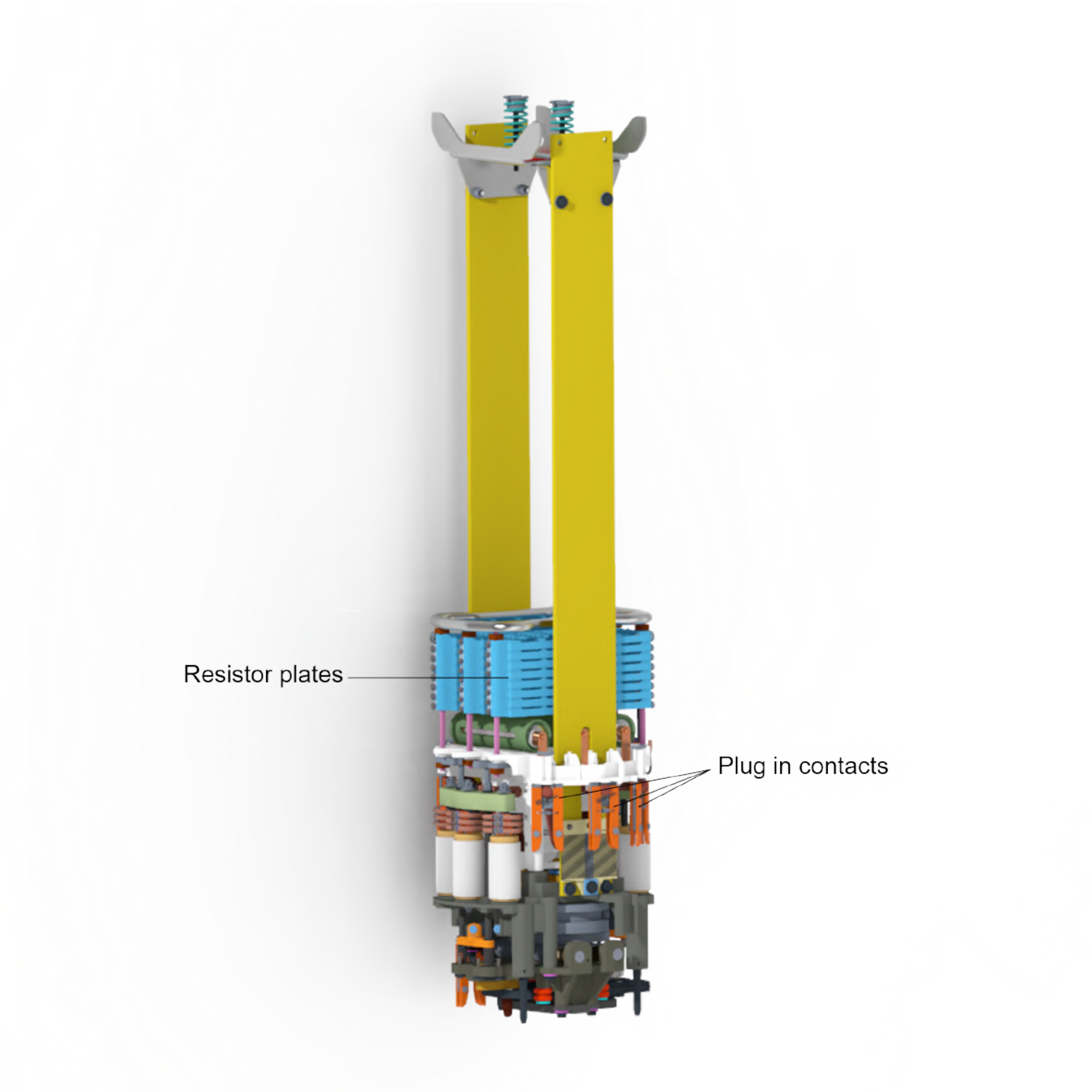

Figure 3.15: Concept "Resistor Sandwich" mounted inside of the OLTC.

In Figure 3.16 we can see the straight forward electrical connection more clearly. This figure also shows the redesigned surge arrester with the connections on the ends of the surge arresters rather than along the side as Hitachi Energy's VUCL surge arrester is set up today.

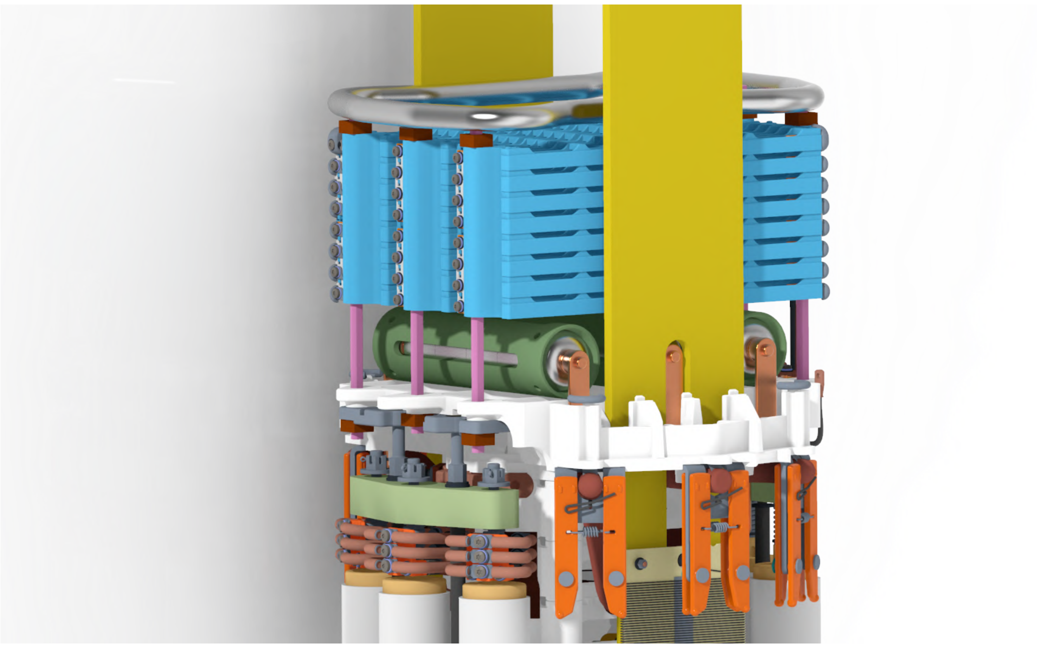

Figure 3.16: Close-up of concept "Resistor Sandwich".

Conclusions from design review
Resistor Sandwich is a promising concept given the simple design that should require few parts and no interaction from OEM's or the customer. It needs to be further developed with some sort of fixture to lock rotation and movement.

3.4.2.3 SixStanding

Concept "SixStanding" is a further development of concept "Alternative 4" from the first concept generation phase, see Figures 3.17 and 3.18 .

Figure 3.17: Concept "SixStanding" mounted on OLTC.

The implementations and updates made from the previous design review on concept "Alternative 4" are mainly that the surge arresters are moved from the shielding rings down to underneath the tap selector contacts, this enables the surge arresters to hang from the tap selector contacts, therefore being both mechanically and electrically connected to the tap selector contacts. The other side of the surge arresters are connected to the bottom section of the OLTC mechanically and electrically through rigid copper rods and plates. The tap selector contacts would have to be modified so that the surge arresters can be fastened in the vertical direction while the lower connections holds the surge arresters still in the horizontal plane.

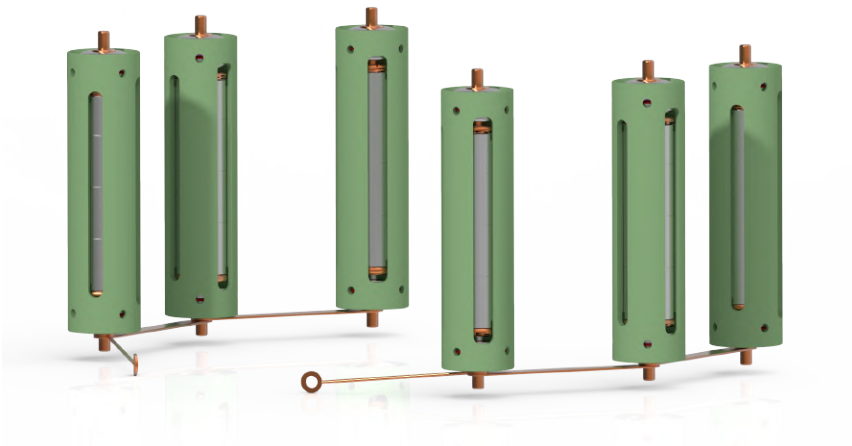

Figure 3.18: Close-up of concept "SixStanding".

All six surge arresters and the lower connection rods and plates can be clearly seen in Figure 3.18. The connection is a series connection and ties in into the factory mounting for the shielding ring legs as can be seen in Figure 3.17.

Conclusions from design review
Interesting concept that will need a sturdier solution for the bottom connection points to handle vibrations better. The tap selector contacts seen i Figure 3.17 can be modified slightly if that helps with location and installation of the surge arresters.

3.4.2.4 Design review summary of phase 2

All concepts will be continued with further development, mostly regarding locking movement and rotation. A new concept will also be generated, it will try to locate the surge arresters around the outside of the diverter switch inside of the housing, which will be a challenge due to space limitations, but it needs to be tested so that an opportunity is not missed.

3.4.3 Phase 3

3.4.3.1 BackPack

No major changes has been implemented to concept "BackPack" in the third phase. The change implemented was a locking system so that the surge arresters are unable to move and rotate, see Figure 3.19. The locking system consists of tabs that fits perfectly into the grooves of the surge arresters, this locks rotation and movement in all directions. Cable ties are used for securing the surge arresters in dynamic situations with mechanical vibrations, that are present while operating the OLTC.

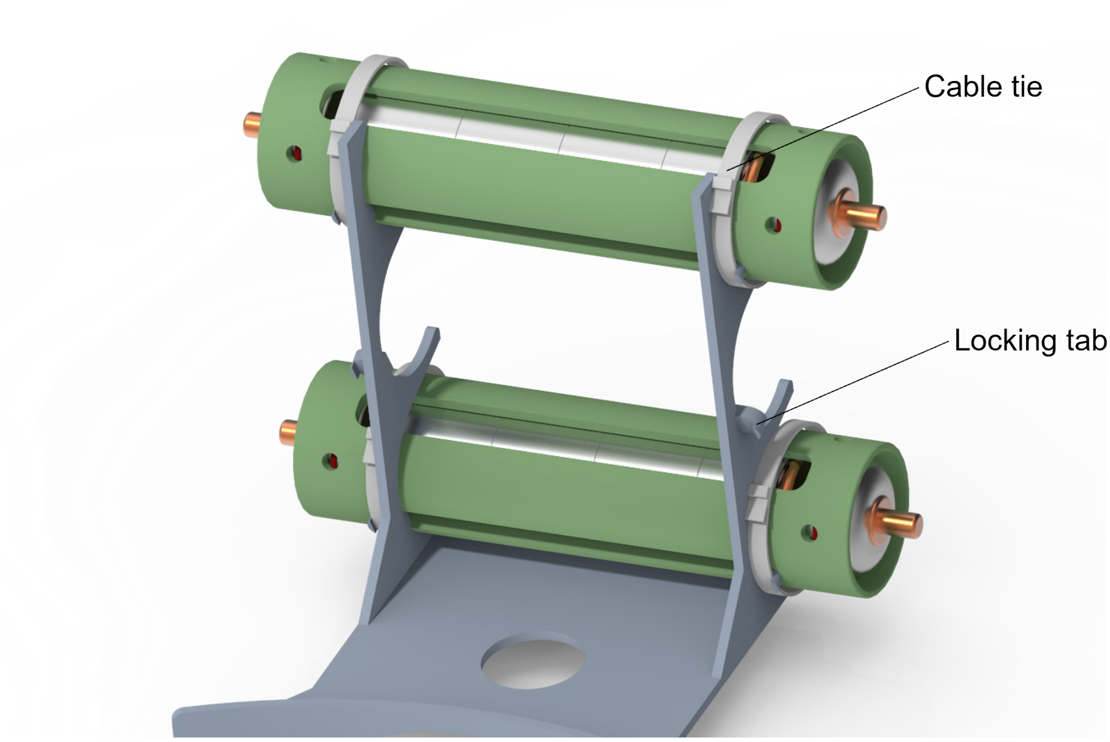

Figure 3.19: Close-up on updated concept "BackPack".

3.4.3.2 Internal Bottom

This concept idea was born at the design review in phase two and puts the surge arresters between the bottom section and tap selector contacts which is familiar from "SixStanding", but on the inside of the OLTC housing instead of on the outside, see Figure 3.20. It shares the same advantage as "Resistor Sandwich" with not being visible or affecting the outside of the OLTC, meaning that this solution could be completely assembled in the tap changer factory, requiring no interaction from other OEM's. The ease of inspection and serviceability once installed is poor compared to "Resistor Sandwich" since the surge arresters will stay attached to the bottom section even though the diverter switch is lifted out of the OLTC for inspection or service at the customers site.

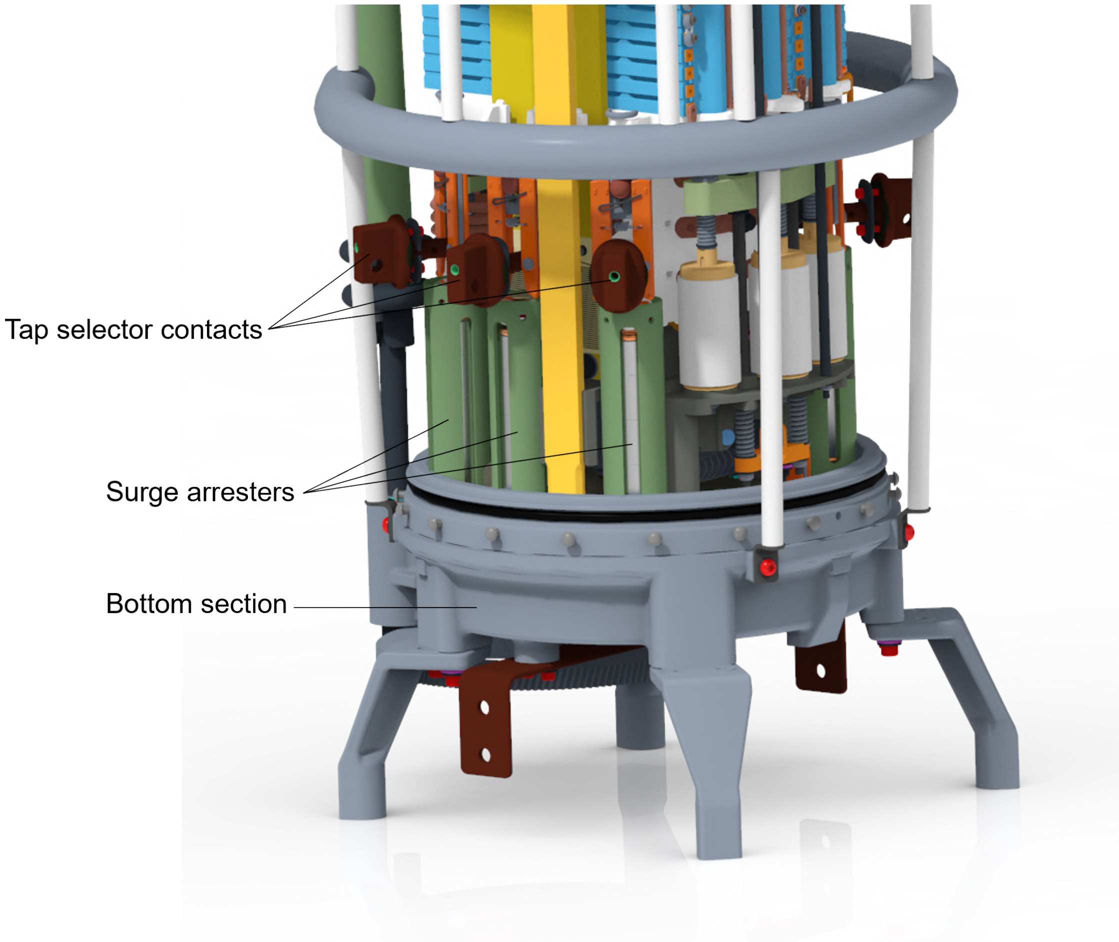

Figure 3.20: Concept "Internal Bottom" mounted inside of the OLTC housing.

