DESIGN, IMPLEMENTATION AND VERIFICATION OF GAS INSULATED LOAD BREAK SWITCH AT 12 KV VOLTAGE LEVEL

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
THE MIDDLE EAST TECHNICAL UNIVERSITY

BY
AYŞE BERİL HARMANLI

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
ELECTRICAL AND ELECTRONICS ENGINEERING

OCTOBER 2014

Approval of the thesis:

DESIGN, IMPLEMENTATION AND VERIFICATION OF GAS INSULATED LOAD BREAK SWITCH AT 12 KV VOLTAGE LEVEL

submitted by **AYŞE BERİL HARMANLI** in partial fulfillment of the requirements for the degree of **Master of Science in Electrical and Electronics Engineering**, **Middle East Technical University** by,

Prof. Dr. Gülbin Dural ______________________________

Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Gönül Turhan Sayan ______________________________

Head of Department, Electrical and Electronics Eng. Dept, **METU**

Prof. Dr. İsmet Erkmen ______________________________

Supervisor, Electrical and Electronics Eng. Dept, **METU**

Examining Committee Members :

Prof. Dr Ahmet Rumeli ____________________

Electrical and Electronics Eng. Dept, **METU**

Prof. Dr İsmet Erkmen ____________________

Electrical and Electronics Eng. Dept, **METU**

Prof. Dr Mirzahan Hızal ____________________

Electrical and Electronics Eng. Dept, **METU**

Prof. Dr Nezih Güven ____________________

Electrical and Electronics Eng. Dept, **METU**

Öğr. Gör. Dr. Halas Bilge Mutluer ____________________

Europower Enerji ve Otomasyon teknolojileri A.Ş.

Date: 10 October 2014

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last Name : Ayşe Beril HARMANLI

Signature :

ABSTRACT

DESIGN, IMPLEMENTATION AND VERIFICATION OF GAS INSULATED LOAD BREAK SWITCH AT 12 KV VOLTAGE LEVEL

HARMANLI, Ayşe Beril

M.S., Department of Electrical and Electronics Engineering

Supervisor: Prof. Dr. İsmet ERKMEN

October 2014, 164 pages

In this thesis, the engineering design contributions on arc extinguishing method, relevant arc stretching issue, selection of magnet to obtain expected magnetic force, contact structure and magnet selection parameters, insulation medium properties and design effects, operation mechanism, arc modeling and derivation of the design arc modeling formula on 12 kV SF_6 gas insulated load break switch is handled. By these contributions of the thesis, the design, prototype manufacturing and verification of the design via testing at an accredited laboratory is investigated.

Literature survey is completed related to arc models, arc extinguishing methodology and operation mechanism. As the outcome of this literature survey and the market search the designed load break switch is implemented with an arc extinguishing method based on forcing the arc to diminish via the magnetic force effect of the magnet within contacts. As the operation mechanism, rotation around central axis is applied. The arc extinguishing method and mechanism structure selection are based on the design target of extinguishing the arc in less duration within less separation between contacts compared with other products in market.

Arc models starting with Cassie and Mayr models are investigated, and the Cassie model is selected as the most suitable model. Derivation of the Cassie formula and its application on the design is studied. Maxwell and Matlab simulation results are investigated and compared with the mathematical calculations. The SF_6 gas parameters as the insulation level are studied and simulated. Contact structure and magnet selection parameters with the spring constant calculations are studied.

Key words: Switchgear, RMU, Load breaker, SF_6, Arc, Arc modeling

ÖZ

12 KV GERİLİM SEVİYESİNDE GAZ İZOLELİ YUK AYICISI HÜCRESİ TASARIM1, PROTOTİP YAPIMI VE TASARIMIN UYGUNLUĞUNUN DOĞRULANMASI

HARMANLI, Ayşe Beril

Yüksek Lisans, Elektrik ve Elektronik Mühendisliği Fakültesi

Tez Yöneticisi: Prof. Dr. İsmet ERKMEN

Ekim 2014, 164 sayfa

Bu tezde, 12 kV seviyesinde SF_6 izoleli yük ayırıcısı tasarımında arkın söndürülmesi, buna bağlı arkın uzaması konuları, gereken seviyede manyetik güç elde etmek için mıknatıs seçimi, kontak yapısı ve mıknatıs seçilmesi ile ilgili parametreler, izolasyon ortamının özellikleri ve tasarıma etkileri, mekanizma yapısı, ark modellemesi ve tasarıma uygun ark model formülünün türetilmesi konularında mühendislik katkıları ele alınmıştır. Bu tezin katkısıyla hücresinin tasarımı, prototip imalatı ve tasarımın akredite laboratuvarlarda testlerle doğrulanması ele alınmıştır.

Ark modelleri, ark söndürme yöntemleri ve mekanizma yapısı ile ilgili literatür incelenmiştir. Bu literatür incelemesi ve piyasa araştırması sonucunda, tasarlanan yük ayırıcısında ark söndürme yöntemi olarak kontak içerisine yerleştirilmiş mıknatıs yardımı ile ark üzerinde manyetik güç etkisi yaratılması suretiyle, ark uzatılarak sönümlenmiştir. Mekanizma yapısı olarak da merkez etrafında rotasyona dayalı yapı seçilmiştir. Ark söndürülme yöntemi ve mekanizma yapısı seçiminde hedef alınan tasarım parametresi olan piyasadaki diğer ürünlere göre daha kısa sürede ve kontaklar arasında beklenen mesafeyi azaltarak arkın sönümlenmesi baz alınmıştır.

Cassie ve Mayr başta olmak üzere ark modelleri incelenmiş ve Cassie modelin tasarıma en uygunu olduğu saptanmıştır. Cassie formülünün türetilmiş ve tasarıma uygulanmıştır. Maxwell ve Matlab simulasyon sonuçları ile matematiksel hesaplamalar karşılaştırılmıştır. SF6 gazı özellikleri incelenmiş ve simule edilmiştir. Kontak yapısı ve mıknatıs seçimi ile yay sabiti hesaplamaları üzerinde durulmuştur.

Anahtar kelimeler: Hücre, RMU, Yük ayırıcısı, SF_6 , Ark, Ark modellemesi

To my father…

ACKNOWLEDGEMENTS

I would like to thank to my supervisor Prof. Dr. İsmet Erkmen and my co-supervisor Prof. Dr. Mirzahan Hızal, for their technical support and motivation during this thesis work. It was a big chance to work with valuable and experienced professors.

I would like to express my deepest gratitude to Dr. H. Bilge Mutluer, because of his great effort and support on my study can truly say that, his endless encouragement is one of the most important milestones on my thesis work.

Ramin Malek as my manager treats as a father to me during my work. He was always there whenever needed with his valuable experience and technical approach.

The developed system is the result of a research and development project in the company that I worked for the last 3 years. I would like to thank to EUROPOWER for all the opportunities offered.

I would like to show my appreciation to my colleagues Houseng Shoar and Selami Arslan for their substantial contribution to the thesis in terms of mechanical design works respectively.

I would like to thank to my father for his great courage and trust.

İpek Harmanlı, as my twin sister, deserves special thanks for sharing all my life. She was there any time even I need someone to tell me that I can success it.

Finally, I would like to thank to all my friends for their existence in my life.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

φ_l	Power factor angle
U_R	Test voltage on Phase R
U_S	Test voltage on Phase S
U_T	Test voltage on Phase T
DC	Percentage on DC component
K	Spring factor
W	Work
U_l	Voltage applied on phases
U_2	Recovery voltage on load side
T_{SC}	Duration of short circuit
T_b	Breaking time
P_c	Control pressure
P	Power
I_s	Current on phase S
I_R	Current on phase R
I_T	Current on phase T
T_m	Making time
T_{st}	Current settlement time
T_C	Closing time
T_O	Opening time
T_A	Arcing time
I_{ma}	Peak value of making current
X	Distance
I_c / I_o	Closing/ opening current control
U_S	Supply voltage
U_C	Control voltage

S	Contact movement
τ	Time constant
G	Conductance
e	Electron charge
H	Magnetic flux intensity
B	Magnetic flux density
A	Magnetic flux
q	Charge
E	Electric field
V_{dr}	Drift velocity
V_{en}	Frequency of electro neutral collision
F	Force
f	Frequency

ABBREVIATIONS

MV	Medium voltage
GIS	Gas insulated switchgear
RMU	Ring main unit
CT	Current transformer
VT	Voltage transformer
SLD	Single line diagram
TRV	Transient recovery voltage
CB	Circuit breaker
LV	Low voltage
LBS	Load break switch reactor
HV	High voltage
PD	Pressure distance

CHAPTER 1

INTRODUCTION

1.1 Overview of Components in the Electrical Power System Distribution

The changing dynamics of the electrical energy structures has started with the 18th century to now on, emerging fundamental topics: Energy reliability and availability. These topics create a great market for the components that protect the generation, transmission and especially the distribution systems from the faults that might cause long term outages. In this Section, the main focus is the distribution system and its components with their mission on the reliable, safe distribution network.

The electricity used for domestic usage, in factories are low voltage one phase or three phase energy. The generation plants generate energy typically at medium or low voltage (up to 40 kV, depending on the geographical and technical properties of the plant or the source of energy). However due to the expected loss on long distance transmission of energy, it is disadvantageous to transfer the generated energy to the distribution nodes at its generated voltage. On transmission lines, current is the component determining the loss on the transmission components. To be able to keep current value as minimum, it is needed to increase the voltage level via step- up generation substations. At the final node of the transmission system, the voltage level needs to be step down as per the distribution system requirements. In Figure 1.2, an example for the passage between transmission and distribution systems with single line diagram modelling is seen. After the secondary side of the power transformer, the distribution network limits are started.

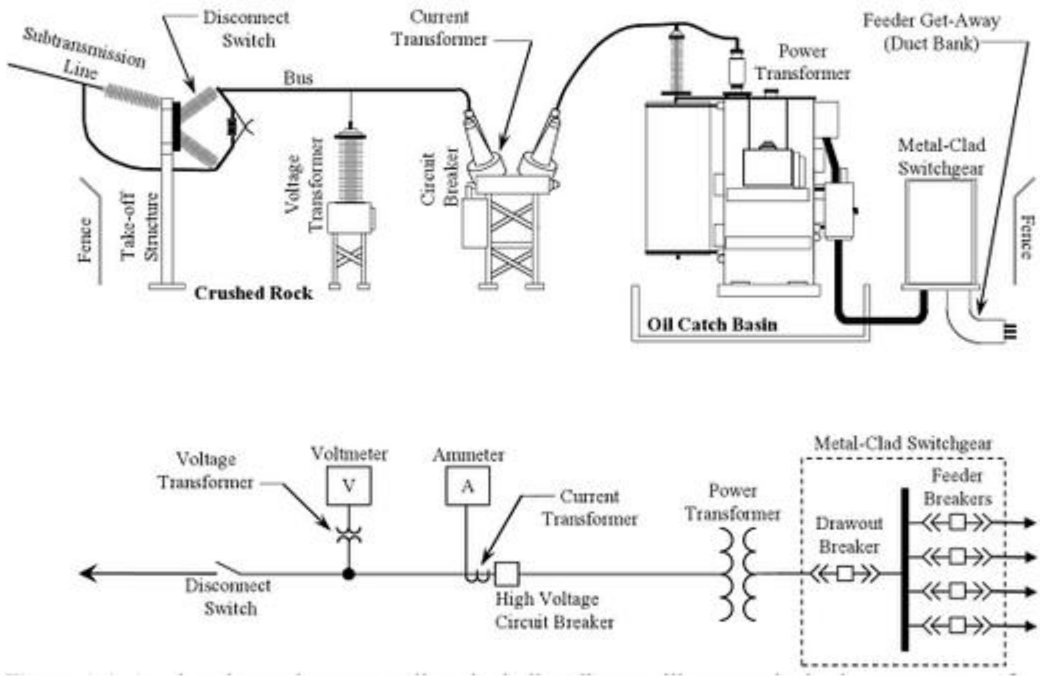


Figure 1: The transition between subtransmission station to distribution station [6]

The main distribution system components can be listed very basically as below:

- Transformers
- Medium Voltage Switchgear and switching devices
- Overhead line components
- Cables and underground connection components

- Protective relays
- Substation Automation- Smart grid configurations
- Compensation equipment

The importance of the distribution system components has increased due to several reasons. The first reason is the increased importance given to improve the power system continuity and reliability which is getting a demand with increasing industrialization. This reason makes the MV switchgear components more and more important. Secondly, to decrease the duration of outages via coordinated distribution network and to limit the fault point as narrow as possible becomes a crucial consideration with worldwide regulations. To success the coordination within networks, protective relays, as a component connected to the switchgears and substation automation, get more fundamental. The coordinated switchgear network is also very important to ensure that any fault faced in the distribution network needs to be cleared fast without leading any adverse effect on the remaining distribution network or transmission network.

The switchgear is a connection and protection device of the distribution network. The switching devices used in switchgears are mainly disconnecting switches, circuit breakers and load break switches. These devices have different functionalities and abilities that are used regarding the switchgear connection point. Therefore the system requirements determine the switchgear elements and combinations.

The switchgear usage purpose can be listed as;

- Protecting the system from any kind of temporary or permanent system fault including short circuit, overcurrent, under-over voltage, under-over frequency, etc. via CB+ Relay combinations.
- Leading to the distribution system coordination
- Limiting the temporary fault durations via auto reclose property on CB+ relay combinations.
- Causing load addition or subtraction from the grid

- Protecting the expensive distribution network components such as cables and transformers

The switchgears can be classified based on many different parameters. This thesis is based on the switchgear classification regarding the insulation medium material and function of the switchgear

Load Breaker function in gas insulated MV switchgear at 12 kV voltage level is investigated thoroughly in Chapter 2.

Figure 2: 12 kV Modular type gas insulated switchgear as incoming and outgoing feeder with load break switch and transformer protection with load break switch and fuse combination

This switching unit includes a load break switch panel as the incoming of the ring, a load break switch panel as the outgoing of a transformer or a motor and another load break switch panel as the outgoing of the ring. Each of the 3 switching devices are in conjunction with the busbar, a conventional three-position switch as an isolator, which in this case may be in the form of a so-called linear-travel switch.[2]

1.2 The Classification of the Switchgears

The switchgears that are used in the modern electrical power systems can be classified according to many aspects. These classification aspects vary depending on the switchgear usage field and usage purpose. This thesis adopts the topic of load break switch application in gas insulated switchgear at 12 kV voltage level. Therefore the considered classification parameters in this thesis are the insulation medium and the voltage level. The first classification aspect is regarding of the insulation material between the movable contacts of the switching device which is mentioned in detail at Sections 1.2 and 1.3. The second classification aspect is the classification regarding of the voltage level. To understand the classification of switchgears regarding the voltage level, firstly it is necessary to understand the transaction of energy, the reason of voltage levels and demanded insulation requirements on different voltage levels.

Electricity is generated, transmitted through different regions and distributed to the customers via constructed generation, transmission and distribution systems. Electricity and the paths used until it reaches to the end customer get more and more important especially after 18^{th} century with the Industrial Revolution. Nowadays, energy and electricity market are the one of the most crucial markets on the worlds.

Generation Subsystems are composed of generation plants, that produce electrical energy from another form of energy such as hydropower, wind power, fossil fuel via typically turning motion of an alternator by a prime mover to generate power with the voltage between 0.4 kV and 40 kV, and generation substations , which connect generation plants to transmission lines through a step- up transformer that increases voltage to transmission level. [1]

Transmission Subsystems transport electricity over long distances from generation substations to transmission or distribution substations. The transmission system is composed of substations, switching stations and subtransmission systems. Transmission switching stations serve as node in the transmission system that allows transmission line connections to be reconfigured. Transmission substations are transmission switching stations with transformer that step down voltage to subtransmission levels. Subtransmission system transport electricity from transmission substation to distribution substations. [1]. In Turkey the transmission voltage level is mainly 154 or 380 kV while the subtransmission voltage level is 36, 10.5, 6.3 kV.

Distribution Subsystems is composed of distribution substations, primary distribution system and secondary distribution system. Distribution substations are nodes for terminating and reconfiguring subtransmission lines plus transformers that step down voltage to primary distribution level. Primary distribution systems deliver electricity from distribution substations to distribution transformers. The primary voltage range is 4.16 kV to 40 kV with the most common 34.5 kV in Turkey. The distribution transformers, which have typically 5 kVA to 2500 kVA power rating, convert primary distribution voltages to utilization voltage. Secondary distribution systems deliver electricity from distribution transformers to customer service entrance. This is the distribution starting node as the output of the distribution transformer. Voltage level is typically 220 V single phase or 380 V three phase in Turkey [1].

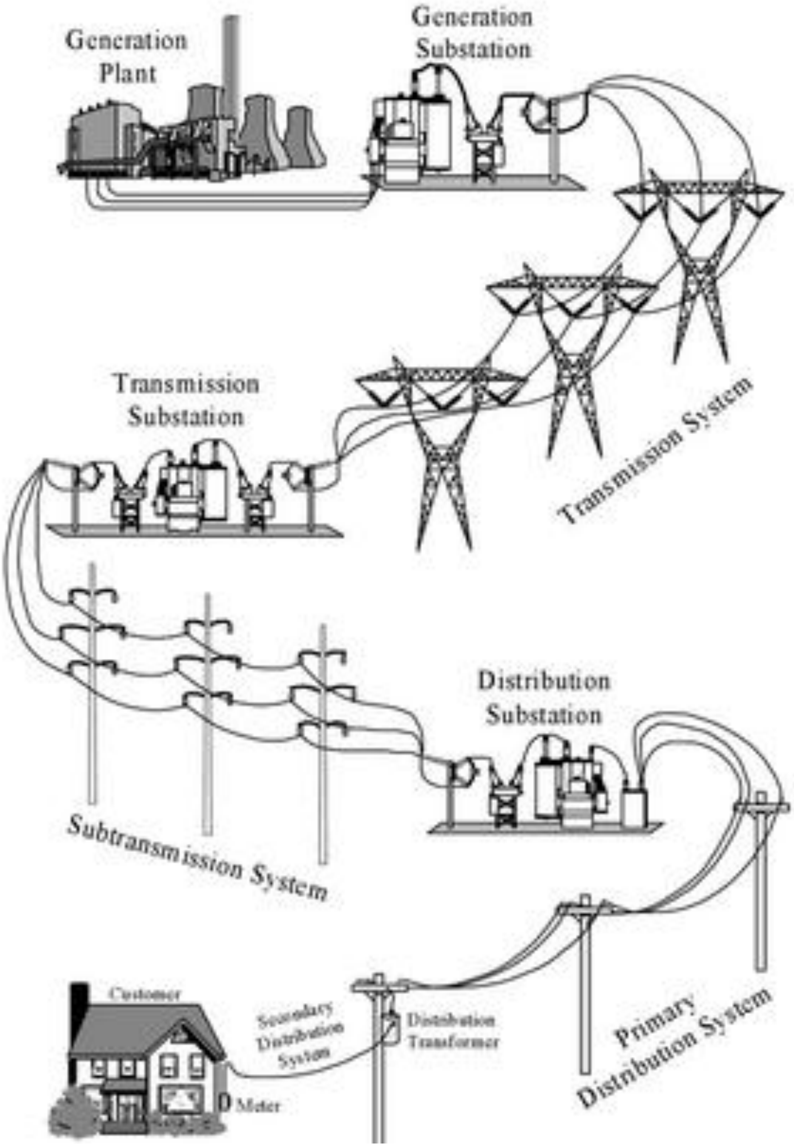


Figure 3: Electricity generation, transmission and distribution modelling

1.3 SF_6 Gas Insulated Switchgear Usage in Distribution and Transmission Network

After the invention of the SF_6 gas at 1975, SF_6 gas has become an important material that used in industrial applications and scientific studies. The SF_6 gas has very outstanding features that make it very important energy studies such as MV and HV applications. The voltage level manners the creepage distance between the conducting ends that has different potential levels. The creepage distance between the conductors matter the voltage difference as well as the insulating medium properties between contacts.

Air is an insulator but also a good conductor. The electrical property of the air as an insulating material depends on the environmental conditions especially the humidity, temperature and altitude. To be able to have desired insulation conditions at especially MV and HV on air, it is needed to obtain long creepage distance. After the discovery of the SF_6 gas, the idea of changing the insulation medium between contacts at HV and MV for leading better insulation class and smaller creepage distances became a dominant idea. This is the reason that, SF_6 gas insulation is the most popular insulating material used in MV and HV. Nowadays, with the KYOTO Protocol, there is a tendency on decreasing the SF_6 gas usage in energy field. However, still SF_6 is the most dominated insulation medium in HV and MV.

1.4 Other Insulation Material Applications in Distribution Network

There are many classification methods that can be used for the switchgears. In this thesis, one of the emphasized classification manners is regarding the insulation material between the movable contacts of the switching device. Therefore the types of MV switchgears used in distribution systems other than medium voltage gas insulated switchgear which is explained at Section 1.2 can be classified in mainly three groups according to the insulation medium used in switching element operation contacts: Air insulated switchgear, oil type switchgear and solid insulated switchgear

Table 1: Comparison of MV switchgears regarding the insulation materials

Type	**Advantages**	**Disadvantages**
Air insulated	• Compact structure • Easy maintenance since the components of the switchgear can be reached easily • The insulation medium is air itself, so no aging problem on medium	• Bigger dimensions • Not beneficial on international transportation
Gas insulated	• Can be in modular type or compact type • Low weight • Small dimensions • Beneficial in transportation	• Dangerous for environment • The case of the switchgear needs to be used carefully. Any damage on the case of the switchgear might lead the insulation medium to be distracted. • Difficult maintenance

Table 1 (Continued):

Type	**Advantages**	**Disadvantages**
Solid insulated	• Better insulation level that oil, gas and air types • Environment friendly • Smaller dimensions • Better performance on high voltage levels • Better performance on high current values since the heat transmission in solid is less compared to other equipment	• Expensive than gas, oil and air types • More heavy • Difficult maintenance • Less manufacturer on the world, so less competition • Less flexibility on side for different combinations of switchboards • Aging problem on the insulation medium • Difficult transportation because of its weight
Oil insulated		• Aging problem on the insulation medium • Difficult transportation because of its weight • More heavy • Difficult maintenance • Requires frequent maintenance • Old application, not used any more

1.5 Scope of Thesis

12 kV load break switch application on gas insulated switchgear is designed, prototype manufacturing is completed and the design work is validated by the tests on the manufactured prototype. This thesis work provides engineering contribution to the design process on arc extinguishing method, relevant arc stretching issue, selection of magnet to obtain expected magnetic force, contact structure and magnet selection parameters, insulation medium properties and design effects, operation mechanism, arc modeling and derivation of the design arc modeling formula on 12 kV SF_6 gas insulated load break switch.

Although the main purpose is to design a load break switch, the design of the full switchgear, including the load break switch needs to be completed in order to make it work as a real electrical power unit. Therefore, the load break switch is mounted in a compact type gas insulated switchboard. By this compact kit the load break switch is used as incoming and outgoing feeder and also it is implemented for transformer protection as a load break switch and fuse combination. Firstly, literature survey and market search related to load break switch applications are completed. All material properties; mechanical parts including spring properties used in the load break switch operating mechanism, SF_6 gas properties, copper contact selection parameters are worked in detail. The arc extinguishing methodology is adopted as magnetic force effect of magnet embedded into the busbar contact. This methodology is adopted without the supportive effect of the SF_6 gas puffering, to ensure safer and more reliable extinguishing method comes with fewer arc extinguishing duration with less contact separation requirements. This arc extinguishing methodology is also supported by the selection of operation mechanism as rotational motion around the central axis. The mathematical calculations related to the arc extinguishing, related magnetic force effect and magnet parameters are completed. The mathematical calculations are supported and compared with Maxwell and Matlab simulation results and computations. After the study and simulation on currently applied theories, design stage and prototype assembly are completed. The prototype as a full switchboard enclosure is prepared for design validation. In power system, the simulations are not sufficient to validate a prototype. The verification of the design could be accomplished by only performing the type tests declared in TEDAŞ MYD 95-002 that addresses to IEC 62271-200. Some of these tests are done in Europower accredited laboratory; others are done in some other accredited laboratories. The results of the tests are defined at Chapter 4 separately. At the conclusion part the comparison between the test results and the design parameters/ expectations are discussed.

The designed 12 kV compact gas insulated switchgear has 3 switching modules in it; line incoming load break switch module, line outgoing load break switch module, and transformer protection as load break switch+ fuse combination module. The verification of this designed switchgear is accepted as the verification of load break switch design at 12 kV insulation level.

This research has made the following contributions to the area of MV gas insulated switchgear:

- The target of this thesis work is to obtain arc extinguishing manner with parameters of less arc extinguishing duration with less distance between the contacts which means smaller rotation angle of the operation mechanism.
- The 12 kV gas insulated switchgear is designed and validated without using external arc limiting devices. This design method adopts the arc extinguishing method as the magnetic force applied by the permanent magnets in the contacts. Other frequently used methods, limiter or rotating puffering arc extinguishing methods are not preferred in the design stage. As the contribution of this thesis on the load breaker design parameter is that, the arc extinguishing mechanism is totally based on magnetic force effect without any impact of puffering. Rotational puffering is simply blowing the SF_6 gas as the insulation material with high dielectric property to the source point of the arc to suppress the arc formation. This method is not a safe method for arc extinguishing since SF_6 gas dielectric property will decrease

due to the contaminations and ionization occurred with the effect of arc or other causes in time. Therefore, depending on insulation material suppression effect on arc ,which will lose its dielectric strength and also might face with change on its pressure, is not an acceptable arc extinguishing method according to the design limits of our load breaker.

- The 12 kV load break switch used in the gas insulated switchgear within the scope of this thesis is the first known local manufactured load break switch that adopted magnetic arc extinguisher without any effect of rotary puffering as arc extinguisher which leads a safer design with long life time.
- The operation mechanism types are investigated and the rotation around the central axis model is selected and applied to the design. It is ensured that this operation mechanism also supportive in terms of selected arc extinguishing method and simulation results.
- The design criteria of gas insulated switchgear with load break switch are investigated with all aspects by concerning all components.
- After the prototype verification, the product gets commercialized and it turns to a real commercial business.
- The parameters of SF_6 gas as the insulation medium is studied and simulated by using related calculations and Maxwell simulation results. The SF_6 gas insulation medium is compared with air. The contact structure within SF_6 gas medium is verified in terms of potential distribution during arc extinguishing distance.
- Literature survey on arc models is completed and necessary comparisons among the models are completed
- The Arc modeling based on Cassie model is adopted to control the design parameters related to the arc extinguishing. The derivation of the Cassie model formula with its adaptation on our system is completed. The formula and calculation results are compared and supported by Maxwell and Matlab simulation results and plots.