The space inside of the OLTC near the bottom section is limited. Mounting six surge arresters directly underneath the tap selector contacts implies modification of both the bottom section and the diverter switch as Figure 3.21 shows. The modification are possible and will not affect performance but will be expensive, from discussion with Hitachi Energy.

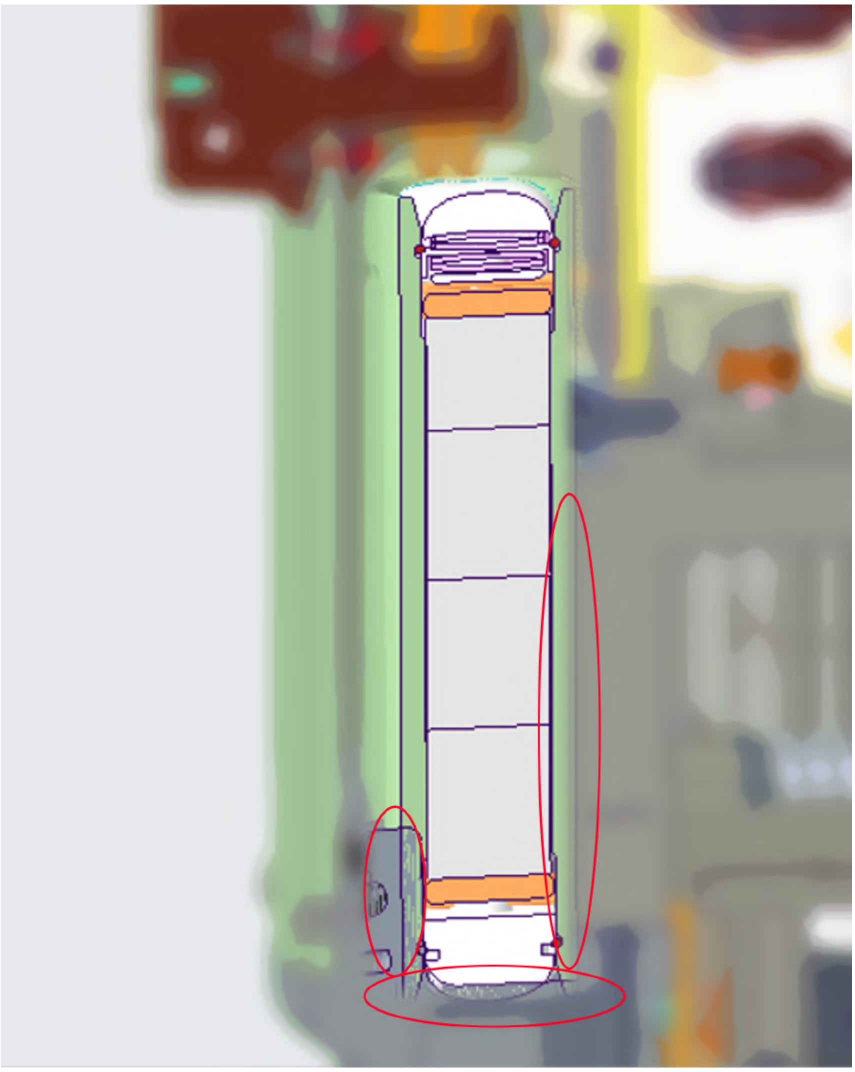

Figure 3.21: Close-up of main issue with concept "Internal Bottom".

3.4.3.3 Resistor Sandwich

The same concept from phase two was used without any modifications, see 3.4.2.2. The reason being that the level of detail was sufficient and that there were no concerns from the design review that called for an updated CAD model of "Resistor Sandwich".

3.4.3.4 SixStanding Shieldring

The concept "SixStanding Shieldring" is based on the "SixStanding" but with implemented improvements in terms of the lower attachment points. This concept utilises a modified shielding ring from another OLTC variant. The original purpose with the shielding ring is to avoid electric discharges due to the high voltage, but it has now been modified to also support the weight of the surge arresters as well as connecting them electrically to ground, through the bottom section, see Figure 3.22. The modified shielding ring is fastened to the OLTC by four existing screws to the bottom section.

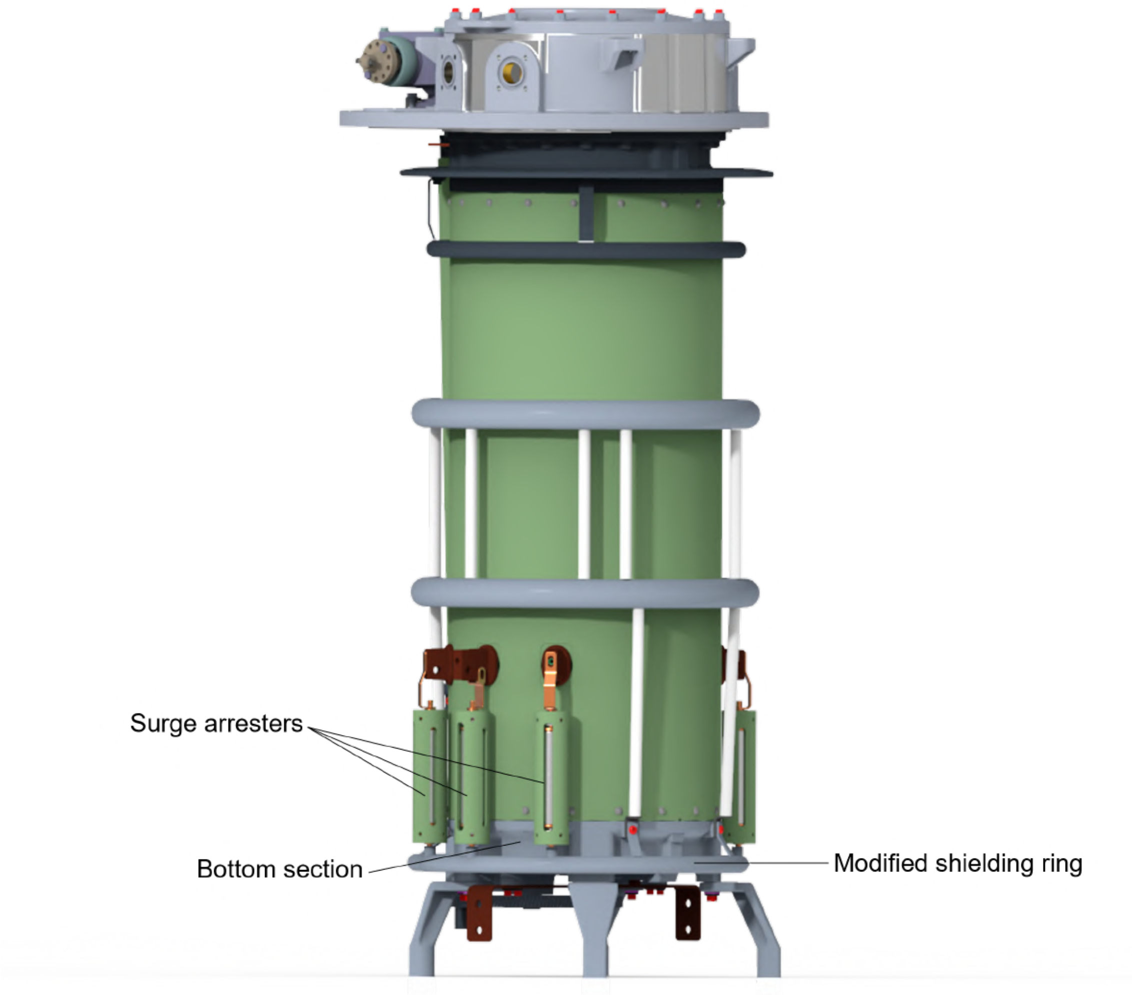

Figure 3.22: Concept "SixStanding Shieldring" mounted on OLTC.

Two variants of connection brackets to the tap selector contacts has been modelled as well as two new variants of tap selector contacts, Figure 3.23.
There is one tap selector contact that is wider than the original contact, this is mainly done to allow for more room between the large wires to the tap selector, see Figure 1.1, but another benefit is a larger mating surface to the connection bracket, yielding a better electrical connection.
The other variant of tap selector contact sticks out further, allowing for the other new variant of connection bracket to mount inside of the connection point for the large tap selector wires, making room for the thick wires to be routed outside of the surge arresters down to the tap selector. The surge arrester are mounted to the modified shielding ring by screwing them into the threaded cylindrical attachment points that are welded to the standard shielding ring.

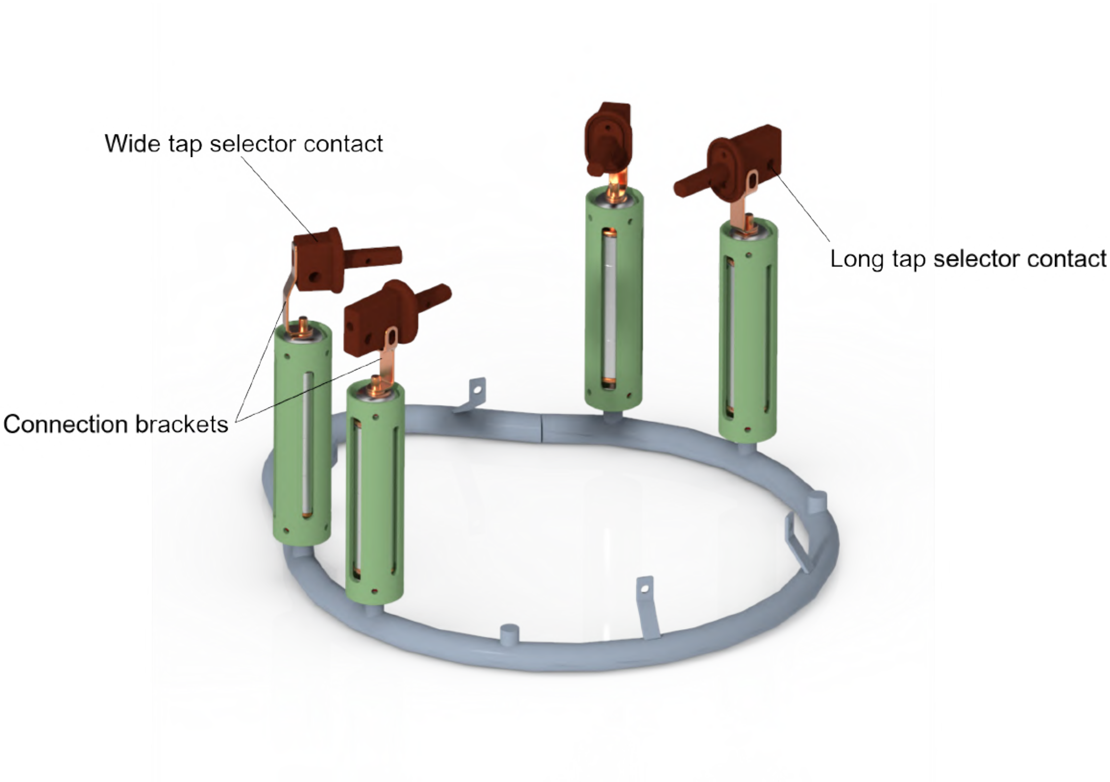

Figure 3.23: Close-up of concept "SixStanding Shieldring".

3.4.3.5 SixStanding Casting

Concept "SixStanding Casting" is also an update of the original "SixStanding" concept. The difference with this concept and the previous concept with the shielding ring mounting solution is that this concept has a different mounting bracket. Compared to the modified shielding ring, this solution is in theory more robust since it uses a plate design with reinforcement gussets, a triangular shape that is known for it's load bearing capabilities, the attachment holes are closer to the weight of the surge arresters, giving less leverage and the surface area connecting the holder and bottom section is greater for increased robustness. The improved concept "SixStanding Casting" can be seen in Figure 3.24.
The addition "Casting" in the name comes from that the holder is attached to the bottom section of the OLTC, which is a casted part, there is a lot of material in the bottom section at the hole locations, so drilling and tapping holes would not be a problem.

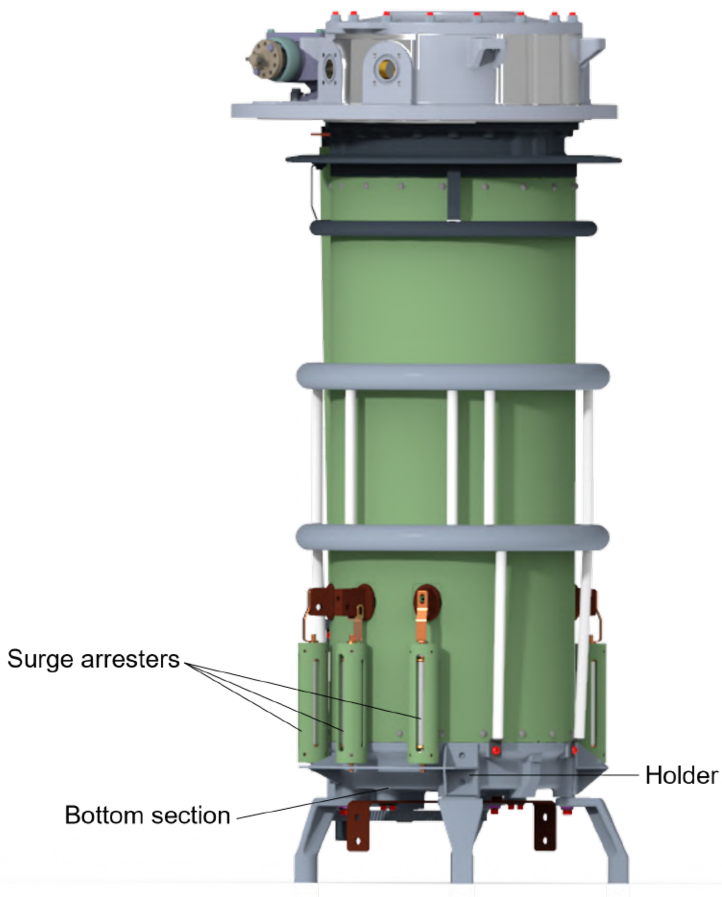

Figure 3.24: Concept "SixStanding Casting" mounted on OLTC.

The same proposals for tap selector contacts and connection brackets from "Six-Standing Shieldring" 3.4.3.4 are applied in this concept as well, i.e one wider tap selector contact and one longer with the corresponding connection brackets as can be seen in Figure 3.25. There are holes in the bracket for the surge arresters connection points to go through, the surge arresters are then fastened with a conical washer, flat washer and nut or alternatively a flat washer and a locking nut, preventing vertical movement, the connection bracket up top stabilises the surge arresters in side to side movement.

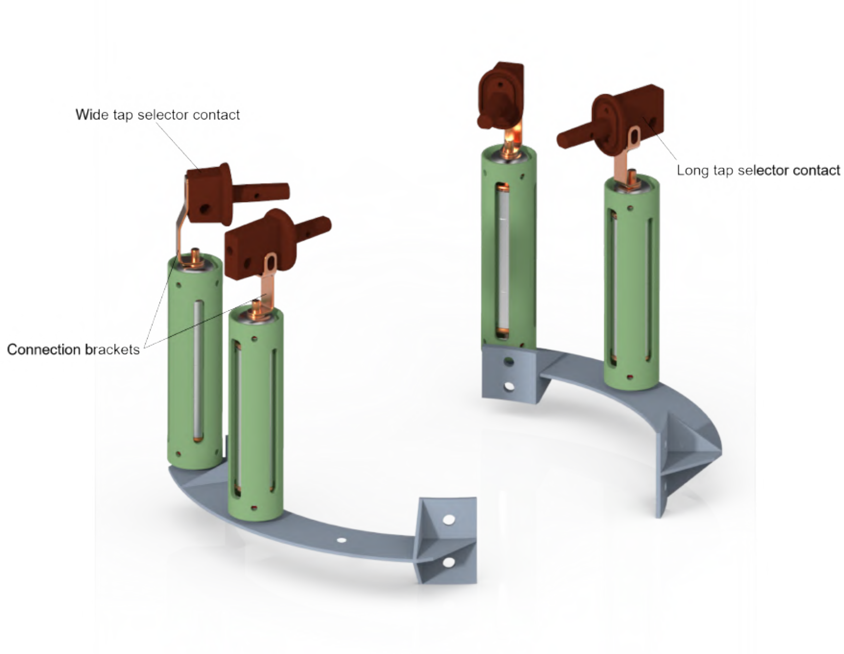

Figure 3.25: Close-up of concept "SixStanding Casting".

3.5 Concept selection

3.5.1 Concept scoring

The concept scoring matrix used for concept selection can be seen below in Table 3.3.

Table 3.3: The concept scoring matrix.

		Concept									
		BackPack		Internal Bottom		Resistor Sandwich		SixStanding Casting		SixStanding Shieldring	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Ease of accessibility	9%	2	0,2	3	0,3	5	0,4	2	0,2	2	0,2
Ease of assembly	13%	2	0,3	3	0,4	4	0,5	5	0,7	5	0,7
Ease of implementation	9%	2	0,2	1	0,1	3	0,3	3	0,3	2	0,2
Ease of installation OEM	18%	2	0,4	5	0,9	5	0,9	5	0,9	5	0,9
Ease of retrofitting	7%	2	0,1	1	0,1	3	0,2	1	0,1	1	0,1
Number of parts	2%	3	0,1	1	0,0	5	0,1	4	0,1	5	0,1
Product cost	16%	4	0,6	1	0,2	4	0,6	2	0,3	2	0,3
Technical risk	20%	2	0,4	1	0,2	4	0,8	3	0,6	3	0,6
Time to market	2%	4	0,1	2	0,0	3	0,1	4	0,1	4	0,1
Visual appeal	4%	2	0,1	4	0,2	5	0,2	3	0,1	3	0,1
	Total Score	25	2,4	22	2,3	41	4,2	32	3,3	32	3,2
	Rank	4		5		1		2		3	
	Continue?	No		No		Develop		No		No	

Selection criteria were chosen based on the requirements list and supplemented with new criteria deemed suitable for comparing concepts following discussions with Hitachi Energy.

The selection criteria will be described in detail below in the value scales section. Some of the criteria are correlated in some aspects, such as ease of implementation and time to market, an easy solution to implement will have a shorter time to market while a difficult solution will take more time to implement, generally speaking. But there is more to it, a solution could be easy to implement from a technical standpoint, but could require time consuming activities such as type testing and redefinition of OLTC specifications etc, yielding a longer time to market.

A selection criteria that is most likely directly tied to time to market is technical risk, the meaning of technical risk will be described later but a high risk will most likely result more testing to make sure that the technical risk won't cause any problems electrically or mechanically for the OLTC, this increases the time to market since testing is a time consuming activity. It is still interesting to include both selection criteria since it represents if a concept has a long time to market due to a high technical risk or due to other factors.

Number of parts and product cost are also selection criteria that affect each other in some ways. A large number of parts could give a high product cost while fewer parts can result in a lower cost, this is under the circumstances that the the production costs and material costs does not differ to much. A high number of parts that are made out of cheap material with production and machining costs could be less expensive then few parts that are made out of expensive material with high machining costs. Therefore, it is still relevant to have both of these selection criteria.

3.5.1.1 Value scales

Ease of accessibility

Ease of accessibility, Table 3.4, is the time required for a field technician to access the surge arresters, starting from on top of the transformer tank with all necessary equipment available. Note that access to the surge arresters only means that inspection can be done, a complete disassembly and disconnection of surge arrester may take longer than gaining access.

Table 3.4: Value scale for ease of accessibility.

Ease of accessibility	
Minutes	Value
> 120,1	1
90,1 - 120	2
60,1 - 90	3
30,1 - 60	4
< 30	5

Ease of assembly
Ease of assembly, Table 3.5, is measured in extra time consumption for assembling the surge arrester system at the corresponding assembly line. The different concepts will need assembly at different points of the OLTC assembly, BackPack would for example need to be assembled at the same station that assembles the insulting shaft to the OLTC, see Figure 3.12 while Resistor Sandwich could be assembled in an early stage at the diverter switch assembly line, see Figure 3.15.

Table 3.5: Value scale for ease of assembly.

Ease of assembly	
Minutes	Value
> 30,1	1
20,1 - 30	2
15,1 - 20	3
10,1 - 15	4
< 10	5

Ease of implementation
Ease implementation, Table 3.7, is the amount of months it would take to go from a concept idea to a finished product that a customer can order, this includes all necessary tests such as type testing if needed and updating of relevant documents such as drawings, Bill Of Material (BOM) lists, technical guides etc.

Table 3.6: Value scale for ease of implementation.

Ease of Implementation	
Months	Value
> 6,1	1
4,1 - 6	2
3,1 - 4	3
2,1 - 3	4
< 2	5

Ease of installation OEM
The level of difficulty for an OEM to install the OLTC, Table 3.7, depends on if the surge arresters are interfering with their process of installing an OLTC. The main OEM in mind is Hitachi Energy Transformers, a manufacturer of transformers that also sales complete units including OLTC's. Mounting of surge arresters inside of the OLTC will not result in any change in their process, yielding a value of 5. But surge arrester mounting location that affects the cable management or approach to lowering the OLTC into the transformer tank would add time to the installation, resulting in a lower value in the value scale.

Table 3.7: Value scale for ease of installation at OEM.

Ease of installation OEM	
Minutes	Value
> 30,1	1
20,1 - 30	2
15,1 - 20	3
10,1 - 15	4
< 10	5

Ease of retrofitting
Retrofitting is a term used for the process of updating an older system, in this case, an older OLTC that already is in use by a customer, with new technology, in this case surge arresters. Retrofitting is considered a sustainable practice as it often maximises the use of existing resources, minimises waste, and reduces the environmental impact associated with demolition and new construction. The amount of time to perform retrofitting, Table 3.8, of surge arresters is measured from when the work begins on top of the transformer tank with all required tools available.

Table 3.8: Value scale for ease of retrofitting.

Ease of retrofitting	
Minutes	Value
> 210,1	1
120,1 - 210	2
60,1 - 120	3
30,1 - 60	4
< 30	5

Number of parts
Number of parts, Table 3.9, is the total amount of new or modified items for the installation of surge arresters. This includes the surge arresters, connectors and holders. Standard fastening hardware such as screws and washers are excluded from number of parts.

Table 3.9: Value scale for number of parts.

Number of parts	
#	Value
> 36	1
31 - 35	2
26 - 30	3
21 - 25	4
< 20	5

Product cost

The product cost, Table 3.10, is an estimation of material costs, cost of processing such as water cutting and tooling such as new casting forms in relation to the current VUCL surge arrester solution, hence the percentage rating. Engineering hours, increase of assembly time, testing etc will be excluded due to time constraints for doing a proper judgement of these.

Table 3.10: Value scale for product cost.

Product cost	
%	Value
> 200	1
< 200	2
< 150	3
< 125	4
< 100	5

Technical risk

Technical risk, Table 3.11, represents the level of uncertainties and potential risks associated with a concept based on previous knowledge about OLTC behaviour from Hitachi Energy. An idea with no similarities to previous implemented and field tested solutions that also has technical risks in terms of new materials or fastening solutions would give a "High" technical risk while a solution that mounts the surge arresters in a location already proved and tested in terms of debris and heat etc would yield a "Low" technical risk level.

Table 3.11: Value scale for technical risk.

Technical risk	
Scale	Value
High	1
Moderately High	2
Medium	3
Moderately Low	4
Low	5

Time to market

Time to market, Table 3.12, is measured in number of months from start of development to the point when the product is available for the customer to order, this process includes development, testing and the launch process.

Table 3.12: Value scale for time to market.

Time to market	
Months	Value
> 24,1	1
15,1 - 24	2
9,1 - 15	3
6,1 - 9	4
< 6	5

Visual appeal

Visual appeal, Table 3.13, is a subjective measure among a group of Hitachi Energy employees as jury. A high rating is given when the appearance of the concept fits the OLTC and diverter switch, ideally it should look like the placement of surge arresters was planned for in an early stage of the OLTC and diverter switch design process.

Table 3.13: Value scale for visual appeal.

Visual appeal	
Subjective	Value
Low	1
Moderately Low	2
Medium	3
Moderately High	4
High	5

3.5.1.2 Weight matrix

The resulting weights used in the scoring matrix, Table 3.3, is shown in Table 3.14. The highest ranking and most important criteria is "Technical risk", the level of uncertainties and potential risks associated with a concept, scoring 9 points or corresponding 20 % in weight. The least important criteria is "Time to market", not important since there is no direct pressure from the market and since there already is a solution available that works fine for now, this results in a low weight of 2 % for "Time to market".

Table 3.14: The Weight matrix.

	Ease of accessibility	Ease of assembly	Ease of implementation	Ease of installation OEM	Ease of retrofitting	Number of parts	Product cost	Technical risk	Time to market	Visual appeal	Sum of points	Share of total points in % (Weight)	Ranking
Ease of accessibility		0	0	0	1	1	0	0	1	1	4	9%	5
Ease of assembly	1		1	0	1	1	0	0	1	1	6	13%	4
Ease of implementation	1	0		0	1	1	0	0	1	0	4	9%	5
Ease of installation OEM	1	1	1		1	1	1	0	1	1	8	18%	2
Ease of retrofitting	0	0	0	0		1	0	0	1	1	3	7%	6
Number of parts	0	0	0	0	0		0	0	1	0	1	2%	8
Product cost	1	1	1	0	1	1		0	1	1	7	16%	3
Technical risk	1	1	1	1	1	1	1		1	1	9	20%	1
Time to market	0	0	0	0	0	0	0	0		1	1	2%	8
Visual appeal	0	0	1	0	0	1	0	0	0		2	4%	7

3.6 Final concept generation

3.6.1 Detailed design

The following concepts are based on the concept "Resistor Sandwich", the highest ranking concept from the previous concept selection process. Since all concepts are alike in mounting location, there will be a higher level of detail on each mounting solution instead, so that another iteration of the concept scoring can take place.

3.6.2 Surge arrester variants

Three different types of electrical connectors were modelled to see which type would be the most suitable for the application. Through discussion at Hitachi Energy, it was concluded that the connector type with internal threads is preferred, see Figure 3.27, since it does not have any sharp edges, which are common locations for electric flash overs. The connectors seen in Figures 3.26 and 3.28 will not be used or developed further.

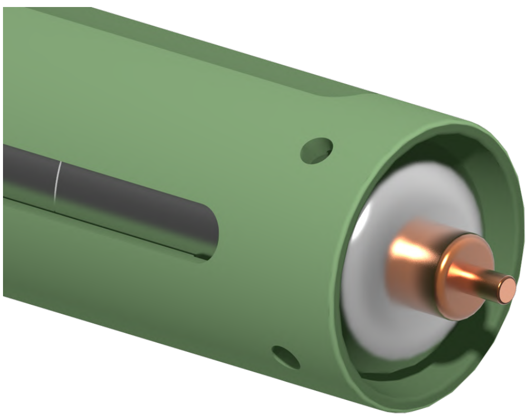

Figure 3.26: Connector with external threads.

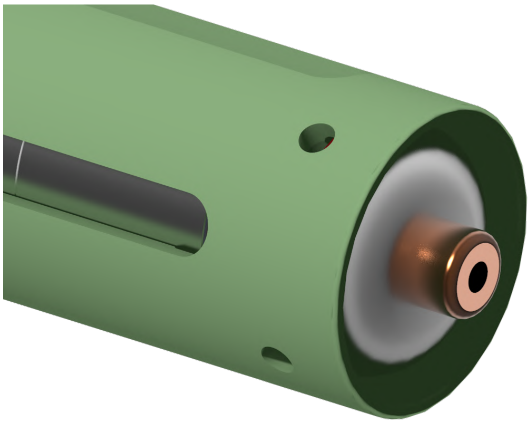

Figure 3.27: Connector with internal threads.

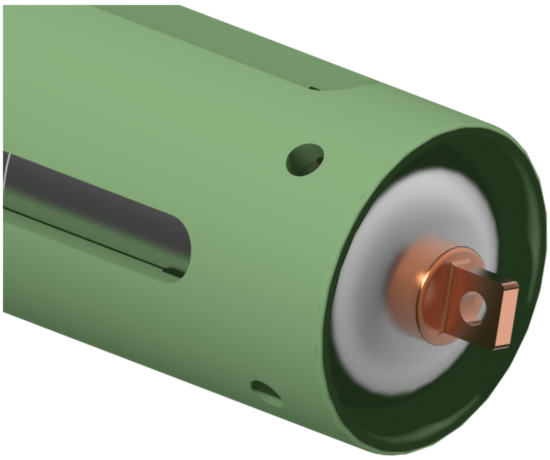

Figure 3.28: Flat connector.

3.6.3 Phase 1

3.6.3.1 DualPlates

The idea with "DualPlates" is that the surge arresters are held down by the weight of the resistor plates. Alignment of the plates is achieved through the six threaded rods, normally used for aligning and securing the resistor plates as can be seen in Figure 3.29. Utilising these does not require any extra components for fastening, one downside is that the clamping force can vary due to binding along the threaded rod, both for the top plate but also for the resistor plates, in that case, lowering the fastening force for the surge arresters.

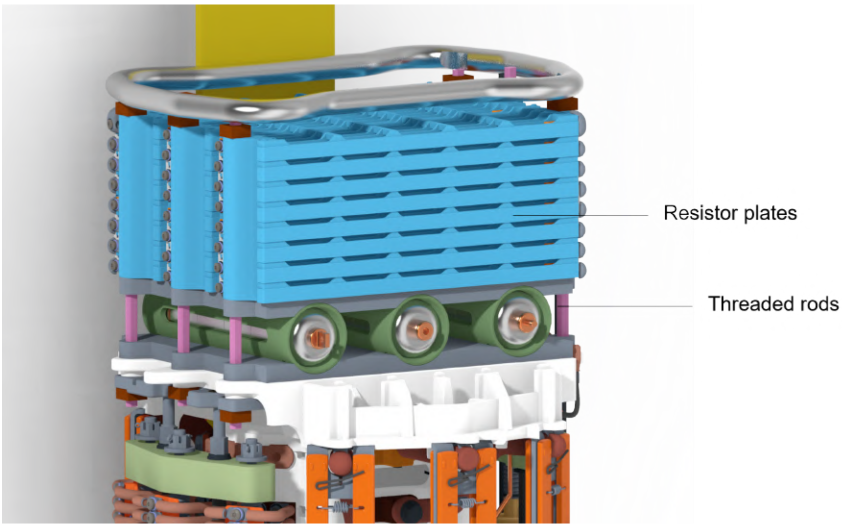

Figure 3.29: Close-up of concept "DualPlates".

Rotational and lateral movement is prevented through the elevated ribs as Figure 3.30 shows. The elevated ribs fits into the wider slots that run along the surge arrester and by doing so preventing the surge arrester from moving. A possible issue with this concept arises in the case where only one surge arrester is used, instead of two or three, the side slots would not work in that case due to uneven support for the resistor plates and the middle slot will not give support to the ends of the resistor plates.