- Maxwell simulation results are acquired to compute the electrical and magnetic parameters related to the contact structure of the load breaker. The magnet selection parameters are calculated and the proper magnet is selected for the arc extinguishing mechanism. The magnet selection is done from the rare earth type magnet class with neodymium magnet.
- Mechanical design parameters such as spring selection parameter are investigated. Necessary calculations are completed to determine the k constant of the selected springs.

The outline of the thesis is as follows:

In Chapter 2, the MV gas insulated switchgear is taken as the general topic. All possible components that are currently used in MV gas insulated switchgear application are investigated. All possible configurations are taken in the consideration. The materials and devices used in gas insulated switchgear are explained in detail. The main components that are based on the design topic of thesis are described including load break switch and SF_6 gas. Circuitry diagram, figures and component based explanations are given in this Section. Also other configurations and components that might be used in gas insulated switchgear are referred in this Chapter.

Chapter 3 is the part that refers structural design and engineering contribution of the thesis on the design process of 12 kV gas insulated switchgear with load break switch configuration. The main contribution is to obtain an arc extinguishing methodology which leads less duration of arc extinguishing with less contact separation. All design parameters are referred in detail. After the overview of all design criteria, the component merging to finalize the system assembly is mentioned. The working principle and milestones on operation are also explained in this Section. The literature survey on arc modelling, arc extinguishing methods and operation mechanism are mentioned in this Section. The arc modeling, magnetic selection, SF_6 gas medium milestones and electrical features related to the contact structure of the load break switch are developed in this Chapter. Mathematical calculations related to mechanism, arc extinguishing, SF_6 gas medium, magnet selection and verification of contact structure in SF_6 gas medium are provided in this Chapter. All Maxwell and Matlab simulation results are given and interpreted, necessary comparisons are also provided in this Chapter.

In Chapter 4, the validation of the design of the prototype is taken into consideration. The type tests that are required for the design approval in terms of international specifications are investigated separately. The test set up, the purpose of the test, the outcomes of test and simulation results are shared. Since the test results met the international specifications by IEC 62271-200 and TEDAŞ MYD 95-002, the prototype is validated to be commercialized in domestic and international markets.

Finally, in Chapter 5, the theoretical design is justified with the implementation and verification tests. The results are discussed and further work is proposed in order to improve the design. The future plans for converting this prototype study to a mass production, the strategically plans are also mentioned.

CHAPTER 2

GAS INSULATED SWITCHGEAR COMPONENTS AND MECHANISMS

2.1 Gas Insulated Switchgear General Properties:

In modern power generating stations, power switching stations and power substations; gas-insulated switchgears are widely used as switching equipment since by this way, the area required for the installation of the station can be reduced and the maintenance of the station components can be maintained easily. In this kind of switchgear apparatus, a suitable gas such as SF_6 gas ,having an excellent electrical insulating property, is filled within a sealed vessel or metal enclosure which is maintained at the earth potential, and high-potential loading conductors are disposed within this sealed enclosure in a relation electrically insulated from the enclosure by an electrical insulator. Due to the fact that the electrically insulating gas such as SF_6 gas is contained within the sealed enclosure of the gas insulated switchgear apparatus for the purpose of electrical insulation of the high-potential loading conductors from ground, the distance required for the electrical insulation between the conductors and ground, i.e. ground insulation distance, can be greatly shortened compared with that in a conventional air-insulated switchgear apparatus, and the distance required for the electrical insulation between different phases, i.e. interphase insulation distance, can also be greatly shortened. Thus, the overall size or volume of the switchgear apparatus can be greatly reduced [5].

In other words, due to the SF_6 gas electrical and thermal characteristics, improved gas insulated switchgear has shortened axial length between main busbar and the connection conductors.

Gas insulated switchgear application on MV is frequently used especially in the areas where the land is limited and also at the places where the climate conditions are severe. Especially, at the distribution points where the attitude is higher than 1000m from the water level, SF_6 is preferred as the insulation material for switchgears because of its heavy weight. Therefore, in these conditions gas insulated switchgears are preferred instead of air insulated switchgear. In some countries such as UAE, Saudi Arabia, medium voltage GIS is the main component of the distribution system while AIS is totally out of topic at the distribution network. The reason behind of this application is the SF_6 gas advantageous thermal property in terms of its cooling effect during the flow of the current.

MV gas insulation switchgears can be classified in many different manners. One of them is the configurationally connection type. MV Gas insulated switchgears could be in compact or modular structure. The compact structure leads the standard, basic configurations to be manufactured easily and to decrease any risks that might occur at the connection points between separate panels. Compact type switchgear could be classified as extensible type and non- extensible type. Extensible compact GIS could be enlarged via external busbar connection with the modular MV GIS switchgear or with any other extensible type compact switchgear. Another classification of MV gas insulated switchgear could be modular type. Modular construction leads flexibility in the distribution network configuration. By using modules separately or connecting modular switchgears with extensible compact type switchgears, different configurations could be attained.

Figure 14 shows an example distribution network starting from the transmission substation to primary distribution network. As it is seen, at the transmission substations the voltage level is decreased to distribution voltage level which is 12 kV for this case. The distribution is composed of 4 different branches.

Figure 4: Compact type 12 kV gas insulated switchgear

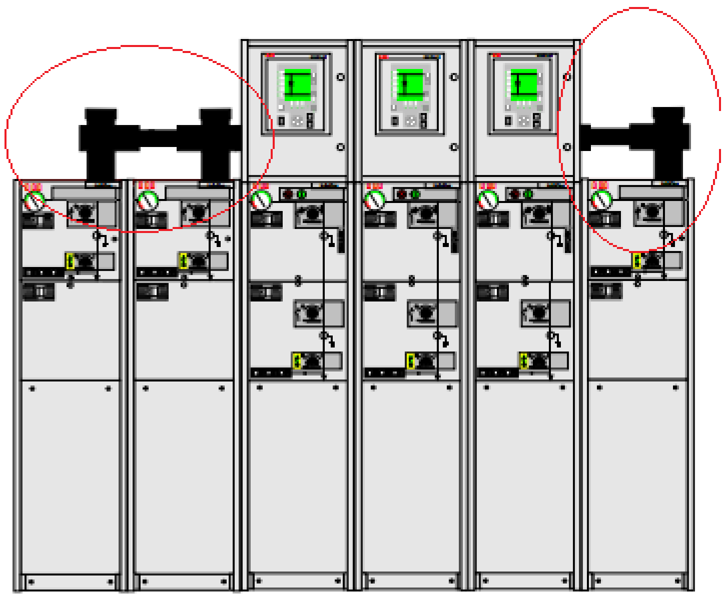


Figure 5: Compact type extensible 12 kV gas insulated switchgear shown with the extension bars as circle

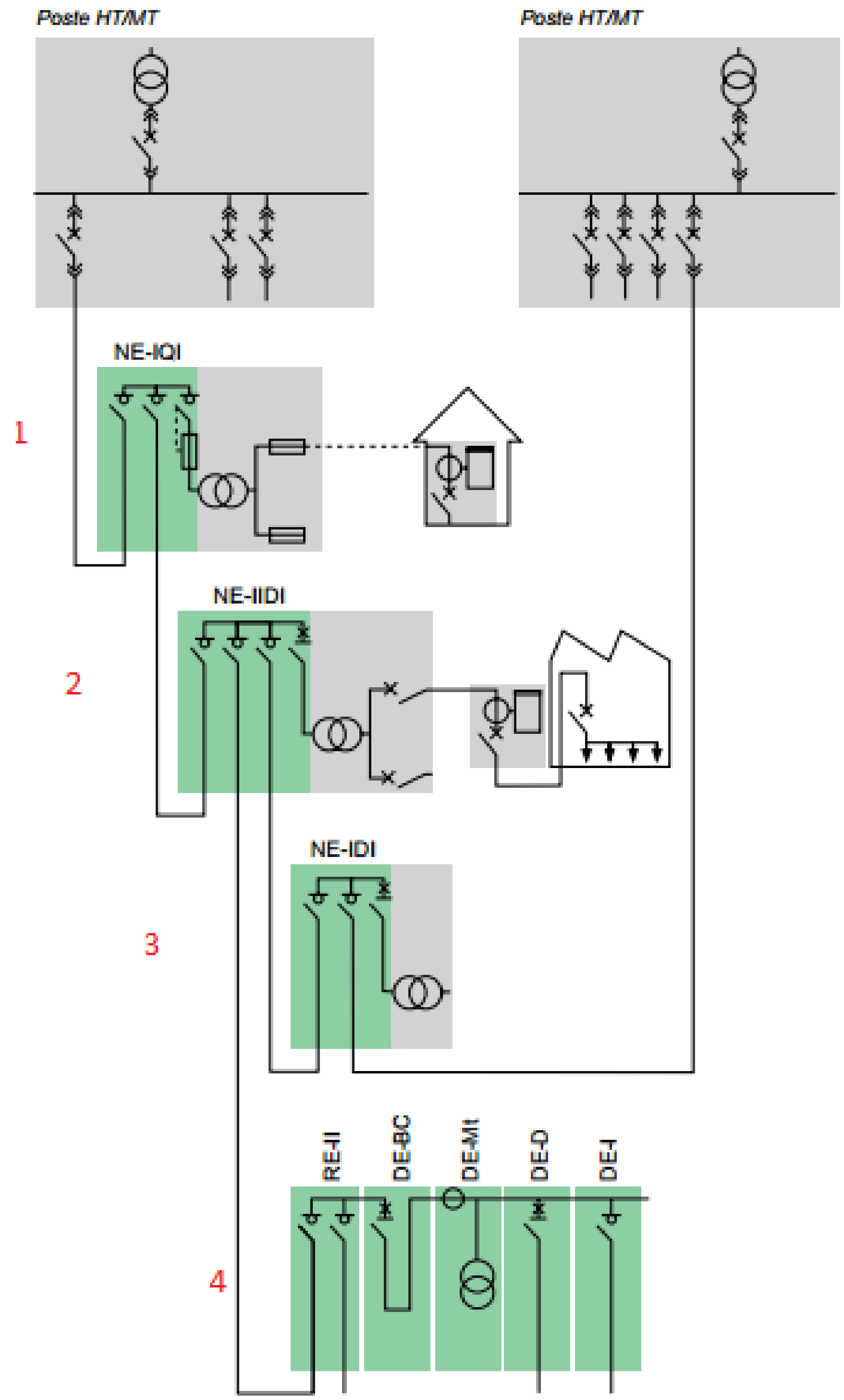


Figure 6: Example distribution network constructed by using 12 kV gas insulated switchgear, taken from Schneider RM6 GIS catalogue [25]

Table 2: Branch description related to Figure 14

Branch	Description
0	There are 2 transmission substations with the secondary outage of 12 kV. After that step, other branches are exemplifying the distribution network cases starting from secondary side of the transmission. These substations are the starting points of the distribution network.
1	The system shows the primary distribution, distribution transformer and the entrance of the secondary distribution to a residential point. The switchgear used in the primary distribution is a compact type 12 kV gas insulated switchgear composed of 3 non separable (compact) and non-extensible modules. In basic designation, this is a LLF compact unit (which is corresponding to IDI in Schneider branded designation). There is one incoming line as load breaker which leads to entrance of the electricity to the main busbar of the switchgear coming from the MV outgoing of branch-3. The second unit is the outgoing line of the branch-1 with load breaker which acts as the incoming line of the branch-2. The third unit is the transformer protection with load breaker and fuse combination for protecting the transformer from any overcurrent problems and so maintaining the safety of the residential customer point. This compact type gas insulated switchgear is the design and prototype manufacturing issue mentioned at the Chapter 3.
2	The system shows the primary distribution, distribution transformer and the entrance of the secondary distribution to an industrial customer point. The switchgear used in the primary distribution is a compact type 12 kV gas insulated switchgear composed of 3 non separable (compact), load breaker + load breaker and circuit breaker combination and one extension as modular switchgear with load break switch. There are two incoming lines as load break switch which lead to entrance of the electricity to the main busbar of the switchgear coming from the branch-1 and branch-3. Also there is one unit of outgoing feeder as the incoming of branch- 4, one transformer protection unit with circuit breaker. Such a configuration is seen in Fig. 2.5.

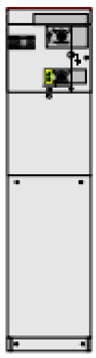
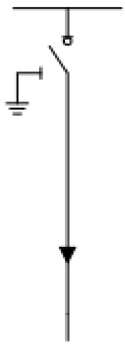
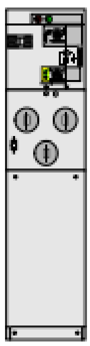
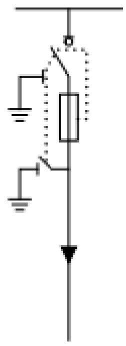
Table 2 (Continued):

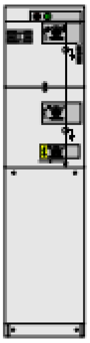
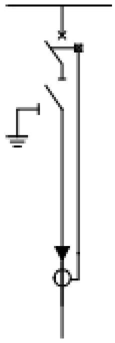
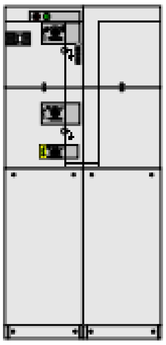
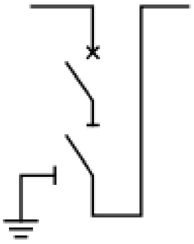
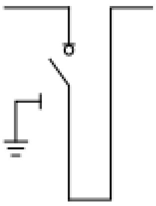
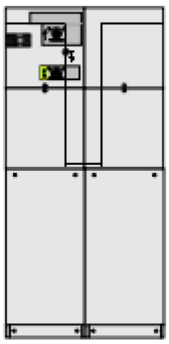
Branch	Description
3	The system shows the primary distribution, distribution transformer and the entrance of the secondary distribution to an unknown industrial, residential or any other kind of customer point. The switchgear used in the primary distribution is a compact type 12 kV gas insulated switchgear composed of 3 non separable (compact) and non-extensible modules. In basic designation, this is a LLCB compact unit (which is corresponding to IQI for Schneider branded designation). There is one incoming line as load break switch which leads to entrance of the electricity to the main busbar of the switchgear. The second unit is the outgoing line of the branch-3 with load break switch which acts as the incoming line of the branch-2. The third unit is the transformer protection with circuit breaker and protective relay for protecting the distribution transformer from any find of overcurrent, short circuit, over/under voltage, over/under frequency, etc. problems and so maintaining the energy safety and reliability of the industrial customer point.
4	This switchgear is composed of one compact and extensible unit composed of 2 load break switch and 4 extension modules. These extension modules are one current voltage measurement switchgear, one load breaker module, one circuit breaker module and one coupling+ bus riser module.

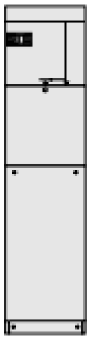
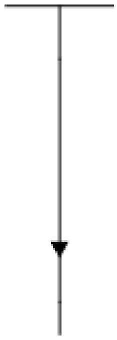
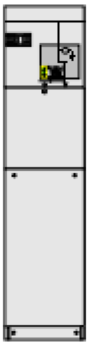
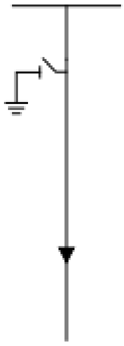
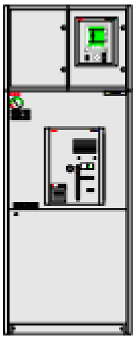
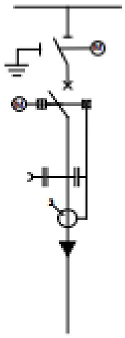
2.2 Switching Configurations and Components Used in a Gas Insulated Switchgear

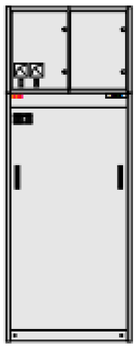
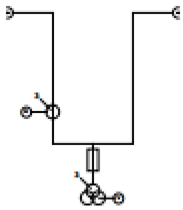
Gas insulated switchgears could be designed in many different configurations regarding the system requirements. The switching components have different functions and properties. In Table 2, the standard configurations used in modular or compact type gas insulated switchgear are symbolized and explained. In Section 2.2.1 the properties of the switching elements will be described.

Table 3: Gas insulated switchgear module configurations with different switching elements

 	Incoming/ Outgoing feeder with load breaker: The switching apparatus is load breaker. Mainly used as cable entry or outages. Load breaker is used for open and close operation on system when the load is on the circuit within the nominal ratings.
 	Load break switch + fuse combination for transformer protection: The switching apparatus is load breaker and fuse combination. Load breaker used for open and close operation at nominal current value while the fuse is used for limiting the current value supplied to the transformer. Therefore fuse is basic protective equipment for overcurrent conditions.

 	Vacuum circuit breaker unit: This unit is composed of only circuit breaker and protective relay with CT to be able to open on normal system conditions and also on the fault conditions.
 	Bus Sectionalizer unit with circuit breaker: This unit can section and couple two separate busbar and system via a circuit breaker operation. Since on the system there is no CT or VT, and so no protective relay, circuit breaker could be operated manually even on the fault condition. The disconnector is used for maintenance reason of the circuit breaker and earthing of the circuit breaker open contacts.
 	Bus Sectionalizer unit with load breaker: This unit can section and couple two separate busbar and system via a load breaker operation. That can only operate on nominal load / current values.

 	Direct cable connection: This unit is used as direct incoming or outgoing without any protection or switching elements.
 	Cable connection with earthing switch: This is the direct cable connection but also with the earthing switch leads to the earthing of the cable and the main busbar.
 	The protective unit with circuit breaker and disconnector combination: In this unit, circuit breaker is used with a protective relay and current transformer. Circuit breaker can operate on load and also on fault via the directive of the protective relay. Protective relay gets information about system via voltage and current transformers or sensors. Regarding the program embedded into relay, the tripping operation of the system on undesired system cases will be

	acquired via circuit breaker operation.
 	Voltage and current measurement and metering unit: This unit is used for metering on system and determining -power usage of customer via measurement devices.

2.2.1 Load Breaker as a Switching Component

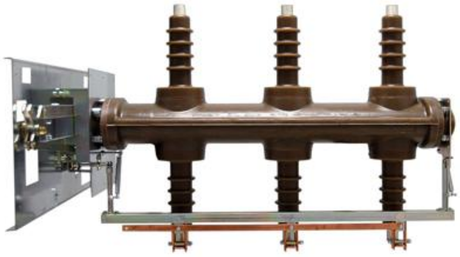
A load break switch could be also referred as switch and disconnector apparatus basically working on 2 conditions. Firstly, it can maintain open and close operation while the system is de-energized. At that instant the system is out of any direct current application, therefore open and close operation will be an issue of mechanical, nothing electrical on the system. At that instant load break switch is working as a basic disconnector. Secondly, the load break switch can perform the open and close operation while the system is under energy and the system ratings are met nominal conditions. At that moment, the load break switch can open and close the system via its mechanism of arc extinguishing and fast mechanical separation mechanism. Load breaker with insulation medium of SF_6 gas is the main design topic that will be handled at the Chapter 3. All possible arc extinguishing mechanism of a load breaker will be defined at Section 2.3. The apparatus can perform the switching and disconnecting operations with insulation medium of air, gas, oil or vacuum, while the frequently used model and the topic of this research is the apparatus working on insulation medium of gas- SF_6. In particular, it relates to an apparatus which, in the closed position, is able to convey in a controlled manner, in keeping within the limits set forth in relevant regulations, the rated current required by the load to which the apparatus is connected and withstand the short-circuit current which may arise as a result of a fault at its terminals. The apparatus according to the invention is able to establish, in its open position, the short-circuit current due to a fault at its terminals. Finally, in the open position, it is able to ensure a disconnecting level suitable for the voltage level of the installation, again in accordance with the regulations [6].

A load breaker mechanism which leads to movement of the moveable contacts with respect to the fixed contacts which also reflects to the arc extinguishing mechanism have 3 different types. The first type is the rotational type around a central axis, the second type is the linear movement and the third type is the hinge type [6]. The details of these operating mechanisms will be explained at Section 2.3 with the arc extinguishing mechanisms.

2.2.2 Disconnector as a Switching Component

A disconnector is basically a load breaker with no load breaking capacity but only disconnecting the system while the system is de-energized. Therefore it has no arc extinguishing mechanism. Some main usage of disconnector are the overhead line primary distribution to ensure that no probability of energizing the system while there is a maintenance service on the pole type distribution transformer, or to be used before a circuit breaker in any kind of MV or HV switchgear to ensure that while the circuit breaker is under a maintenance service, the operator is safe since the contacts of the circuit breaker is disconnected from the main busbar via open disconnector on both sides. It is reasonable to say that a disconnector is just a security element of system without any on load switching capability.

(a)



(b)

Figure 7: The disconnector: (a) external type disconnector suitable for overhead line pole mounting (the contacts are at the air), (b) SF_6 gas type disconnector where the contacts are embedded inside of an epoxy case and the medium between the contacts is SF_6 gas.

2.2.3 Circuit Breaker as a Switching Component

A circuit breaker is the switching device that is able to operate on energized system, de-energized system, on the fault and even on the short circuit. The operation of a circuit breaker could be managed by a protective relay which acquires information from the current and voltage transformer on the system, working as the brain of the circuit breaker that sends command to the circuit breaker related to the tripping operation. A medium voltage circuit breaker which comprises an insulating base frame supporting: a pole assembly having, for each phase, an interruption unit housing a fixed contact and a movable contact reciprocally couplable/ uncouplable between an open and a closed position; an actuator to actuate the opening and closing operation of circuit breaker; and, a control and diagnostic unit comprising a control box [7].

Circuit breakers usually consist of a pole assembly having, for each phase, a fixed contact and a movable contact. This latter is typically movable between a first position, in which it is coupled to the fixed contact, and a second position, in which it is uncoupled from said fixed contact, thereby realizing the opening and closing operation of the circuit breaker. The pole assembly is usually mounted on a base frame which is generally made of many separate components of metallic material, assembled by screws and/ or welding. An actuator, for actuating the opening and closing operation of the circuit breaker, and a kinematic chain, linking the actuators to the movable contacts, are usually also mounted on the base frame. Medium voltage circuit breakers also usually comprise a number of auxiliary devices aimed at carrying out auxiliary functions for the circuit breaker. Such auxiliary functions normally include a number of coils for the opening, closing, trip, shunt, under voltage or blocking operations. Other auxiliary functions that need to be performed in a medium voltage circuit breaker are the spring charging operation of the actuator device for the mechanical operated circuit breaker. Also, auxiliary contacts are normally foreseen in order to detect the status of the main contacts of the circuit breaker. In addition, for each operation (e.g. shunt, tripping, under voltage, block released, etc.) a dedicated coil, operating under a predefined supply voltage is normally required. The usual assembly process of a circuit breaker, normally foresee a number of steps in which some of the components of the frame are assembled before mounting the actuator, poles and kinematic chain, while some other components of the frame are assembled after the actuator, poles and kinematic chain have been mounted [8].

A circuit-breaker for electric substations is able to protect the line directed to the user. A line isolator, after the circuit-breaker has opened the line directed to the user from the voltage supply busbar, is able to disconnect the line physically. Finally, an earthing isolator, again after the line isolator has disconnected the line directed to the user from the voltage supply busbar, earths the line directed to the user in order to avoid the occurrence of discharges or induced currents [9]. The circuit breaker actuating shaft and a disconnector actuating shaft are coaxial.

Figure 8: The SF_6 gas insulated circuit breaker with left side operated mechanism

2.3 Opening and Closing Mechanisms in Isolating Switches:

Arc is a thermal and static discharge that occurs at current value more than 1 A with the cause of voltage drops. Arc can feed itself. Arc results with the current occurrence at mainly non-conductive media.

Electrical flashover is usually caused by inadvertent contact between an energized conductor such as a busbar with another conductor or an earthed surface. This is often the result of incorrect use of test probes, faulty or poorly specified instruments or dropped tools and can be made more likely when the equipment is subject to condensation, dust or corrosion. The magnetic field from the resultant fault current will cause the conductors to separate or the tool to be blown back producing an arc, which ionizes the air, making a conducting plasma fireball. The effects of the flashover can radiate several meters away from the point of the arc, injuring other people that might be nearby. When an electrical flashover occurs, conductors can vaporize expanding to thousands of times their original volume and the high release of thermal energy superheats and rapidly expands the surrounding air. The result can create a pressure wave called arc blast, which is literally an explosion [18].

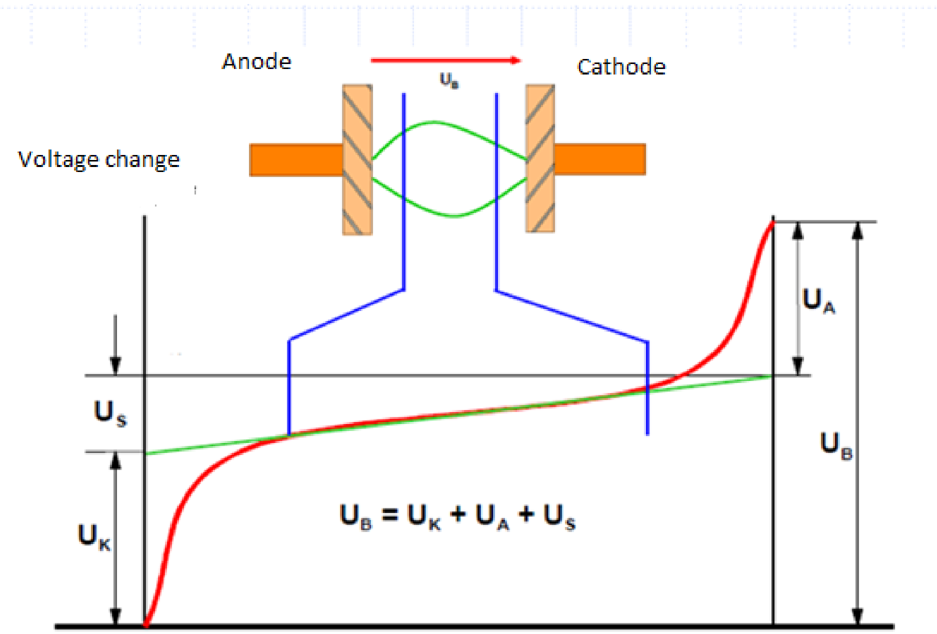


Figure 9: The arc occurrence process related to variation in voltage between anode and cathode

In load break switch applications there are mainly 3 types of contact dispatching mechanism which are hinge type, linear movement type and rotating type with a central axis of rotation.

In rotating switch and disconnector with the mechanism type of rotation around a central axis, the movable contacts are in the form of contact blades which extend diametrically from a central axis of rotation about which they are able to rotate. In the first position of rotation, the movable contacts are in contact with the fixed contacts, while in the second position the movable contacts and the fixed contacts are at an isolating distance [6].