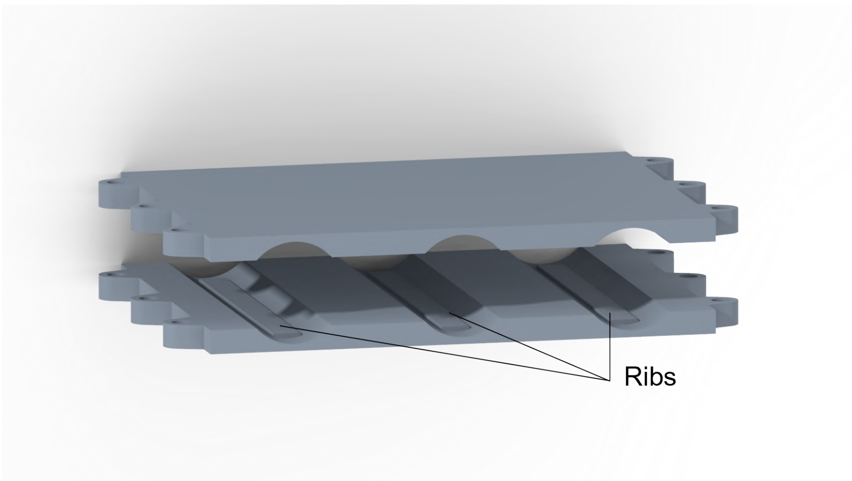

Figure 3.30: Concept "DualPlates".

3.6.3.2 Separate DualPlates

As the name suggests, this concept is based on the "DualPlates" concept above but made into narrower separate pieces to save material, see Figure 3.31. The same reasoning with resistor plates as holding force and threaded rods as alignment is applied.

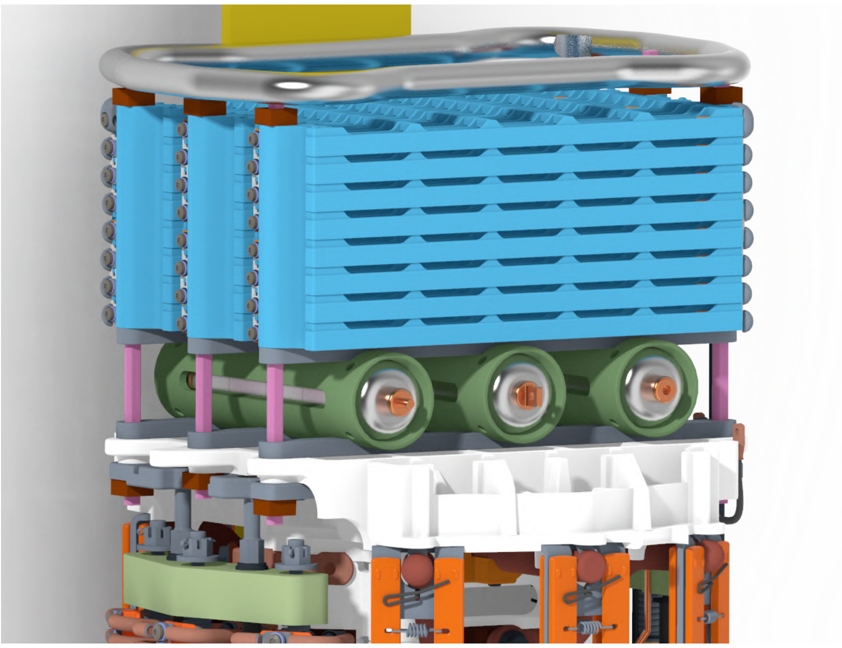

Figure 3.31: Close-up of concept "Separate DualPlates".

The same type of elevated ribs are used from "DualPlates "to lock rotational and lateral movement, see Figure 3.32. Less than half the amount material is used compared to the normal "DualPlates", all six holders are the same, giving only one new part.

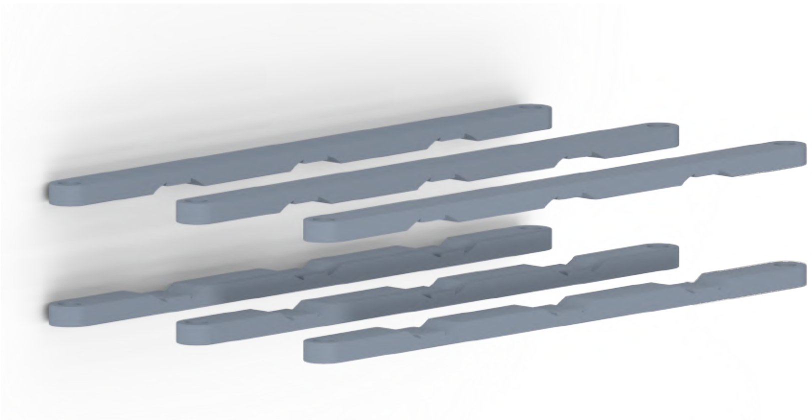

Figure 3.32: Concept "Separate DualPlates".

3.6.3.3 TieDown

This concept has in contrast to the two previous concepts separated resistor support and surge arrester clamping force. As previously the bottom plate is aligned with the threaded rods and in addition there are spacers located around each rod for the resistor plates to rest upon and a separate clamping mechanism for the surge arresters, as Figure 3.33 shows. An unknown aspect, or technical risk with this concept is how resistor plates will handle the lack of even support from underneath under longer time periods, the casings might deform and bend from their own weight in combination with high oil temperatures.

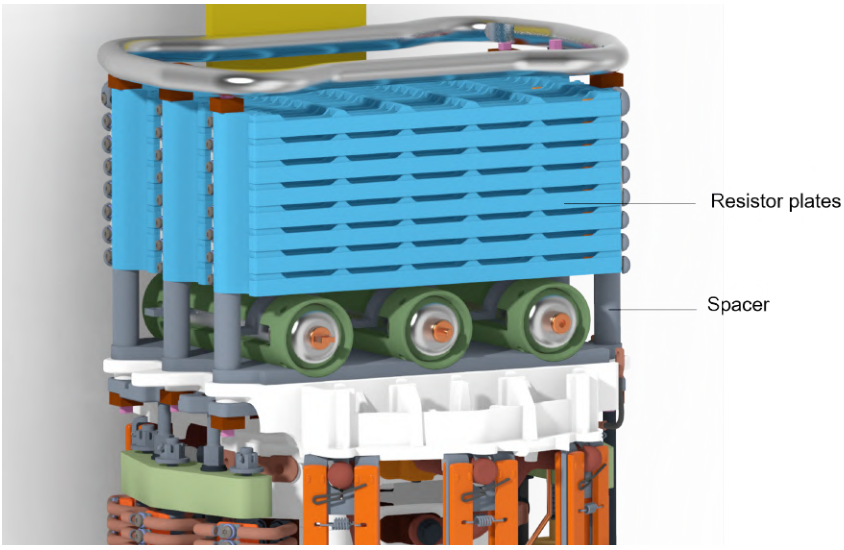

Figure 3.33: Close-up of concept "TieDown".

The surge arresters are then held down by a cap, similar in design to most main bearing caps found in combustion engines, see Figure 3.34. The advantage with this is that each surge arrester can be tighten individually with screws (not modelled), assuring an even clamping force across all surge arrester independent of the quantity. The trade-off with this is a high number of parts, requiring more time to assemble. A similar solution as previously is applied for locking movement and rotation, but this time using the smaller slot of the surge arrester, with a corresponding elevation is the holder. The reasoning for this is to get additional input from the upcoming design review.

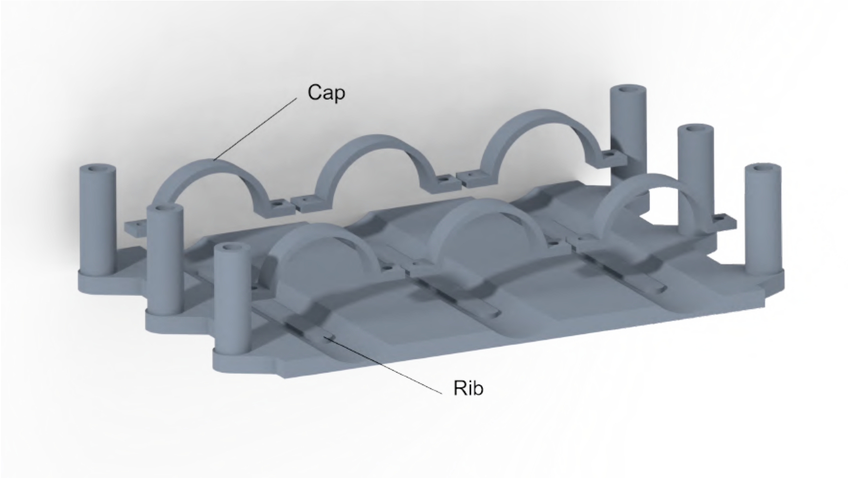

Figure 3.34: Concept "TieDown".

3.6.3.4 TieDown Spring

This concept aims to think outside the box in terms of fastening mechanism by using the small springs from the contact fingers. As Figure 3.35 shows and the name suggests, this concept is based on "TieDown". The differences will be shown more clearly in Figure 3.36 below.

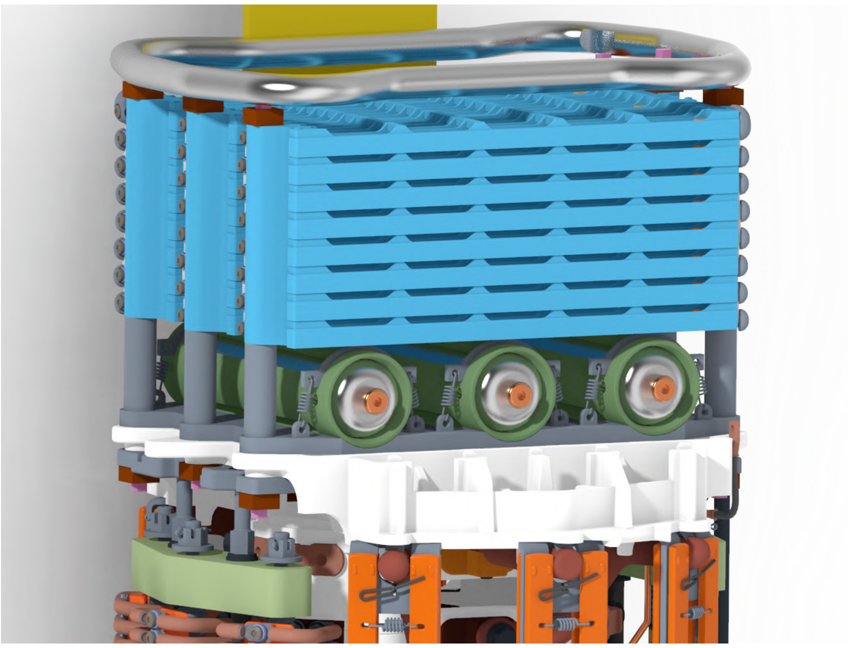

Figure 3.35: Close-up of concept "TieDown Spring".

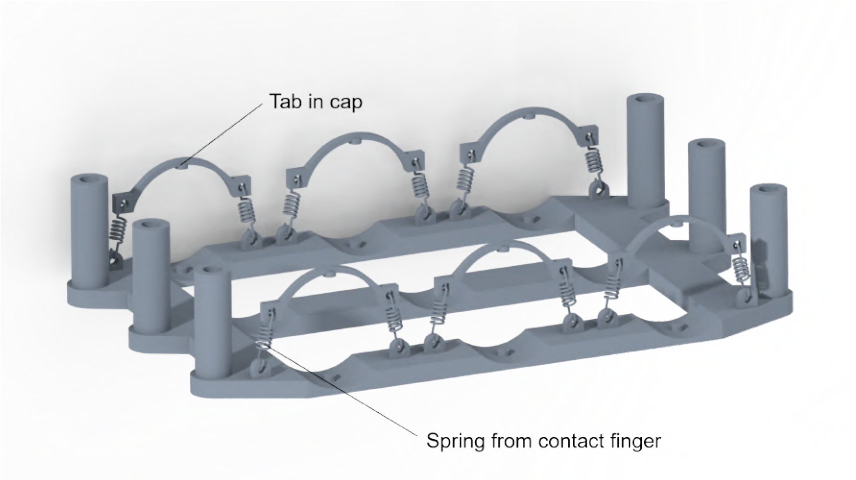

Figure 3.36: Concept "TieDown Spring".

The main difference is as previously mentioned the springs that are creating the downwards pressure, but the caps are also modified to incorporate rotational locking through tabs that fits into the holes in the surge arrester body. The bottom plate is also modified with large cut outs to save material and the same type of tabs as the caps to help lock rotation and translation.

3.6.3.5 Conclusions from design review

The conclusion from the design review was to keep the concepts as they were and focus on creating a different type of solution to have a broader range of solutions to choose the final concept from. All previous solutions were based on the idea to have some sort of structure underneath the surge arresters and something above to lock them in place. After discussion with Hitachi Energy it was concluded that a solution using only one part for both top and bottom support would be interesting, the surge arresters could then be inserted from the side instead from above, this could also enable an easier disassembly process in case of an assembly mistake at the factory or for service/inspection later down the road. In contrast, the previous concepts could require disassembly of the resistor stack if an assembly mistake would have been made.

3.6.4 Phase 2

3.6.4.1 Box

This is concept one of two incorporating the ideas from the previous design review. Figure 3.37 shows how the surge arresters are encapsulated by three holders that also supports the weight of the resistor plates without putting any considerable force on the surge arresters, as discussed at the design review. This type of holder is also enabling an easier disassembly since the surge arresters are slid into the sides, only requiring the lifting plate one one side to be removed rather than the stacks of resistor plates and, saving approximately 30 minutes in disassembly and re-assembly time. Rotation and side to side movement is locked by the electrical connection, the connectors on the surge arresters has a slot for the connection plate to fit into, which then locks rotation when the connection plate is fastened. The connection plates also locks side to side movement when fastened to the electrical connection point.

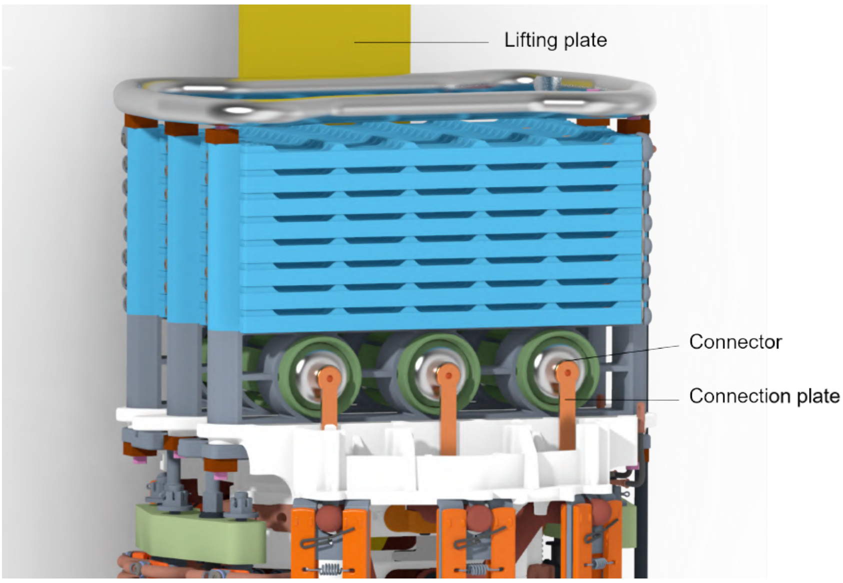

Figure 3.37: Close-up of concept "Box".

The holder itself can be seen in Figure 3.38, all three holders are the same for a lower number of individual parts and there is no rotational or side to side movement locking mechanism since that is incorporated in the electrical connection as previously mentioned.