In linear switch and disconnector, there is an upper fixed contact and a lower fixed contact of sliding type. A conducting tube or bar is moved vertically with a rotational

movement, while maintaining the electrical contact between the busbars (or the tube) and the lower contact movable. The apparatus is able to assume two positions: the first position in which the movable conducting tube or bar is inserted inside the upper fixed contact and the second position in which it is situated at an isolating distance from there [6].
In rotating hinge-type switch and disconnector, an axis of rotation is formed on the lower contact, about which the movable contact rotates, in the first position being in contact with the upper fixed contact and in the second position being situated at an isolating distance from there [6].

2.4 SF_6 Gas as an Insulation Medium:

SF_6 gas is a very stable gas that has many unique properties which makes it used in many industrial and scientific study areas.

Fluorine, obtained by electrolysis, is allowed to react with sulphur and a strongly exothermic reaction, giving rise to a remarkably stable gas [10].

$$S + 3F_2 \rightarrow SF_6 + 262\ \text{kcal}$$

During this chemical reaction many other chemicals are produced such as SF_4, SF_2, S_2F_5, S_2F_{10}, as well as impurities due to the presence of moisture, air and carbon anodes used for fluorine electrolysis. These are removed via many purification manners [10].

SF_6 is one of the heaviest known gases. Its density at 20°C and 0.1 MPa (that is one atmosphere) is 6.139 kg/m3, almost five times higher than that of air.

Table 4: Physical properties of SF_6 gas

Parameter	**Value**
Density	6.14 kg m^{-3}
Thermal conductivity	0.0136 WQ m^{-1} K^{-1}
Critical point_ temperature	45.55 ^{o}C
Critical point_ temperature	730 kg m^{-3}
Critical point_ pressure	3.78 MPa
Sound velocity	136 m s^{-1}
Refractive index	1.000783
Formative heat	-1221.66 kJ mol^{-1}
Specific heat	96.6 J mol^{-1} K^{-1}

The main reasons of SF_6 gas usage as a HV/MV insulation medium are:

a) The SF_6 gas volumetric specific heat is 3.7 times that of air which is a very important affect for reducing the heating effect on electrical equipment. Therefore SF_6 gas is also working as a cooler in an electrical system.

b) SF_6 gas is a great arc extinguisher because of its outstanding characteristic on thermal conductivity. Its thermal conductivity is lower than air, very similar to gas like helium, hydrogen and higher than air. At high temperatures, regarding the arc extinguishing modeling, SF_6 exceptional characteristics make it to be used as an arc extinguisher by thermal transport. The dissociation process absorbs a considerable amount of heat which is released when the molecules reform at the periphery of the arc, facilitating a rapid exchange of heat between the hot and cooler regions [10].

c) SF_6 gas has electro negativity molecule character. Therefore it has a great tendency to capture free electrons forming heavy ions with low mobility making the development of electron avalanches very difficult [10].

d) The dielectric strength of SF_6 is 2.5 times higher than air at same conditions. Also SF_6 is a better dielectric when it is compared with Nitrogen [10].

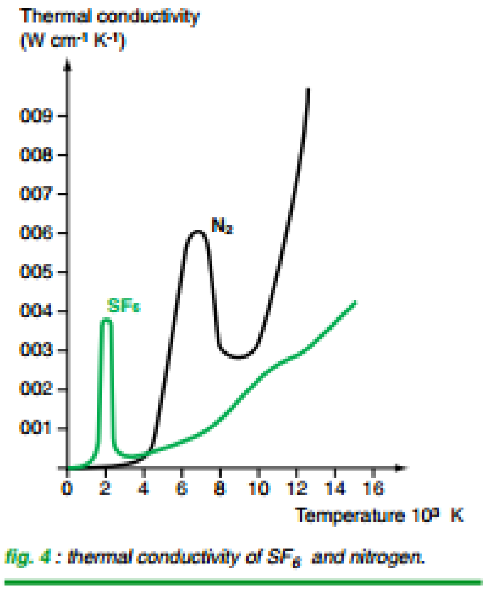


Figure 10: Thermal conductivity of SF_6 and Nitrogen [10]

a) Low operating energy for the switching devices.

b) No risk of fire.

c) Not toxic hazard.

d) Independence of the installation site altitude, allowing the use of standard products at altitudes higher than 1000 m above the sea level.

e) High protection against ambient conditions resulting in two very important properties:

- Contaminant conductive deposits cannot build up to degrade solid insulators, so preventing one of the most frequent causes of serious failures.
- Electrical contacts are protected against chemical corrosion that can reduce their performance, and potentially lead also to a final failure of the equipment.

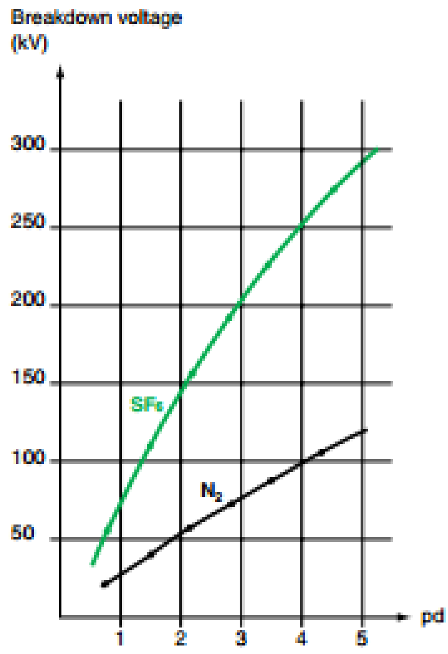


Figure 11: Breakdown voltage of SF_6 and Nitrogen as a function of product between 2 spheres of 5 mm diameter [10]

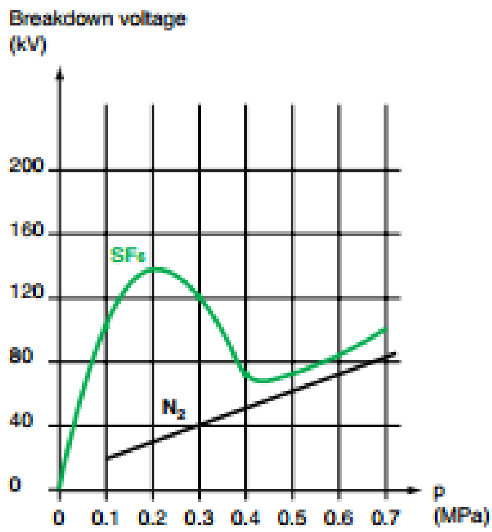


Figure 12: Breakdown voltage of SF_6 and Nitrogen as a function of pressure for a non-uniform electrical field [10]

f) The level of partial discharges will not increase during operation. Therefore deterioration of insulation material by radiation and chemical reactions due to partial discharges will not occur. As a result, the full dielectric properties will remain practically on the level of new equipment over the total service life time. In fact the dielectric withstand capability of all live-parts of the switchgear is not prone to ageing.

g) Favorable ergonomic conditions, due to the small volume and relatively light weight.

h) Easy choice of optimal installation site (independent to prevailing environmental local conditions, close to the electrical load demand, etc). SF_6 insulated switchgear is used, for example, in places subjected to hazard of flooding, or underground.

i) Recommended use in severe climatic conditions (sea shore, heavy industrial pollution, etc.)

j) Extremely low probability of failure, due to the good performance level, and the protection of the insulating system from any degrading influence.

k) Low maintenance, for the same above mentioned reasons.

l) Long service life.

m) Low operating energy, making easy to implement remote control and/or automation schemes. This -in turn- can contribute to a fast restoration of the service after a fault in the network. Moderate consumption of material resources (plastic, metals, etc.) [2].

n) Relatively low cost of first installation and operation.

o) High continuity of service.

p) Low visual impact, which makes easier the social acceptance of the installations.

q) Safety for the public and property, due to the low probability of serious failures, limitation of fire hazard, etc.

r) Efficient design of the power supply system. In fact the location of the equipment optimally with respect to the local demand reduces the losses of energy with a double result: better technical and economic performance of the network and less energy generation with its environmental side-effects [11].

CHAPTER 3

DESIGN OF THE LOAD BREAK SWITCH

3.1 Objective of the Thesis and the Contributions of the Thesis to the Design Process

The process of designing load break switch and switchgear based on load break application is a process that contains many electrical and also mechanical design limits. This design process is an engineering study with many different aspects. Before starting the design process, first of all the main design criteria and features are defined. In Turkish market there are many different brands of gas insulated switchgear with load break switch application. These products are investigated, compared and the disadvantages that need to be improved are defined explicitly to determine the design parameters and limits. It is seen that, even there are many load break switch applications; none of them can meet the operation expectation on arc extinguishing in proper time with minimum required energy and contact distance. Moreover, this disadvantageous issue leads short life time of switchgear with safety arguments.

After defining the target as improving this faced disadvantageous property in other applications as a design parameter, the required engineering study and research on this issue is adopted as the subject of this thesis. In other words, the objective of this thesis is the relevant engineering study as a part of load break switch design in the field of ideal arc extinguishing with auxiliary design limits. The objective is to acquire an arc extinguishing mechanism with minimum required duration and with minimum rotation angle on the breaker mechanism. After the definition of the expected parameters on arc extinguishing, as the first step, the characteristic of arc on the designed system is modelled. To determine the modelling methodology, the literature survey on the arc modeling is completed. The two fundamental arc models of Mayr and Cassie models are studied and compared. Other arc models derived from Cassie and Mayr models are also studied. Regarding of these comparisons and survey, Cassie model is adopted as the arc modeling methodology of the thesis.

Before selecting the convenient arc model, the arc extinguishing method with the mechanical operation type of the load break mechanism are selected. Regarding to the market search and literature survey, it is obtained that there are 3 main arc extinguishing methodology, used in load breakers and circuit breakers, which are limiter type, rotational puffering and magnetic force effect via magnet. According to the market search, main application on arc extinguishing on load breakers is based on rotational puffering. Magnetic force effect supported by rotational puffering is a very rare solution. These arc extinguishing mechanism are defined in detail at Section 2.3. As the contribution of this thesis on the load breaker design parameter is that, the arc extinguishing mechanism is totally based on magnetic force effect without any impact of puffering. Rotational puffering is simply blowing the SF_6 gas as the insulation material with high dielectric property to the source point of the arc to suppress the arc formation. This method is not a safe method for arc extinguishing since SF_6 gas dielectric property will reduce due to the contaminations and ionization due to the effect of arc or other causes in time. Therefore, depending on insulation material suppression effect on arc which will lose its dielectric strength and also might face with change on its pressure is not an acceptable arc extinguishing method according to the design limits of our load breaker. Also, this arc extinguishing method requires longer duration for arc extinguishing with longer contact separation for ultimate arc extinguishing. As the contribution of this thesis on the load breaker design parameter, the aim is to obtain an arc extinguishing mechanism which will be safer and leads arc extinguishing in a shorter time with lower contact separation. In another word, in our arc extinguishing methodology, the arc extinguishing has less dependence on quality of the insulation and the strength of the mechanical tripping mechanism. Our arc extinguishing methodology depends on proper magnet selection to provide sufficient magnetic force on the arc to diminish the arc within duration less than 20 ms and 0.51 cm linear distance between the live contact and the rotational contact. As calculated in Section 2.4, 0.51 cm is the minimum arc extinguishing distance that also ensures the potential difference between the live contact and the rotational contact to be sufficient for no breakdown occurrence on the medium of $SF_{6.}$ By neglecting the effect of rotational puffering of SF_6 on arc, the Cassie model selection is also justified which perceives the cooling effect of SF_6 gas medium as negligible for the arc extinguishing method.

As another contribution of this study on the design parameters of the load breaker, the selected operation mechanism of the load breaker is rotational central axis. According to the market search and literature survey, other frequently use methods for load breaker and circuit breaker are hinge type and linear separation which are defined in detail at Section 2.3. Rotational central axis method is the safer method which also requires minimum energy to be applied for open or close operation. Linear type is totally invalid for load break applications which are mainly used for circuit breaker design. Hinge type method leads the open-close mechanism to get the fundamental parameter to keep the contacts separation as acceptable limits. Therefore, rotation on central axis method as the mechanism structure is the most proper structure that will support the objective of the relation between arc extinguishing within less contact separation. The important parameter after adoption of the mechanism structure is to design the spring usage purposes and the spring selection parameters related to the k constant and the required energy to be transferred to rotational movement.

The objective of the design is defined and supported by the contribution of this thesis on the related design parameter. The relevant steps and the process application are covered in this Section with all details.

3.2 General Design Parameters

In this thesis, the primary aim is to investigate all 12 kV GIS manufacturer working principles and obtain the optimum product with outstanding features that leads more economical and technically safer product. Before starting the design stage, firstly the design Criteria as listed in Table 5 are defined regarding the international standard explanations and target countries' technical specifications. The combination is designated as LLF which consists of 2 line feeder with load break switch and 1 transformer protection feeder with load break switch and fuse combination as seen in the Figure 14.

The base international and local standard and specifications taken as reference in the design stage are IEC 62271-200, IEC61271-102, TEDAS MYD 95-002. Especially the IEC61271-102 is the main standard that defines the load break switch technical specifications.

Table 5: Technical requirements of the gas insulated switchgear as compact LLF designation

ITEM		**RATINGS**
Rated voltage	U_r	12 kV
Rated frequency	f_r	50/60 Hz
Power frequency withstand voltage (1 min) across the isolating distance	U_d	50 kV
Power frequency withstand voltage (1 min) to earth and between poles	U_d	60 kV
Lighting impulse withstand voltage to earth and between poles	U_p	125 kV

Table 5 (Continued):

ITEM		RATINGS
Lighting impulse withstand voltage across the isolating distance	U_p	145 kV
Rated current	I_r	630 A
Short circuit breaking current	I_k	16 kA
Short circuit making current	I_o	40 kA
Short time withstand current (main circuit)	I_k	20 kA
Short time withstand current (earthing switch)	I_k	20 kA
Short time withstand current (earthing bar)	I_k	20 kA
Short time withstand current duration	t_k	1 s
Short time peak withstand current	I_p	50 kA
Number of making capacity (LBS and earth switch)	n	5
Arcing withstand due to an internal fault (rms)		21 kA
Arcing withstand due to an internal fault duration		1 s

Table 5 (Continued):

ITEM		RATINGS
Arcing withstand due to an internal fault type of accessibility		AFL
HV live part and fuse compartment protection class		IP 67
Front cover and cable cover protection class		IP 3x
Insulation medium		SF_6 gas
Number of poles		3
Rated filling level for insulation	P_{re}	50 kPa
Minimum functional level for insulation	P_{me}	30 kPa
Pressure relief		Bottom
Busbar		1 x 30 x 7 mm^2
Earthing busbar		1 x 25 x 5 mm^2
Dimensions (H x L x D)		1250x 1600 x780 mm

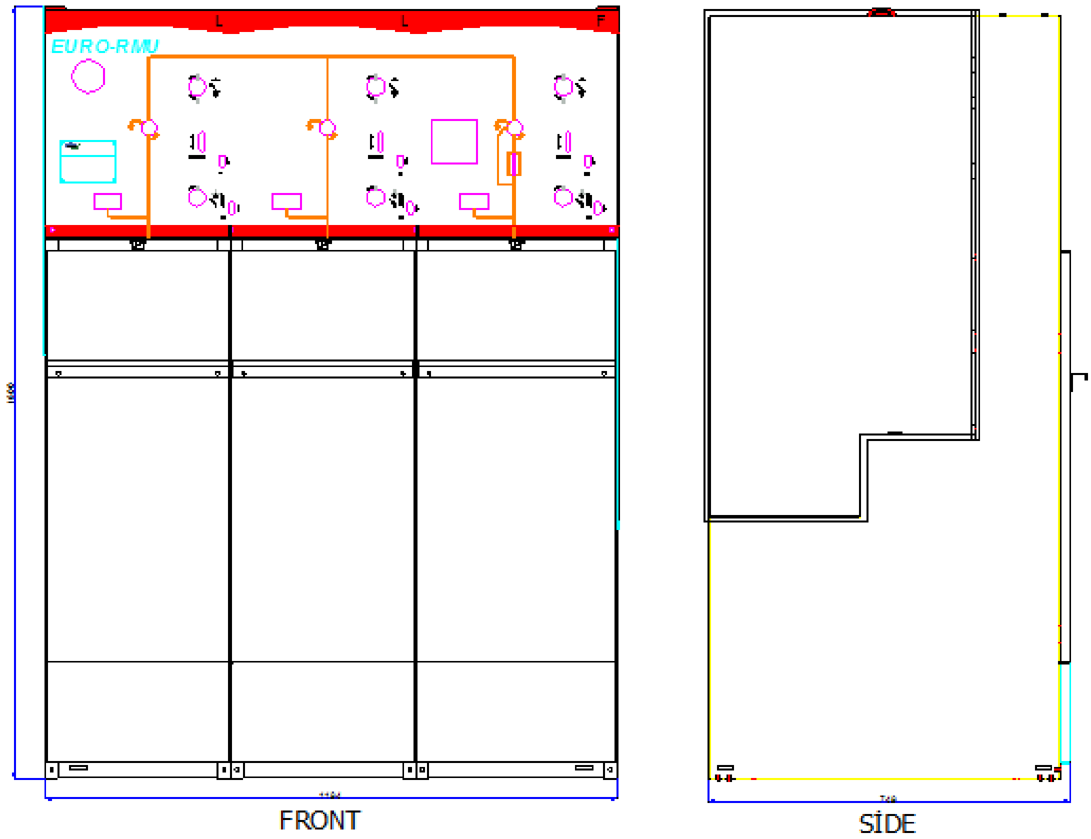


Figure 13: The front and side view of prototype final construction

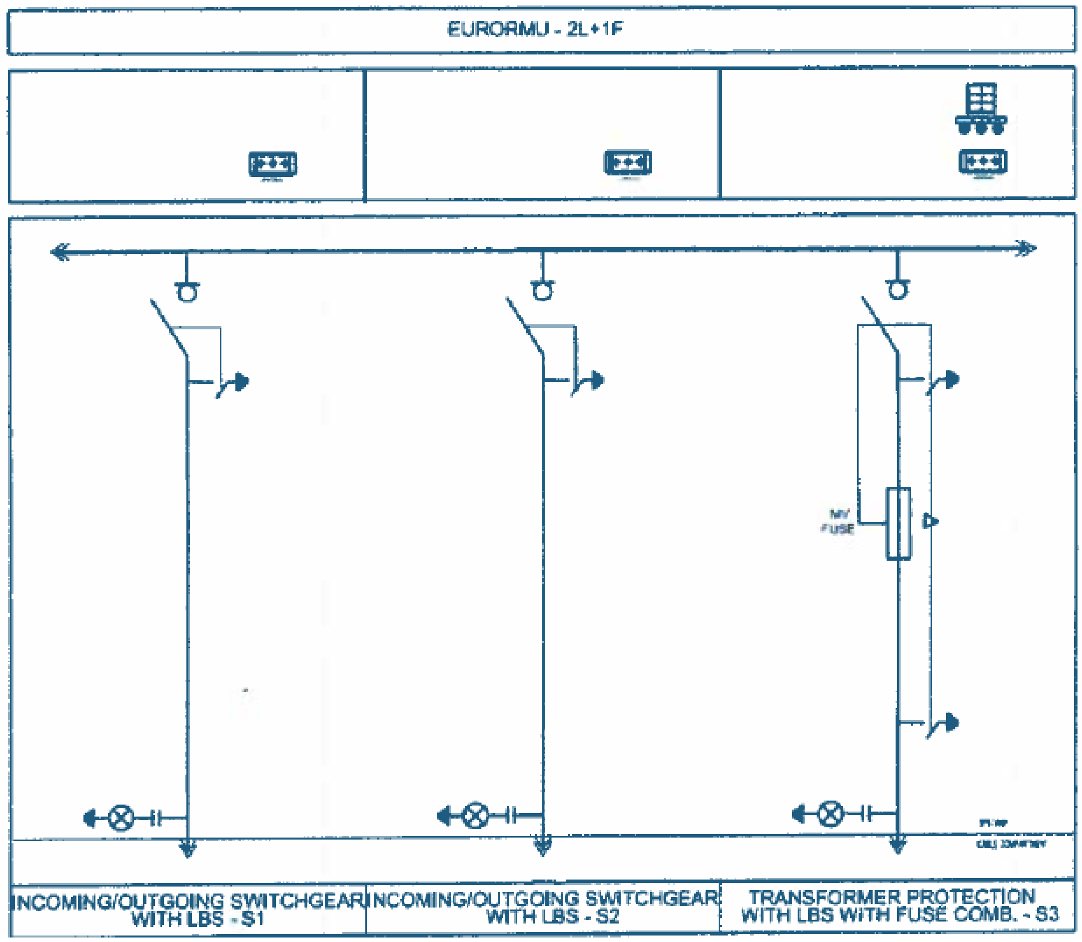


Figure 14: The single line diagram of the compact type gas insulated switchgear

3.3 Mechanical Design Considerations and Auxiliary Circuits

The gas insulated switchgear is composed of many mechanical and electrical parts. All of these are designed specifically by perceiving target standards and parameters. The gas insulated switchgear with 2 incoming/ outgoing units with load break switch and 1 transformer protection unit with load break switch and fuse combination is composed of more than 2800 mechanical and electrical components.

<u>3.3.1 Mechanical Design and Spring Selection</u>

The mechanical vessel is specially manufactured as the enclosure for all switching apparatus. Many important parameters are taken into account during the design stage of the vessel. The vessel is produced by using external welding process. The welding is applied as externally to the vessel since the application of welding internally is a very difficult process. Another advantage of external welding is that, the possible contaminations that will occur during the welding will stay outside of the vessel. Whether internal welding process was preferred instead of external welding process, welding pieces and contaminations might lead insulation problem in the vessel where electrical units are embedded in.

The vessel is manufactured from a special 3 mm thickness of stainless steel sheet. The welding machine and the gas used during welding are specified according to the stainless steel application. The gas used in the welding is Argon gas. Acetylene is an alternative welding gas which is not preferred in stainless steel applications.

Reinforcements are applied to achieve the robustness of the vessel during vacuum implementation where the pressure on the vessel is high that might lead mechanical collapse. Another very important mechanical parameter taken into account during mechanical design stage is the pressure relief windows of the vessel. During an internal arc, the pressure occurred inside of the vessel needs to be relieved in a way. Therefore, pressure windows are designed specifically. These pressure windows need to be tough enough to stay rigid during normal pressure values while needs to be weak enough to ripped out when the relative pressure on the windows increases a certain amount higher than normal value. Because of this reason, the pressure relief windows are made of 0.2 mm thickness of aluminum or stainless steel sheet. These weak pieces are stabilized by flange and sealed to improve the stiffness. Also the location of these pressure relief windows is very important. The pressure relief windows are designed at the bottom end of the vessel. The reason of this design is that the pressure relief windows need to be as far as from the operator as possible. Therefore they cannot be placed on the front end of the vessel. Also since the height of the switchgear is too low, they cannot be placed on the up side of the vessel since still it is so close to the operator. They cannot be placed on the back side of the vessel since generally gas insulated MV switchgears are used as a recumbent installation manner. Therefore, the most proper place for the pressure relief is the bottom side of the vessel Also the bottom side is accepted as an infinite pressure relief chimney because of the cable channel located at the bottom of the switchgear. During the internal arc, the pressure will be relieved from the window and will be diminished after being scattered a few meters in the cable channel.

Also the vessel which is the main unit of the switchgear with all switching components embedded in within the SF_6 gas insulation medium, needs to be carried and stayed in an operation level suitable for easy operation. Therefore a mechanical standing kit is designed and implemented to the switchgears.

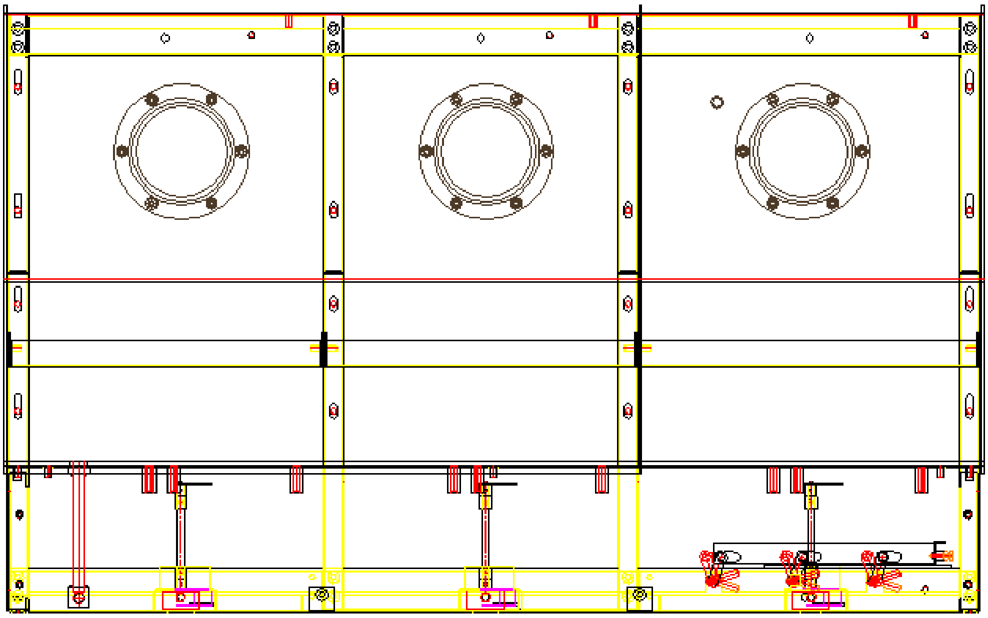


Figure 15: The pressure relief windows of the vessel located at the bottom end of the vessel

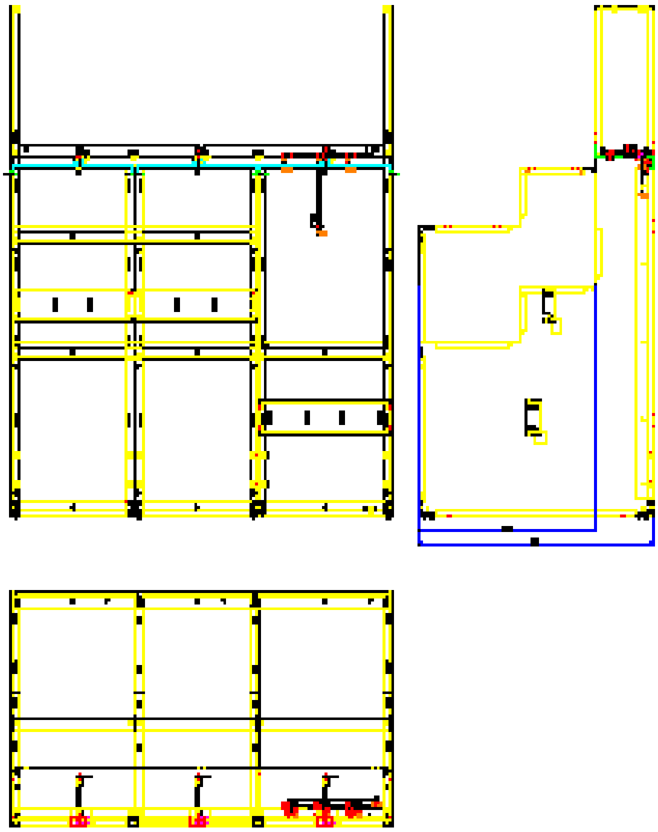


Figure 16: The top view, front view and left view of the final drawing of fully implemented mechanical support of vessel

3.3.2 Design of the Mechanism and Spring Selection

The method adopted for the designed switchgear mechanism is the rotating movement on a central axis. The mechanism and its components are the key components of the switchgear. The tripping and the closing operations are maintained by the mechanism while also it manages the time for tripping under load for extinguishing the arc at the right time without any deformation on the contacts. The end of the central axis shaft, is attached to the front panel of the vessel. After attaching the end of the rotating central axis to the vessel, it is sealed and stabilized. This shaft sealing point is the only node that needs to be concerned for tightness.