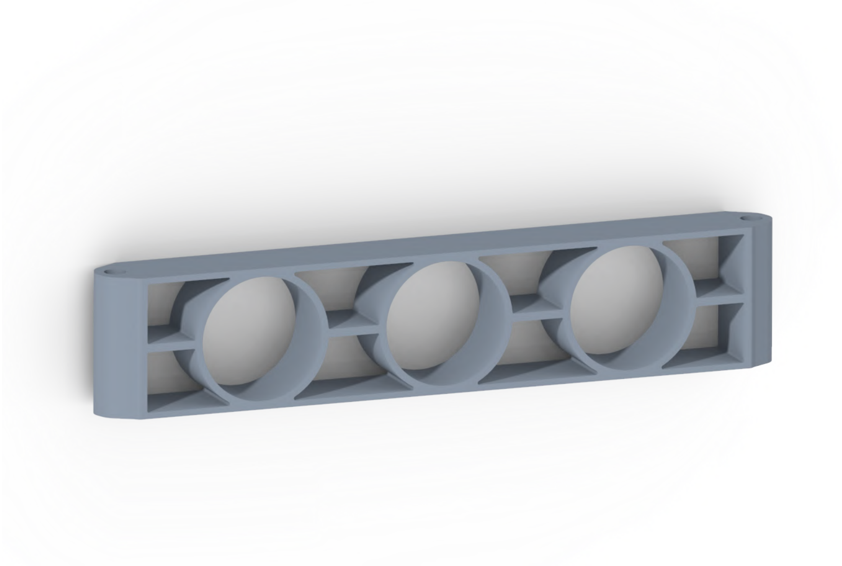

Figure 3.38: Concept "Box".

3.6.4.2 Box Groove

The concept "Box Groove" is nearly exactly the same as "Box" above, see Figure 3.39. The two only differences being the lack of slot in the surge arrester connectors, demanding another approach to lock rotation.

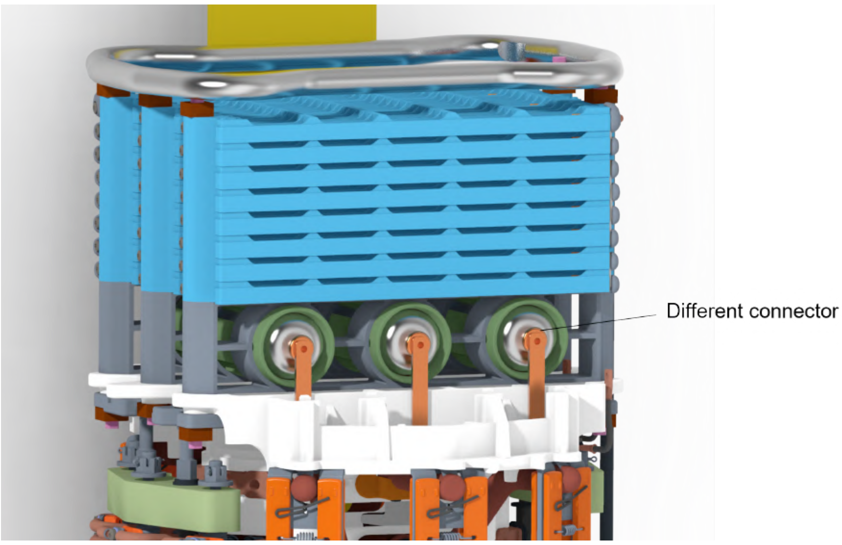

Figure 3.39: Close-up of concept "Box Groove".

The rotational lock is instead implemented as a groove in the holder, this requires a corresponding internal groove in the surge arrester housing so that the grooves can lock into each other and prevent rotation, see the grooves located in the bottom of the holes for the surge arresters in Figure 3.40.

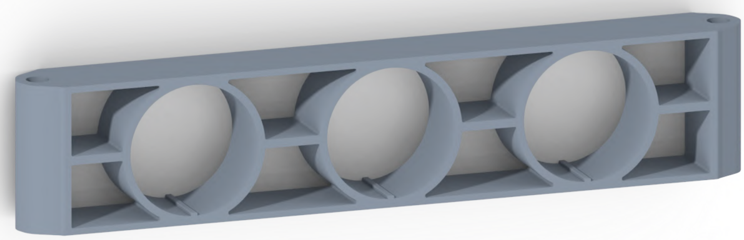

Figure 3.40: Concept "Box Groove".

3.7 Final concept selection

3.7.1 Concept scoring

The concept scoring for the detailed design suggestions was done with the same concept scoring matrix as last time as basis. The selection criteria that got the same rating across all six concepts were then removed to get a more representative total score, the remaining selection criteria are "Ease of assembly", "number of parts", "Product cost", "Technical risk" and "Visual appeal", see Table 3.15.

Table 3.15: The final concept scoring matrix.

		Concept											
		Box		Box Groove		DualPlates		Separate DualPlates		TieDown		TieDown Spring	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Ease of assembly	0,29	4	1,2	5	1,5	5	1,5	4	1,2	2	0,6	1	0,3
Number of parts	0,09	5	0,5	5	0,5	5	0,5	4	0,4	2	0,2	2	0,2
Product cost	0,19	4	0,8	4	0,8	3	0,6	3	0,6	3	0,6	2	0,4
Technical risk	0,39	5	2,0	5	2,0	4	1,6	4	1,6	3	1,2	3	1,2
Visual appeal	0,04	5	0,2	5	0,2	3	0,1	4	0,2	1	0,0	1	0,0
	Total Score	23	4,5	24	4,8	20	4,2	19	3,8	11	2,5	9	2,1
	Rank	2		1		3		4		5		6	
	Continue?	No		Yes		No		No		No		No	

3.7.1.1 Weight matrix

As previously, the weights of the selection criteria were derived by comparing them against each other. An issue with this relative comparison is that "Visual appeal" is not more important than any of the other criteria, therefore it gets 0 points. This does not reflect reality however since visual appeal still have some importance. To solve this issue, 1 % from the share of total points was transferred from "Ease of assembly", "Number of parts", "Product cost" and "Technical risk" to "Visual appeal", resulting in a weight of 4 % for visual appeal, see Table 3.15 and Table 3.16.

Table 3.16: The final weight matrix.

	Ease of assembly	Number of parts	Product cost	Technical risk	Visual appeal	Sum of points	Share of total points in % (Weight)	Ranking
Ease of assembly		1	1	0	1	3	30%	2
Number of parts	0		0	0	1	1	10%	4
Product cost	0	1		0	1	2	20%	3
Technical risk	1	1	1		1	4	40%	1
Visual appeal	0	0	0	0		0	0%	5

3.7.2 Simulation

The mechanical simulation was done before the electrical simulation to make sure that the concept does not need further mechanical simulation unless the electrical simulation calls for large structural changes. The results from the electrical simulation will not be included in the report due to time constraints.

3.7.2.1 Mechanical simulation

The holders and the connection plates will be simulated separately for easier analysis of where the maximum stresses and displacements are located. The resulting von Mises stress from the simulations must not exceed the yield strength, i.e avoiding plastic deformation, of the material used and the deflection must be within reasonable limits to avoid contact with surrounding parts.

The forces affecting the concept is the weight from the resistor plates including a small clamping force from the nut to hold the plates in place and requirement value R1 of 4g, derived from R7 "The solution should be designed to pass the mechanical vibration test, 1ZSC028354 Test specification of mechanical vibration test on VUCL Surge arresters".

The weight of one resistor plate is 2,2 kg, the highest number of stacked resistor plates is eight, this results in $2,2kg \cdot 8 \cdot 9,81m/s^2 \cdot 4g = 690,8N$. The force was then assumed to be resulting in $750N$ including the clamping force from the top nut.

The weight of the surge arresters are 2,6 kg each, this in combination with an acceleration of 4g results in a force of $2,6kg \cdot 9,81m/s^2 \cdot 4g = 102N$

Holder
Material properties were needed before simulation. The material chosen for the holder was G11 composite, an already used material for the OLTC with known oil compatibility, fulfilling requirements R13,14 and 17. G11 has a tensile strength of 375 MPa, compressive strength of 350 MPa and a shear strength of 30 MPa [16], yield strength is not found but is assumed to be higher than 30 MPa and closer to the tensile and compressive strength, given that G11 is not a ductile material.

The maximum von Mises stress in the Z direction is 17,1392 MPa, Figure 3.41 with a downwards force (-Z) on the top surface of 750 N and a bearing load inside of the holes where the surge arresters sits of 102 N each in the negative Z-direction.

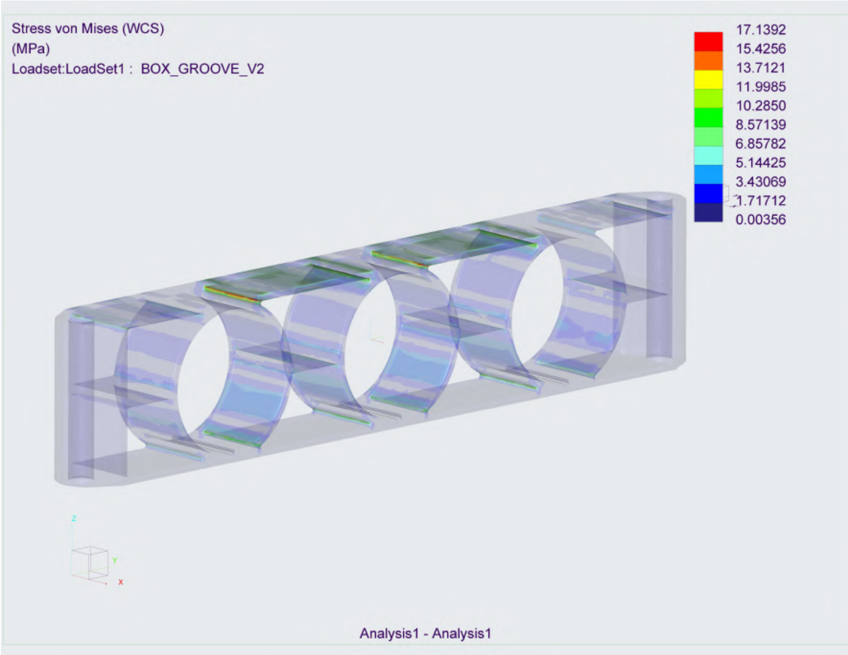

Figure 3.41: Holder von Mises stress in the Z-direction.

Results are similar in the Y-direction, the maximum von Mises stress in the Y direction is 17,1425 MPa, Figure 3.42 with a downwards force (-Z) on the top surface of 750 N and a bearing load inside of the holes where the surge arresters sits of 102 N each in the Y-direction.

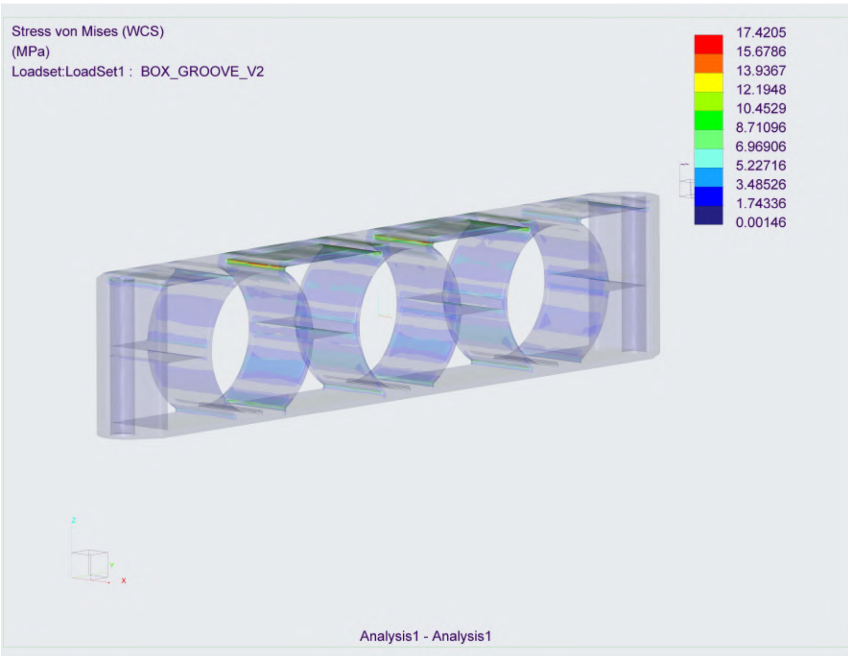

Figure 3.42: Holder von Mises stress in the Y direction.

17 MPa is well below the compressive and tensile limits of 350-375 MPa, meaning that the holder passes the stress simulation.

The displacement is very small at less than a tenth of a millimetre in both Y and Z direction, as Figures 3.43 and 3.44 shows, meaning that the holder has very little deflection and passes the mechanical simulation.

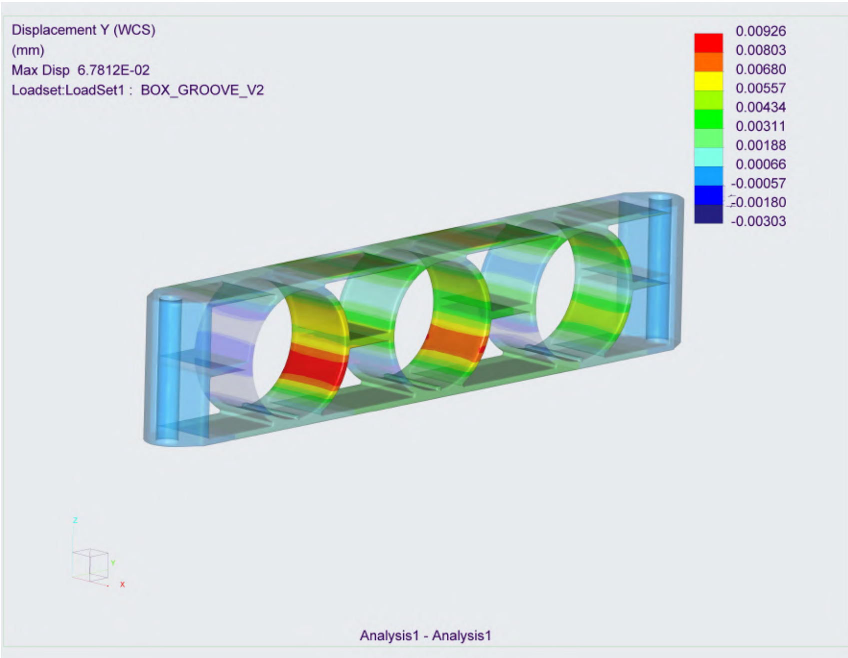

Figure 3.43: Holder displacement in Y direction.

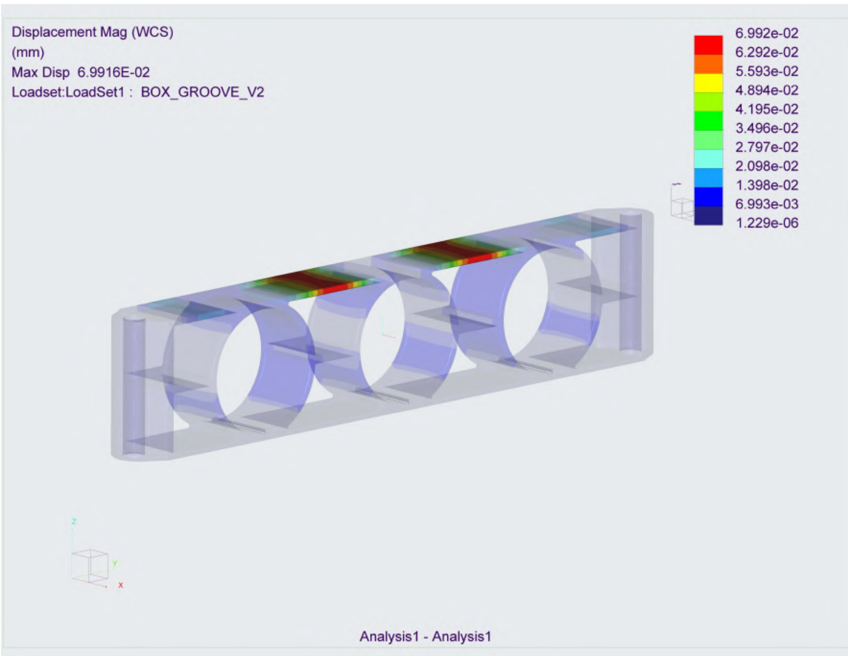

Figure 3.44: Holder displacement in Z direction.