The end of the shaft is stabilized at one single point by using “o” rings, sealing and washers. This is the advantage of rotating central shaft mechanism when it is compared with linear and hinge type mechanism. Since there is only one point where the internal part of the mechanism is attached to the external surface, all consideration related to the tightness of the system is concentrated on that point, where internal mechanism is stabilized on the vessel surface. In linear type for instance, there is many attaching points, so difficult to manage the tightness. Rotating central axis and hinge type methods are more suitable to SF_6 gas insulated switchgear models. Linear type is more applicable to circuit breakers.

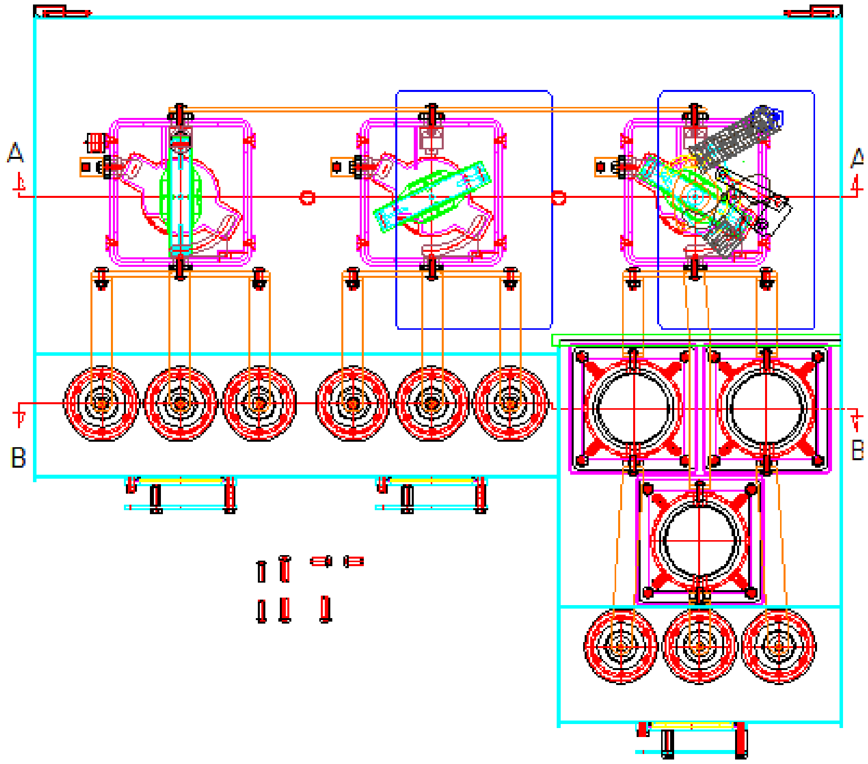


Figure 17: The Section view of the vessel as the load breaker and fuse holder installation are completed

Figure 18: The photo of rotating central axis that the rotation of the mechanism moves around

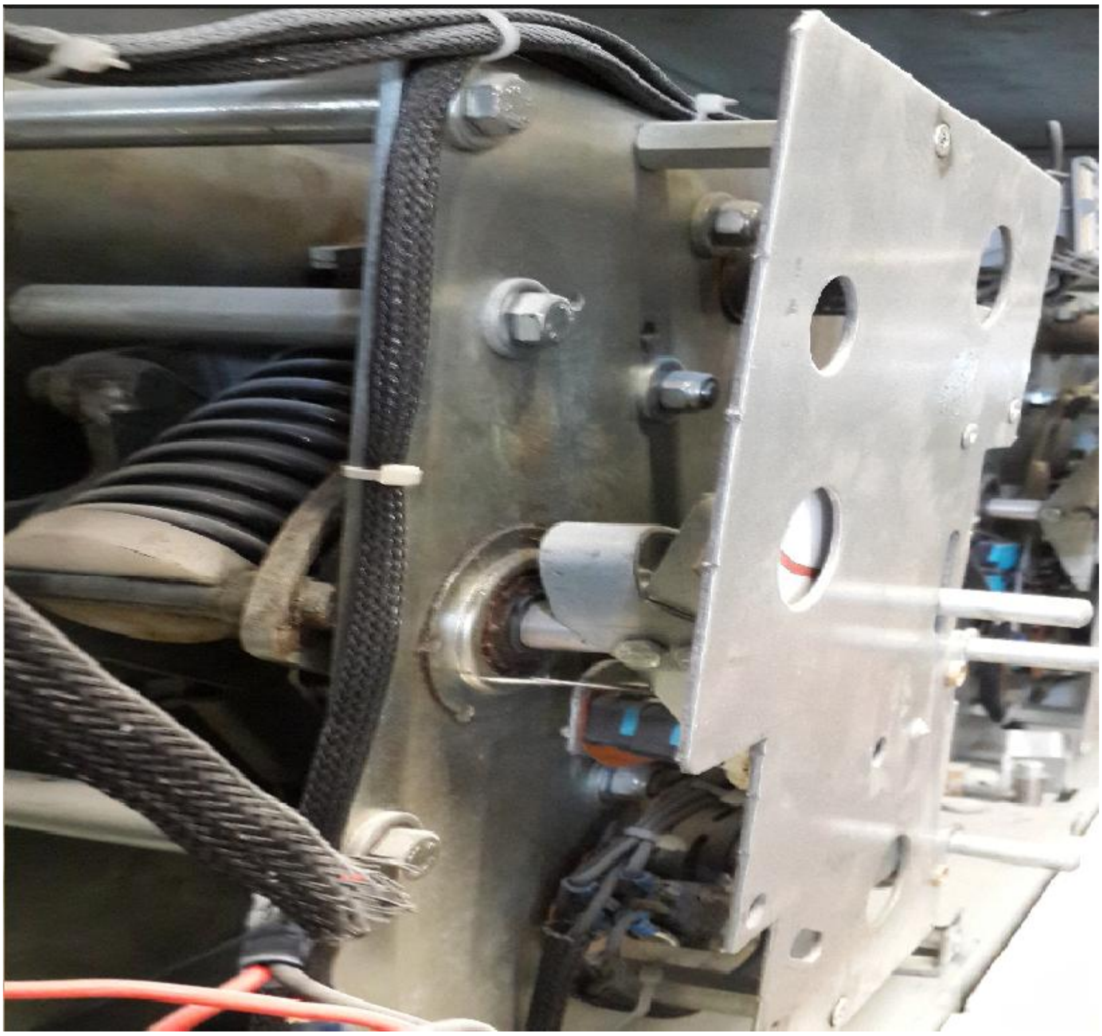


Figure 19: The photo of the mechanism installed on the switchgear

The most important instruments in the mechanism are the springs. Spring design and selection determines the arc extinguishing and load breaking operations. Since the switch is working as a load breaker so tripping the system while the rated current flows and there is 12 kV voltage applied on the circuit, the open and close operations need to be fast enough to lead the contacts to attach or detach without any deformation and leading the inefficient stretching of the arc.

The expected tripping time of the load break switch is in between 40-60 ms. Which is for a 50 Hz system means, within 2-3 cycle the tripping needs to be performed without leading arc stretching. The damping factor causes the tripping to be completed within 2-3 cycle as seen in Figure 20.

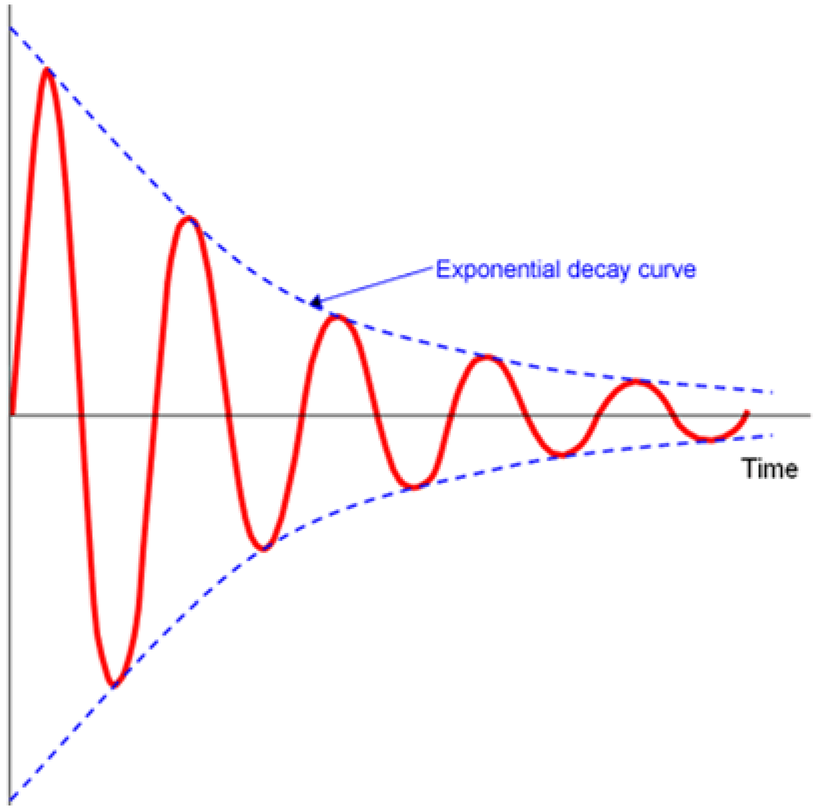


Figure 20: The characteristics of the interrupted current through the load breaker and the damped tripping cycle

As the mechanical design parameters, the selection of the spring regarding the k constant is an important issue to ensure that the mechanism of the load breaker can operate the open and close operations with sufficient force and time values. The spring constant can be calculated regarding of the potential energy stored in the springs and respective mechanism motion. The small spring is the one that is converting its stored energy to the 7 cm linear displacement between contacts (56 degree of rotation on the central axis) which leads totally open operation of the rotating contact.

The design of the LBS is based on 56^{o} of shaft rotation between open and close points. The system between the springs is as following. There are 2 springs that one of them is much strong than the other one. For the strong spring, the potential energy at the beginning is roughly almost double of what it needs for only closing operation. The trigger of the first relief of this spring can be done by hand push buttons or via electrical coils. After the first trigger of the strong spring which we call "West spring", the closing occupation will be completed and the stronger spring will lead to the squashing of the smaller spring. So now on, the small spring is also waiting for a trigger which means the opening (tripping) of the mechanism. So the strong spring is used for closing and preparing the small spring. The small spring is used only for the tripping occupation.

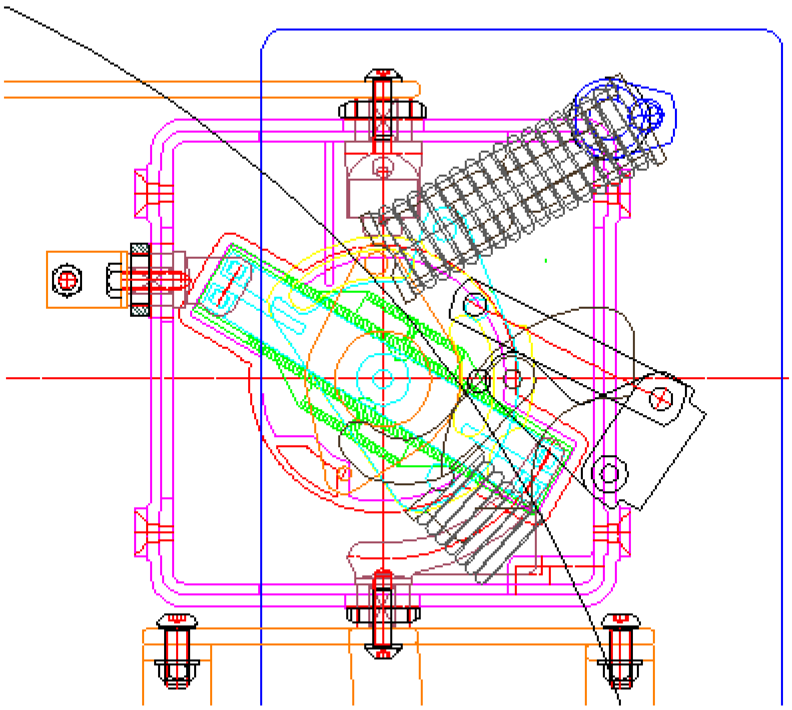


Figure 21: The drawing related to the alignment of springs on the mechanism

During the operation of tripping, the x change on the small spring is 4.4 cm-3.6 cm = 0.8 cm

From the potential energy of the small spring:

$$U = \frac{1}{2} \times k \times x^2 = \frac{1}{2} \times k \times (0.8 \times 10^{-2})^2 \quad [3.1]$$

$$U = \frac{1}{2} \times I \times w^2 = \frac{1}{2} \times m \times r^2 \times 4 \times \pi^2 \times f^2 = 0.2 \times 2 \times \ 8.6 \times 10^{-2} \ ^2 \times \pi^2 \times 3.9^2 = 0.444 \text{ J} \quad [3.2]$$

While, m=0.2 kg, r=8.6 cm, T= 56 x 40 /360 =257 ms ; so that f= 3.9 Hz

$$k = 2 \times \frac{0.444}{0.8 \times 10^{-2} \ ^2} = 13\ 878\ N/m \quad [3.3]$$

The strong spring has 2 segments of charging, 18.5 cm-12.5 cm = 6cm of charging for the closing of the contacts, 22 cm-18.5 cm = 3.5 cm for the charging of the small spring. This relation will give us the k factor of the strong spring;

$$U = \frac{1}{2} \times k_{big} \times (3.5 \times 10^{-2})^2 = \frac{1}{2} \times k_{small} \times (0.8 \times 10^{-2})^2 \quad [3.4]$$

$$k_{big} = k_{small} \times \frac{0.8 \times 10^{-2} \ ^2}{3.5 \times 10^{-2} \ ^2} = 13\ 878 \times 0.0522 = 724.4\ N/m \quad [3.5]$$

The structure, dimensions of the springs and the placement of the springs to the mechanism is shown as seen in Figure 22- Figure 23.