Small connection plate
Copper is the material of choose for both the smaller and larger connection plates, soft copper has a yield strength of 40-80 MPa and when being cold worked, a yield strength of above 300 MPa can be achieved, but with less elongation before break as drawback [17]. A surge arrester dummy, see Figure 3.45 below, was also modelled to connect the two plates on either side to simulate the real world scenario of 102 N pushing on one plate and pulling on the other in the Y-direction.

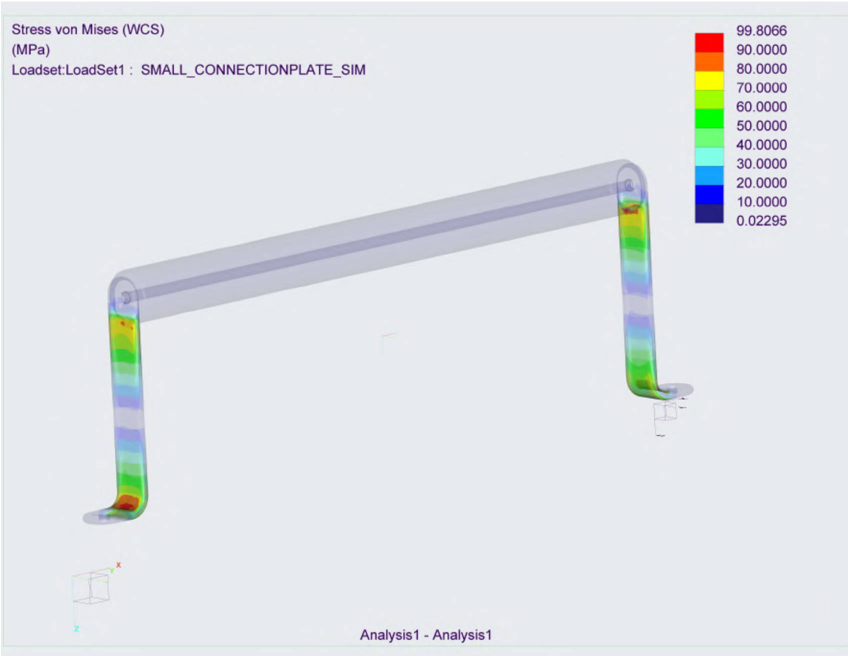

Figure 3.45: von Mises stress for the small connection plate with 3mm thickness.

The plate thickness for the connection plate was set to 3mm from the final concept generation phase, this resulted in a von Mises stress of 99,8066 MPa, see Figure 3.45, which is above the yield stress for soft copper, meaning that plastic deformation would occur using soft copper.

The solution to this problem was to change the thickness of the plate from 3 mm to 5 mm, this resulted in a von Mises stress of 42,4407 MPa instead, Figure 3.46, which is within acceptable limits of the 40-80 MPa aimed for.

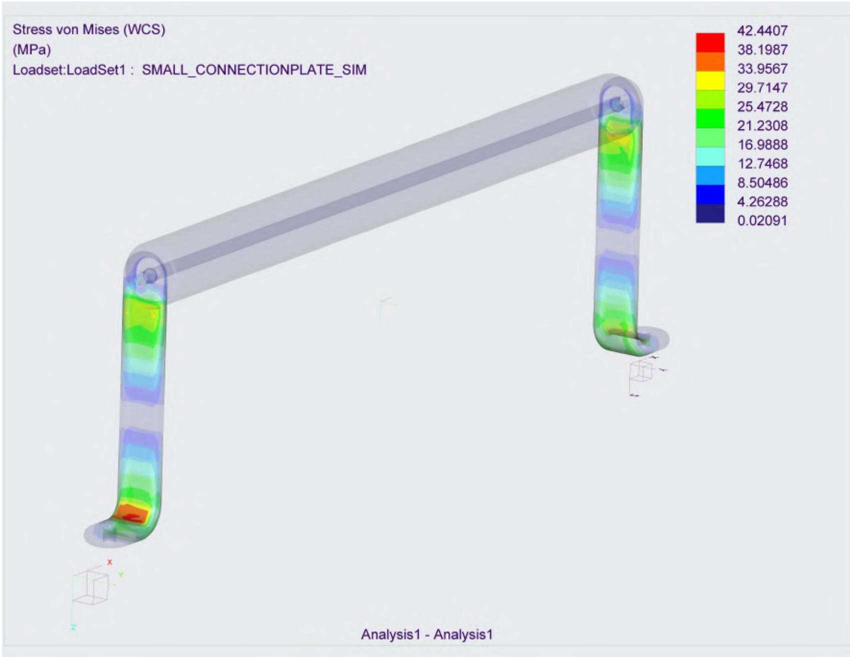

Figure 3.46: von Mises stress for the small connection plate with 5mm thickness.

Deflection of the connection plates is small at around 0,11 mm, see Figure 3.47. This amount of deflection does not introduce any clashing between parts.

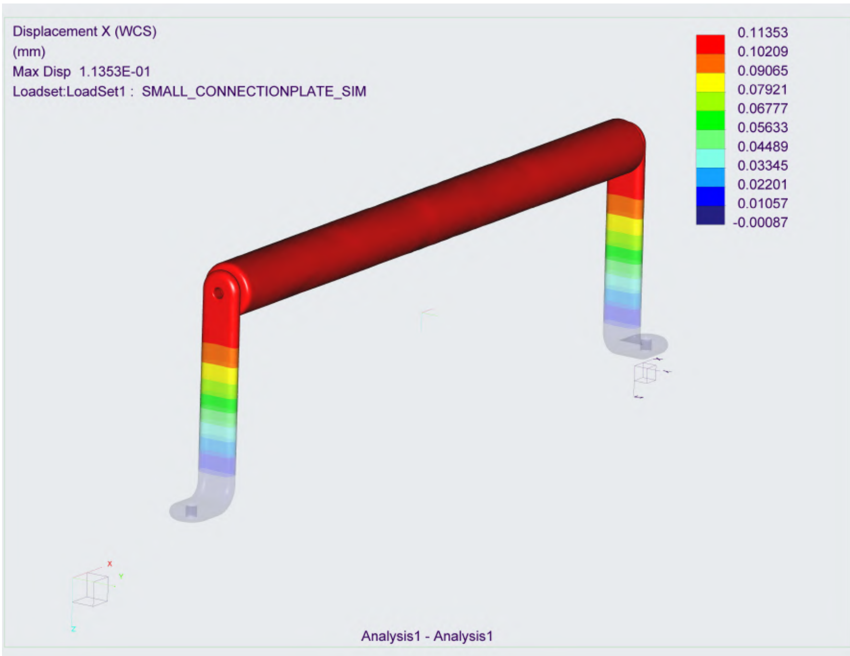

Figure 3.47: Displacement in Y-direction for the small connection plate with 5mm thickness.

The small connection plate passes the mechanical simulation after the thickness change from 3 mm to 5 mm.

Large connection plate

The thickness was changed to 5 mm before simulation due to the previous results for the smaller connection plate. Both the von Mises stress and the displacement is very similar to the results for the smaller connection plate as can be seen in Figures 3.48 and 3.49, which makes sense since the amount of leverage, or height from the attachment point to where the force is applied is the same. This means that the large connection plates also passes the mechanical simulation.

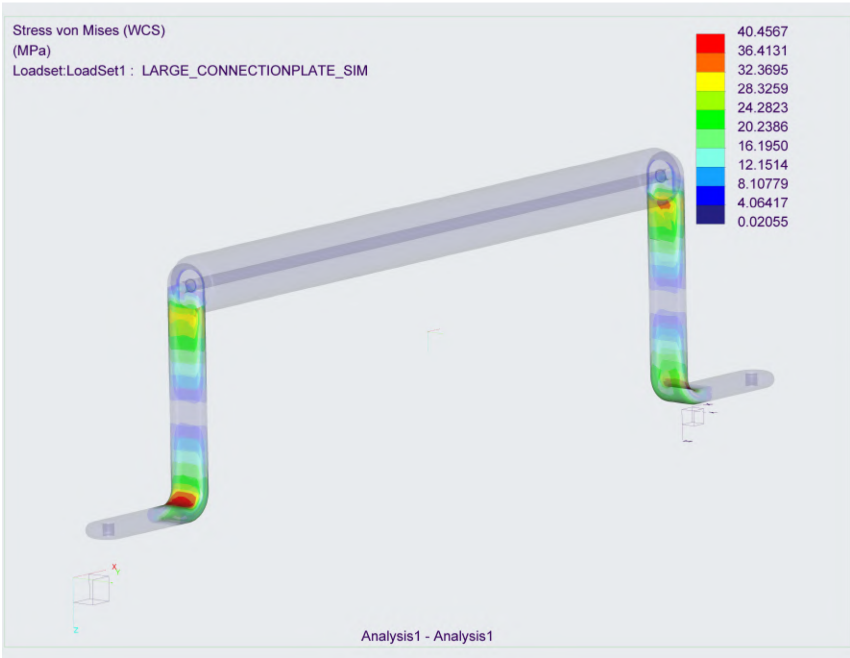

Figure 3.48: von Mises stress for the larger connection plate with 5mm thickness.

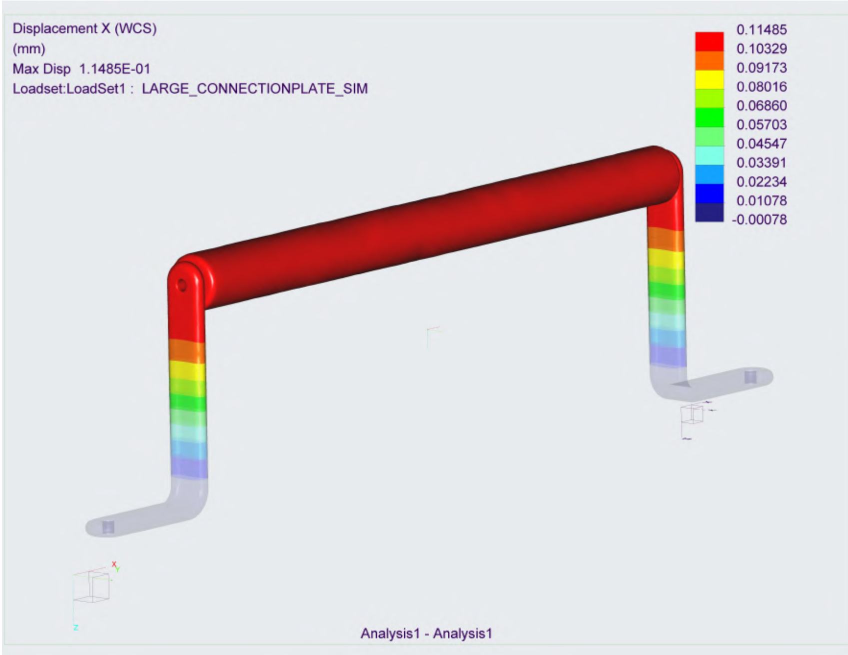

Figure 3.49: Displacement for the larger connection plate with 5mm thickness.

3.8 Final design

All new and modified parts are shown in the exploded view, see Figure 3.50. The surge arresters are modified with new connectors at the ends instead of the connection tabs along the side as today's surge arresters, see Figure 1.5 and a shallow groove along the length of the surge arrester. There are only four different new parts, the short and long connection plates, the electrical connector for the surge arrester and the holder. A complete assembly with three surge arrester requires four short connection plates, two large connection plates, six end connectors and three holders, a total of 15 additional parts, excluding hardware, the already available hardware increases the number of parts to 45.

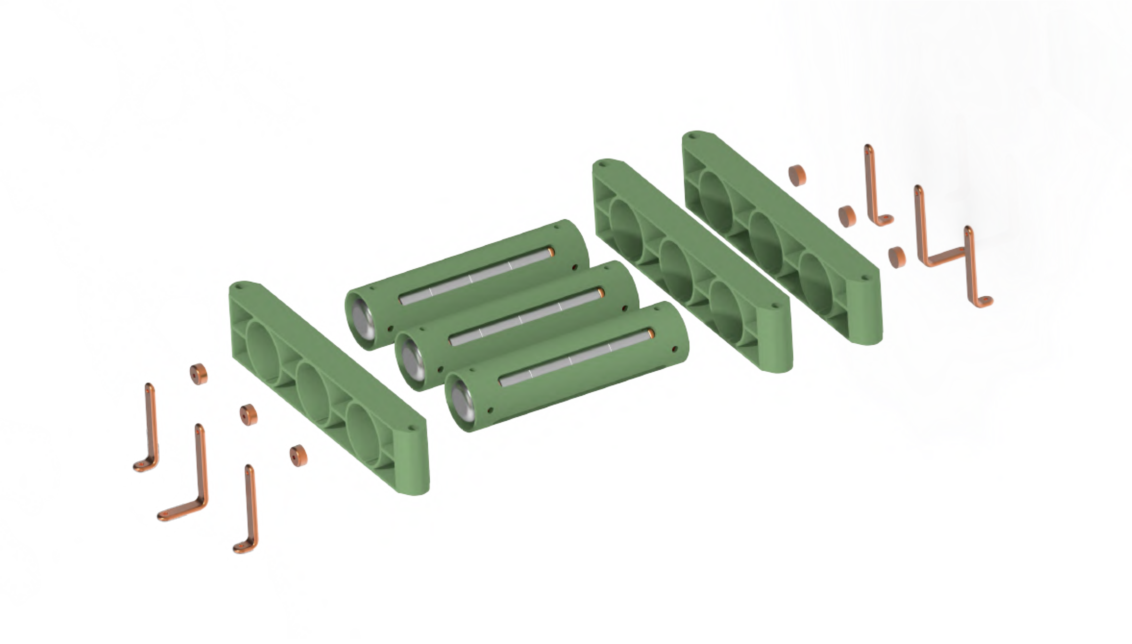

Figure 3.50: Exploded view of the final design.

The required modifications to the surge arresters can be seen in Figure 3.51 above. The modifications are as previously mentioned a groove along the cylindrical housing of the surge arrester and a new electrical connector. The groove would either require new moulding forms so that the groove is made in the moulding process directly or in a later post processing stage where the groove could be cut with a milling machine or similar, the later alternative being cheaper for a low volume of housing due to high cost of moulding forms, but for larger volumes it might be cheaper to have the groove done in the moulding process.

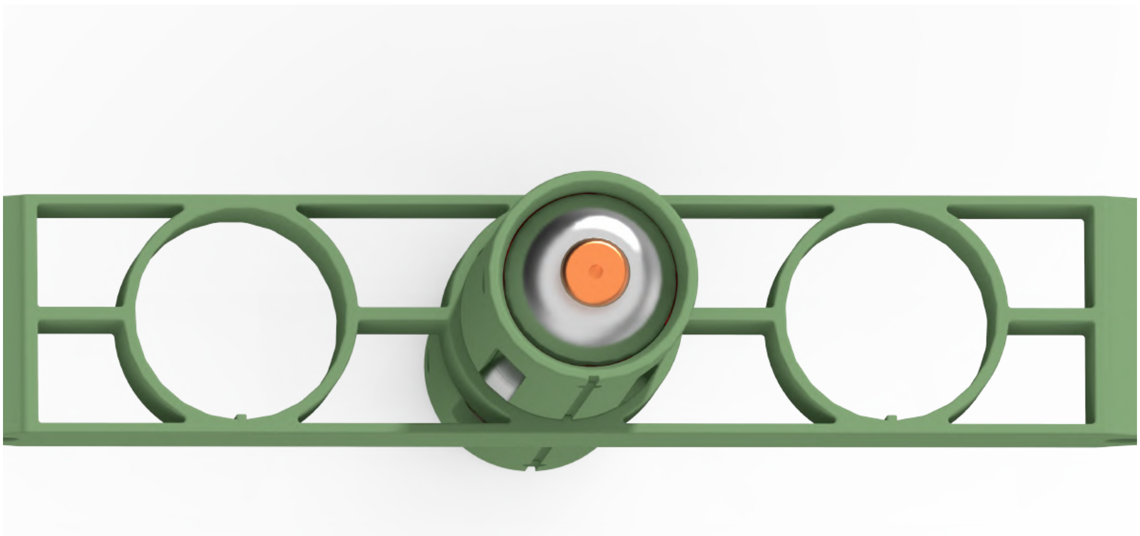

Figure 3.51: The groove and new connector.

The new electrical connectors, seen more clearly in Figure 3.52 would require re-design of the end caps since the connector need to pass through it and be electrically and mechanically connected to the inside of the surge arrester. This would require redesign of the end caps and smaller adjustment on the inside of the surge arrester. The tooling for assembly of the surge arrester would also need to be modified since today's tool utilises the flat spot, where the connector is now located, on the end cap for assembly. Figure 3.52 also showcases the hardware for attaching the connection plates, consisting of a flat washer, conical washer and a M6 screw.

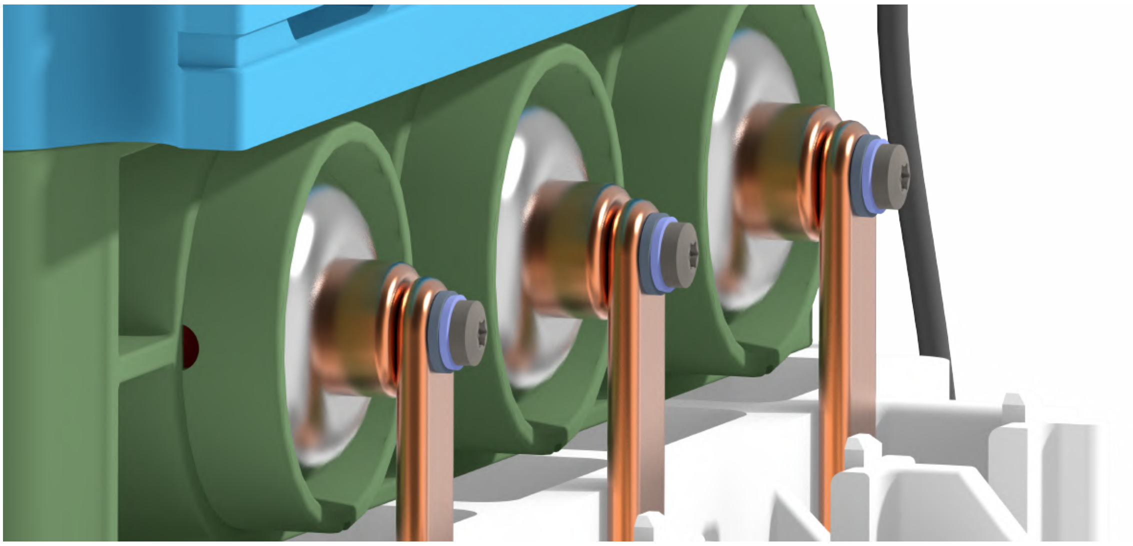

Figure 3.52: New connections and hardware.

Depending on the type of material, the holder, see Figure 3.53, can both be made from a block of material through water jet cutting for example, suitable for composites such as G11 that was used for simulation. The holder could also be made through injection moulding. A suitable material for injection moulding could be Sheet Moulding Compound (SMC), also a material already used inside of the OLTC with known oil compatibility, fulfilling requirements R13, 14 and 17. The ridge that the groove in the surge arrester housing locks into can also be seen in Figure 3.53.

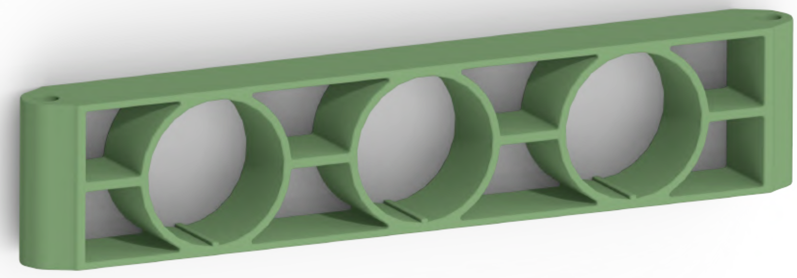

Figure 3.53: The holder.

Both the connection plates can be made out of punched 5 mm thick copper plates with rounded edges, bent into shape with a 90 degree bend, see Figure 3.54.

Figure 3.54: The smaller connection plate to the left and larger to the right.

3.8.1 BOM

Note that the quantity of items is corresponding to three surge arresters, use of only one or two surge arresters would result in a lower number of parts, see Table 3.17.

Table 3.17: Bill of Material for the final concept.

BOM		
Item name	Item description	Quantity
Connection plate, large	Connects the surge arrester to the diverter switch electrically	2
Connection plate, small	Connects the surge arrester to the diverter switch electrically	4
Electric connector	New electrical connector for the surge arrester	6
Holder	Part for holding the surge arrester	3
Screw, M6	Used to fasten the connection plates	6
Surge arrester	Used to protect the OLTC from overvoltages	3
Washer, conical	Used for locking the screw	6
Washer, flat	To protect the surge arrester contact from conical washer	6

3.8.2 Requirement fulfilment

The green markings represents the requirements and/or wishes that are fulfilled, yellow represents the criteria that has not been able to be evaluated yet, see Table 3.18.

Table 3.18: Fulfilment of requirements and wishes.

#	Criteria	Requirement value	Req/ Wish	Weight	Evaluation Method	Reference
	Performance					
R1	Mounting components fulfills requirements on mechanical loads	> 4g	R		Simulation	R&D
R2	Mounting location does not introduce critical dielectric distances		R		Simulation	R&D
R3	Surge arrester performance is not affected by mounting environment		R		Simulation	R&D
R4	The surge arrester system fulfills the protecting function on the correct voltage levels		R		Theoretical	R&D
	Type test					
R5	The solution should be designed to pass the dielectrical type test "1ZSC028341_Test specification of dielectric type test on VUCL with surge arresters"		R		Type test	Standard
R6	The solution should be designed to pass the mechanical endurance test "1ZSC028688_Test specification - Mechanical endurance test on VUCL with surge arresters"		R		Type test	Standard
R7	The solution should be designed to pass the mechanical vibration test "1ZSC028354_Test specification of mechanical vibration test on VUCL Sugre arresters"		R		Type test	Standard
	Assembly					
R8	Few special tools for assembly and maintenance/inspection	< 5 tools	R		CAD	Manufacturing
		< 2 tools	W	4		
R9	Minimal interaction needed from other OEM business	< 10 operations	R		CAD	Manufacturing
		< 2 operations	W	3		
R10	Number of different parts should be limited	< 20 parts	R		CAD	Manufacturing
		< 5 parts	W	3		
R11	Should fit all three types of Hitachi Energy tap selectors (C, III, F)		R		CAD	Manufacturing
R12	The installation of surge arresters requires ____ modification of the existing OLTC	< Major*	R		CAD	Manufacturing
		< Minor*	W	4		
	Material					
R13	Materials used are compatible with temperature changes from -40 to +115 °C over at least 30 years		R		Lists	Standard
R14	No use of forbidden or non-qualified materials		R		Lists	Standard
R15	Reuse as much as possible of the current surge arrester assembly and parts	> 50% in weight	R		Lists	Product planning
		> 75% in weight	W	3		
R16	Reuse materiels with known vapour phase compatibility	> 75% of total weight	R		Lists	Product planning
		100% of total weight	W	4		
R17	Reuse materials with known oil compatibility	> 75% of total weight	R		Lists	Product planning
		100% of total weight	W	4		
R18	Use materials compatible with different types of oils and esters	> 25% of total weight	R		OEM info	Product planning
		75% of total weight	W	3		
	Regulations					
R19	The solution should adhere to internal and external requirements and regulations		R		Examination	Standards
	Maintenance					
R20	Inspection interval	> interval of OLTC	R		Endurance Type test	Customer
		> 2 * interval of OLTC	W	4		
R21	Maintenance	> interval of OLTC	R		Endurance Type test	Customer
		> 2 * interval of OLTC	W	4		

3.8.2.1 Performance criteria

R1: Mounting components fulfils requirements on mechanical loads
This requirement is checked to be fulfilled through mechanical simulation in section 3.7.2.1.

R2: Mounting location does not introduce critical dielectric distances
Has to be checked through electrical simulation, not done yet due to time constraints.

R3: Surge arrester performance is not affected by mounting environment
The displacement tests of the holder, see Figure 3.44, shows that the holder is not deforming in areas that could put pressure on the surge arrester. It is also known from experience that the mounting location is not heat soaked by other OLTC components such as resistors that generates heat.

R4: The surge arrester system fulfils the protecting function on the correct voltage levels
This criteria is fulfilled trough theoretical evaluation.

3.8.2.2 Type test criteria

R5, R6 and R7: The solution should be designed to pass the dielectrical, mechanical endurance and mechanical vibration type test
The solution has been designed to pass these tests, but to confirm if this is true, further research and dynamic simulations would need to be performed along with discussions with type test experts.

3.8.2.3 Assembly criteria

R8: Few special tools for assembly and maintenance/inspection
Only one special tool is needed for assembly of the concept, this is an already existing special tool that needs to be modified in order to assemble the surge arresters with the new electrical connections.

R9: Minimal interaction needed from other OEM business
No interaction is needed from other OEM business since the concepts locates the surge arresters inside of the OLTC which is enclosed to other OEM's such as Hitachi Energy Transformers who connects and installs the OLTC into their transformers.

R10: Number of different parts should be limited
There are four different parts used for the concept, the short and long connection plates, the new electrical connector for the surge arrester and the holder.

R11: Should fit all three types of Hitachi Energy tap selectors (C, III, F)
All tap selector variants can still be used with the diverter switch since all external dimensions are unaffected by the implementation of the concept.

R12: The installation of surge arresters requires Major/Minor modification of the existing OLTC
Only minor modification of the OLTC is needed, the only modification needed is a longer cut out in the lifting plates for the diverter switch. This modification is estimated to have no impact on it's function, this will have to be double checked through simulation.

3.8.2.4 Material criteria

R13: Materials used are compatible with temperature changes from -40 to +115 °C over at least 30 years
No new materials are introduced with this concept, meaning that only materials with known behaviour, performance and longevity is used.

R14: No use of forbidden or non-qualified materials
Since all materials has been used before by Hitachi Energy in the OLTC's, it can be assumed that all materials are approved.

R15: Reuse as much as possible of the current surge arrester assembly and parts
The current surge arrester assembly is reused with the addition of new electrical connections and a machined groove in the surge arrester housing, these modifications are reusing more then 75% of the original assembly.

R16 and R17: Reuse materials with known vapour phase and oil compatibility
All the materials used in the concept has previously been put through a vapour phase process and compatibility tested with the oil.

R18: Use materials compatible with different types of oils and esters
The percentage of total weight of material compatible with different types of oils and esters is unknown due to time constraints. Further research and possibly compatibility testing if an answer is not found will be needed to answer this question.

3.8.2.5 Regulations criteria

R19: The solution should adhere to internal and external requirements and regulations
The concept has not yet been examined regarding internal and external regulations. This would be a time consuming task requiring expertise in the area and is not performed due to time and authority constraints.

3.8.2.6 Maintenance criteria

R20 and R21: Inspection and maintenance interval
Both the inspection and maintenance interval is perceived to be more than two times the corresponding interval of the OLTC by Hitachi Energy OLTC engineers.

3.8.3 Prototype

The prototype was 3D printed and could be mounted to an diverter switch used previously for testing. The colour scheme of the parts does not represents the planned final colours. Figures 3.55 and 3.56 shows the result of the prototype mounted to a diverter switch. The prototype was overall easy and straight forward to install, the only pitfall was that the holders can be mounted upside down in relation to each other, meaning that the ridges used for rotational locking of the surge arrester will not line up, making it impossible to install the surge arresters.

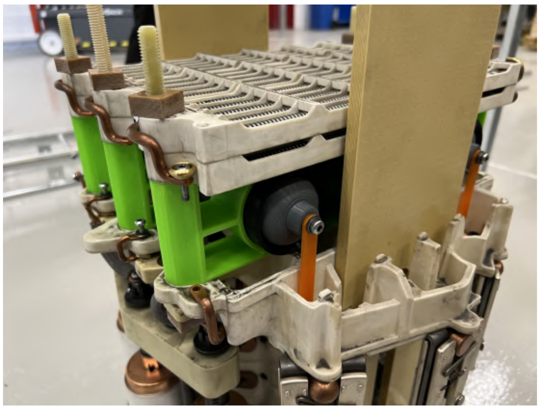

Figure 3.55: Overview of the concept.

Figure 3.56: Close up overview of the concept.

Figure 3.57 shows the profile view of the prototype and the main modification that needs to be performed to the diverter switch, the lifting plate hides the surge arrester in the middle, see Figure 3.58 for how the lifting plate needs to be modified with a longer cut out, creating room for the connection plate to be fitted.

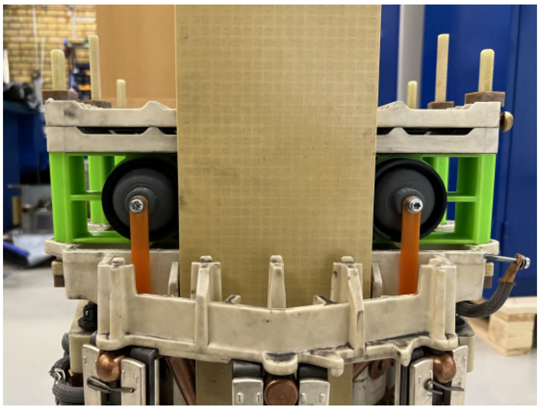

Figure 3.57: Profile view of the prototype.

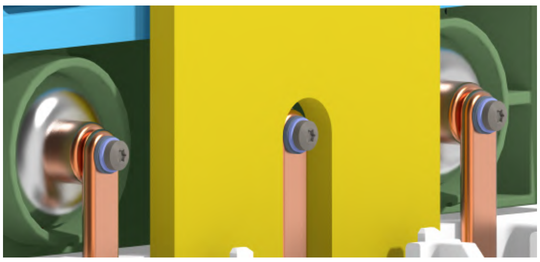

Figure 3.58: How the lifting plate needs to be modified.

Figures 3.59 and 3.60 shows the prototype from a distance and the holders at a closer distance.

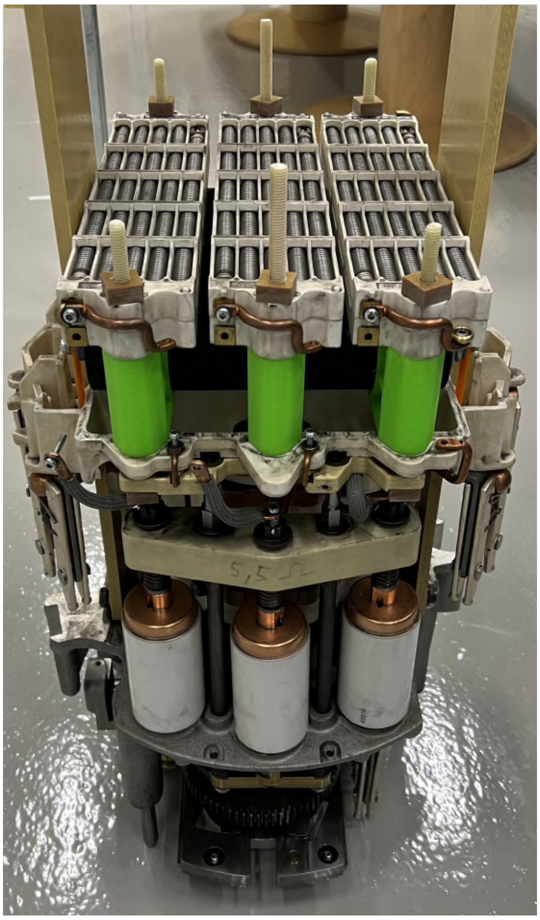

Figure 3.59: Side overview of the prototype and diverter switch.

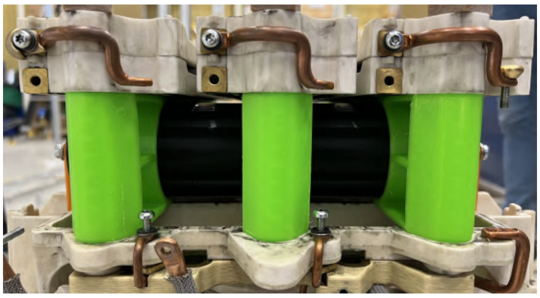

Figure 3.60: Side view close up of the three holders.

To conclude the prototype fitment test, it was successful. The assembly process was easy and intuitive. The prototype also felt surprisingly sturdy given that the parts are printed in a mix of PETG and PLA material. Two employees from production were also invited to see the prototype, they thought it looked easy to assemble and could not find any direct drawbacks with the solution.

3.8.4 FMEA

The FMEA, Table A.1, includes the new items used in the final concept, meaning the connection plates, long and short, Electric end connector for the surge arrester, holder and the modified surge arrester. The highest Risk Priority Number (RPN) is 300 from Item No. 1, Connection plates, Long and short. The Potential Failure Mode is flash-over from dielectric stress with the potential effect of OLTC failure. The potential cause of failure is a non-existing or too small radius along the edges of the item, creating a high concentration of dielectric stress. Severity and Detection is given a value of 10 because the consequences of an OLTC failure is catastrophic and it is very unlikely to detect this issue.

Table 3.19: FMEA of the Final design.

No.	Item	Function	Potential Failure Modes	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Current Preventative action	Occurrence	Current Design Controls Detection	Detection	RPN	Recommended Actions (Future work)
1	Connection plates, Long and short	Electric connection, Movement prevention	Loose connection	Loss of SA function	7	Vibrations loosens screw	Conical washer/ Thread inserts with lockturn	2	Visual inspection/ Torqued hardware	2	28	Vibration test
			Mechanical bending	Loss of SA function	7	Surge arrester movement	Mech. Simulation	2		4	56	Impact test
			Flashover from dielectric stress	OLTC failure	10	Too small radius cause too high dielectric stress	Electrical simulation	3	Not possible, testing required	10	300	Electrical simulation
2	Electric end connector for surge arrester	Electric connection	Poor connection	Loss of SA function	6	Loss of preload	High quality parts	1	Measuring device	7	42	Measurement of preload over time
			Bad threads	Loss of SA function	6	Loss of preload	Following existing guidelines	1	Visual inspection/ Torqued hardware	2	12	Collaboration with supplier
			Reduced machinability	Increasead scrap in assembly	2	Difficult to machine and paint geometry	Out-turn samples	3	Checkpoint during assembly	1	6	Collaboration with supplier
3	Holder	Fixation of surge arresters	Vibration	Material wear of surge arrester and holder	8	Poor fitment	Out-turn samples	3	Checkpoint during assembly	2	48	Quality inspection
			Melting of material	Reduced fixation	6	Too close to hot resistor	Heat compatible material	2	Material data	5	60	Heat test
		Modification of top plate*	Wrong item choosed in assembly	Assembly can not be completed	2	Similar visuals	Different part.no	3	Checkpoint during assembly	1	6	Interlocking to avoid wrong part combination
			Försvagning	Reduced lifespan/cracks	4	Reduced stiffnes of parts	Analyse design	2	Testing	5	40	Analyse and run test
4	Surge arrester	Over-voltage protection	Cracked casing	Reduced performance	7	Too deep grooves	Out-turn samples	3	Visual inspection	4	84	Material test

A larger illustration can be seen in the Appendix A.1.

3.8.5 Cost analysis

This simple cost analysis puts the final designs assembly, manufacturing, material and tooling costs in perspective to the corresponding costs for the existing solutions in percentage, see Figure 3.61.

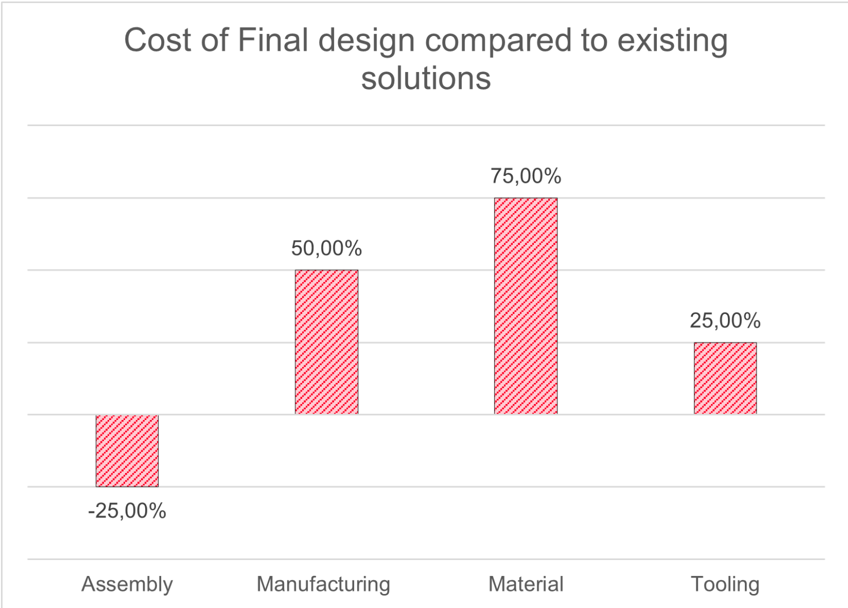

Figure 3.61: Cost analysis.

The existing solutions covers the VUCL surge arrester solution that has been covered previously, see Figure 3.1, but also the so called "arc gap" solutions that has not been covered due to limitations of this thesis. In short the "arc gaps" has the same function as the surge arresters, but the approach to handling the over voltages is different, the arc gaps approach creates electric arcs to dissipate the energy in opposite to the surge arresters that leads to ground.

Assembly

The assembly costs is an estimation of the difference in time between mounting the prototype to a diverter switch versus the average time it takes to assemble the other solutions at the production line. The time it takes to mount the prototype is estimated to be 25 % less than the total time of the existing solutions, there are a lot of factors that plays into this and makes it a coarse estimation. The mounting was done by different people, the prototype assembly was not done with the same tools and other aids as the line assemblies and the prototype cold not be completely assembled due to modifications needed, see Figures 3.57 and 3.58, to name a few factors.

Manufacturing
The manufacturing costs covers both in-house manufacturing and the costs for external suppliers, there is a mix of these. The manufacturing costs are estimated to be 50 % higher for the final design compared to the existing solutions, this is primarily due to the holders since they require either water cutting or similar or moulding depending on the material of choice. The housing for the surge arrester is also requiring a groove to be cut and the electrical end connectors will have to be made, in return the existing solutions are also containing manufacturing costs that can be cut with the Final design such as the mounting cage in Figure 3.1.

Material
Cost of material is estimated to be 75 % higher for the final design compared to existing solutions, this is manly due to the high amount of base material used for the holders in comparison to the existing solutions.

Tooling
Tooling costs are estimated to be 25 % higher for the final design compared to the existing solutions. This value is under the assumptions that only the surge arrester assembly tool needs to me modified and that the holders and connection plates are made by external suppliers. If moulding tools need to be bought for in-house production of the holders for example, the costs would be higher.

4
Discussion

This section will reflect about the approach and discuss the results.
The majority of time on this project has been spent iterating different concept generation phases with design reviews and discussions with the team at Hitachi Energy. The design reviews and discussions has been an important source of information and inspiration for this project. With that said, the research approach of including many iterations of design reviews has been valuable for achieving the aim for this thesis,
"To make a concept design concept design with surge arresters for Hitachi Energy's OLTC model that does not have this feature yet. The final concept design should reuse as much as possible of the current surge arrester assembly and parts for cost saving and maintain the function and performance of the current solution".

The research questions stated in the introduction of the thesis were the following:
- What are the key aspects when designing and mounting surge arresters?
- How does the mechanical, electrical and thermal stresses affect the mounting of the surge arrester and how is this designed for?
- What new factors are introduced with a new mounting location and how does these affect the surge arrester?
- Can the VUCL surge arrester assembly be used for external mounting outside the diverter switch?

Some key aspects found during the development and design of this new surge arrester mounting solution are safety followed by reliability of the solution, no other aspects are important if these aren't fulfilled. The solution needs to be safe for the people working on it and it should not induce any risks for the energy network. Reliability is also important since the lifespan of energy network components, including OLTC's and surge arresters are very long, with high requirements on reliability to avoid power outages.

Electrical stresses has been found to be the most affecting factor considering mounting of surge arresters. Some areas of the diverter switch for example is of the chart due to too high electric stresses. Electric stresses can be mitigated by avoiding sharp edges, which can also be seen throughout the OLTC by the use of radius and round shielding rings. Mechanical and thermal stresses are not as big of a problem, of course it was still needed to be taken into consideration through simulation and testing when designing the mounting solution.

From discussions with the team at Hitachi Energy, it was clear that the surge arresters are not sensitive to vibrations and heat as long it is within the environment inside of the transformer tank or diverter switch housing, i.e. submerged in transformer oil. As long as the surge arresters are placed within that environment there are not any new factors that are affecting the surge arresters significantly.

The VUCL surge arrester assembly could be used for external mounting outside of the diverter switch, a generalisation could however be that the farther away the surge arresters are mounted, the more troublesome and expensive the installation would become since the surge arrester need to be electrically connected to the diverter switch. There are also a lot more variations outside of the diverter switch depending on tap selector types and even transformer tank size/supplier and even customer specific variations, so to summarise, there are more unknowns and variations when the surge arresters are mounted outside of the diverter switch housing.

The final concept fulfils all requirements and wishes that could be evaluated in the time frame of this thesis. Requirements regarding electric simulation, testing and regulations testing has not yet been performed, therefore the results are unknown for those criteria, see Table 3.18.

The prototype test fitment was successful, but it could not be completely assembled due to interference with diverter switch parts that require minor modification in the future. It would have been interesting to be able to perform the complete assembly to make sure that no unexpected problems arises, although there should not be any. The choice of material for the holders were also discussed, performing a moulding of the holders with SMC could have some benefits over G11 regarding the mounting and connection of the resistors as well as visually.

5
Summary and Future work

In conclusion, this study has focused on the development of a new surge arrester mounting solution for a Hitachi Energy OLTC that does not have this feature yet. The overall process to deliver the final design was a typical product development process consisting of problem definition, prestudy, requirements formulation, generation of concepts, concept screening, concept scoring and prototyping.

The results from the thesis can be summarised as:

Problem definition
Through discussions with the team at Hitachi Energy the problem definition was finalised as "*Develop a new mounting solution for fitting VUCL surge arresters to another OLTC model, the solution should fit most versions of said OLTC while retaining the performance and long service life of the VUCL installation.*"

Prestudy
The prestudy gave valuable information about the OLTC and surge arrester. Information was found about requirements about mechanical loads and dielectric distances. Findings were also done regarding material compatibility in vapour phase and oil compatibility. This information was important for the requirement specification and concept generation and selection phases.

Requirements
A requirements specification was formulated based on discussions and findings from the prestudy. The criteria were divided into six main categories, Performance, Type test, Assembly, Material, Regulations and Maintenance.

Concept generation
The first concept generation exercise consisted of three phases, separated by design reviews with the team at Hitachi Energy to get valuable feedback on the concepts generated. The feedback was then implemented in the upcoming phase.

Concept selection
A concept scoring matrix was used to find the highest performing concept in regards to a selection of criteria from the requirements specification. Value scales were used to explain the rating of the concepts for each selection criteria as well as a weight matrix to calculate the relative importance, or weight, of each selection criteria.

Final concept generation
The final concept generation continues to develop the highest ranking concepts in a similar fashion as the first concept generation, but with two phases instead of three. The generated concepts will be evaluated in the final concept selection.

Final concept selection
The final concept selection was done with the same concept selection matrix as previously but with the selection criteria yielding the same rating across the board removed for a larger spread and a more representative total score. The highest ranking final concept was then put through mechanical simulation, examining von Mises stress and displacement.

Final design
This section covers the details about the final design such as a BOM list, requirement fulfilment, prototyping, FMEA and a simple cost analysis.

5.1 Future work

To realise the final design from a concept and prototype to an actual product will need future work for Hitachi Energy. Some interesting aspects concerning this thesis will be mentioned below.

Electric simulation has not been done yet, this will be the first step for future work. The electric simulation will test if the final design can be implemented safely without risking electric flash overs or other risks.

The tool for assembly of the surge arresters will need to be modified to function with the new surge arrester end contacts, implementation of new contacts also means that the surge arrester needs minor modifications "internally" as well.

Choice of material, especially for the holders, is a topic for future work. The materials of interest so far has been G11 and SMC, a deeper analysis of these two materials and possibly new additions will need to be made before production. The analysis could for example include manufacturing methods and costs as well as if the amount of material used has any effect on the surrounding transformer oil.
The choice of material also opens up for a more in-depth cost analysis that covers all costs related to the final concept.
The final design might be limited to be used with the tall diverter switch housing only due to BIL-levels becoming too low in relation to the voltage rating when using a short housing. This is something that needs to be tested and verified in the future.

A more extensive FMEA will need to be carried out to find and mitigate any associated risks with the final concept. The cost analysis will also need to be carried out more thoroughly to find the most suitable manufacturing methods, materials and if in-house manufacturing or supplier delivered parts are preferred.

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A

Appendices

A.1 FMEA

Table A.1: FMEA of the Final design.

No.	Item	Function	Potential Failure Modes	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Current Preventative action	Occurrence	Current Design Controls Detection	Detection	RPN	Recommended Actions (Future work)
1	Connection plates, Long and short	Electric connection, Movement prevention	Loose connection	Loss of SA function	7	Vibrations loosens screw	Conical washer/ Thread inserts with lockturn	2	Visual inspection/ Torqued hardware	2	28	Vibration test
			Mechanical bending	Loss of SA function	7	Surge arrester movement	Mech. Simulation	2		4	56	Impact test
			Flashover from dielectric stress	OLTC failure	10	Too small radius cause too high dielectric stress	Electrical simulation	3	Not possible, testing required	10	300	Electrical simulation
2	Electric end connector for surge arrester	Electric connection	Poor connection	Loss of SA function	6	Loss of preload	High quality parts	1	Measuring device	7	42	Measurement of preload over time
			Bad threads	Loss of SA function	6	Loss of preload	Following existing guidelines	1	Visual inspection/ Torqued hardware	2	12	Collaboration with supplier
			Reduced machinability	Increasead scrap in assembly	2	Difficult to machine and paint geometry	Out-turn samples	3	Checkpoint during assembly	1	6	Collaboration with supplier
3	Holder	Fixation of surge arresters	Vibration	Material wear of surge arrester and holder	8	Poor fitment	Out-turn samples	3	Checkpoint during assembly	2	48	Quality inspection
			Melting of material	Reduced fixation	6	Too close to hot resistor	Heat compatible material	2	Material data	5	60	Heat test
		Modification of top plate*	Wrong item choosed in assembly	Assembly can not be completed	2	Similar visuals	Different part.no	3	Checkpoint during assembly	1	6	Interlocking to avoid wrong part combination
			Försvagning	Reduced lifespan/cracks	4	Reduced stiffnes of parts	Analyse design	2	Testing	5	40	Analyse and run test
4	Surge arrester	Over-voltage protection	Cracked casing	Reduced performance	7	Too deep grooves	Out-turn samples	3	Visual inspection	4	84	Material test

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