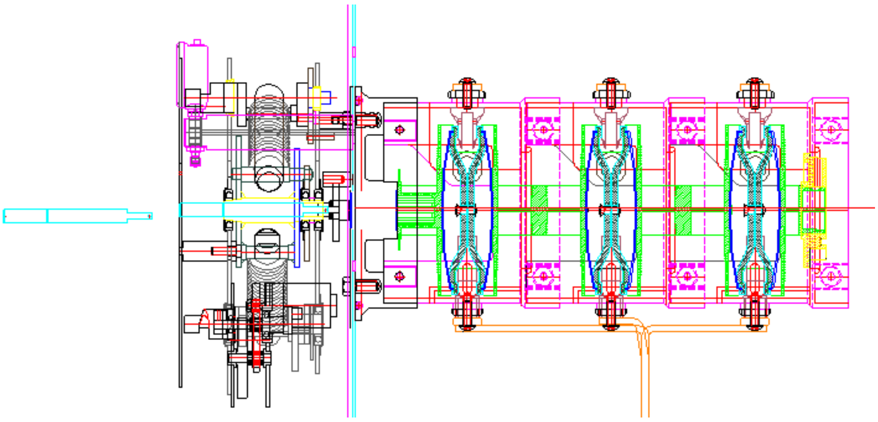


Figure 22: The drawing of the load break switch with the contacts and the mechanism

Figure 23: The photo of load break switch with the contacts and the mechanism

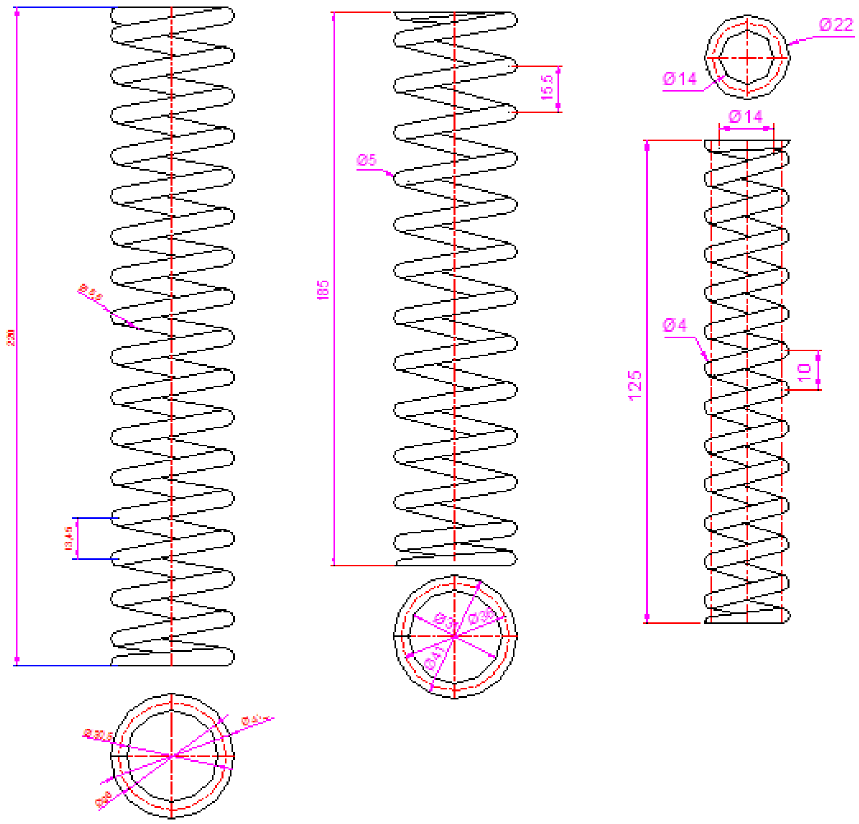


Figure 24: The strong spring, spring for closing and preparing the small spring for tripping

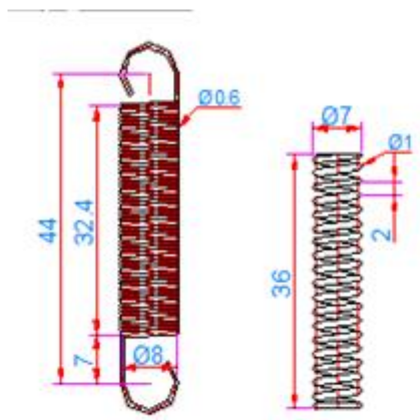


Figure 25: The small spring for tripping

3.3.3 Auxiliary Devices Used of the Switchgear

Some auxiliary devices are used in gas insulated switchgear applications. Some of them are explained in this Chapter. First of all for gas insulated switchgears, manometer is a fundamental auxiliary device that shows the relative pressure inside of the switchgear. Normally if the relative pressure inside of the vessel is lower than 30 kPa, it is dangerous to operate switchgear since the insulation level will not satisfy the requirements.

Also the open and close operations can be performed via push buttons but also using coils. By supplying the 24 VDC/ 48VDC/ 110 VDC to the system regarding the system requirement, the trigger could be done mechanically via the magnet force occurred due to the energized coil.

Micro switches are applied to the mechanism to get information from the SCADA related to open and close positions of switches, spring charge conditions… etc.

Motor application can be used for maneuver of the central axis. Normally as standard, this rotational movement can be done manually via using special handle that fits to the central shaft control point. As an alternative, the central shaft could be controlled remotely by a motor installed on the mechanism.

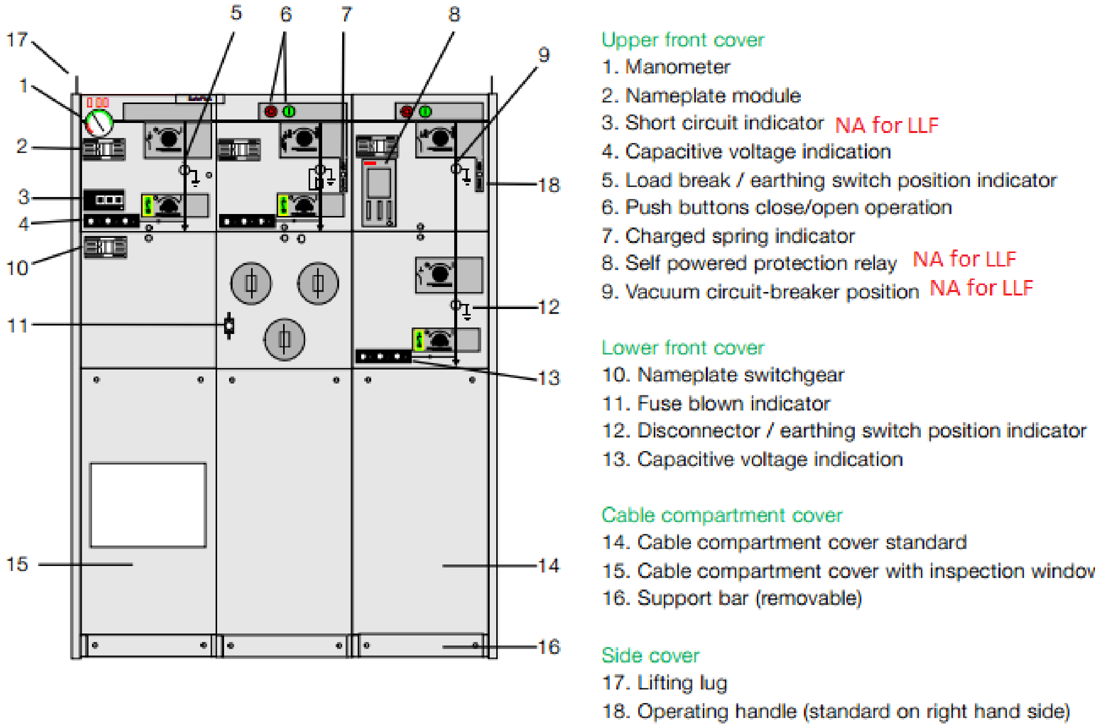


Figure 26: The listed switchgear accessories

3.4 Contact Structure and Magnet Characteristic

The contact structure and the magnet selection are one of the leading effects of this thesis to the switchgear design process. There are 3 stationary and 1 pair of rotating contacts per phase in the load break switch. These contacts are; busbar contact, earthing contact, output contact and the rotating contacts.Contact geometries are given as Figure 27,28 and 29.

All contacts are made of copper. Although the copper is a good conductor, it is a weak material that can melt when it exposes with temperature. Therefore during arc, there is temporary high thermal effect seen on the contact which ends up in the corruption on the contacts. These arc effects that occur during opening and closing operation on load (especially closing on the rated current at low p.f.) will lead small pieces to melt from the copper contacts. These effects will lead to serious deformation on the contacts after a while. So the contacts made of pure copper will have very short life time. To solve this problem there are a few methods. The first one and the most expensive one is to make the contact touching points from a compound of copper and wolfram (tungsten). Tungsten is a very precious element that has 3482°C as melting point. The copper has the melting point of 1085°C. Therefore the compound of copper and tungsten has a melting point more than 2000 °C which makes the contact life expectations higher because of its less aging potential with the explosion of high temperature at the open and close moments. However since this is an expensive method and tungsten is not an element that can be found easily, we adopt another method on our design to make the contacts more durable. The contacts touching points are covered by silver plating so that the melting point at the contact ends is increased. By using the silver plating on contacts, it is seen from the mechanical open and close tests, the contact resistance is still in the expected range after the mechanical open and close tests defined with the relevant standard IEC 61271.

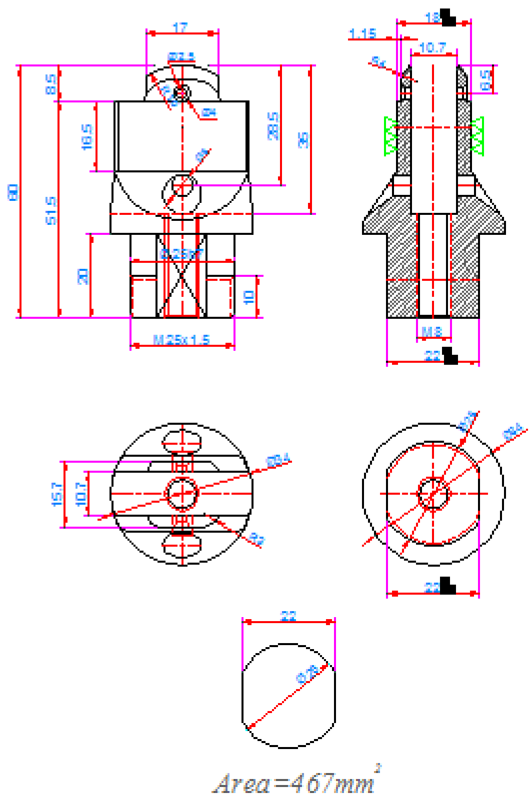


Figure 27: The busbar contact

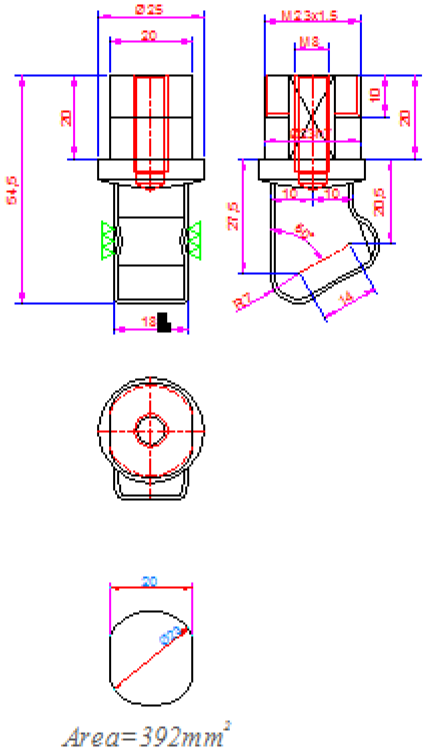


Figure 28: The earthing contact

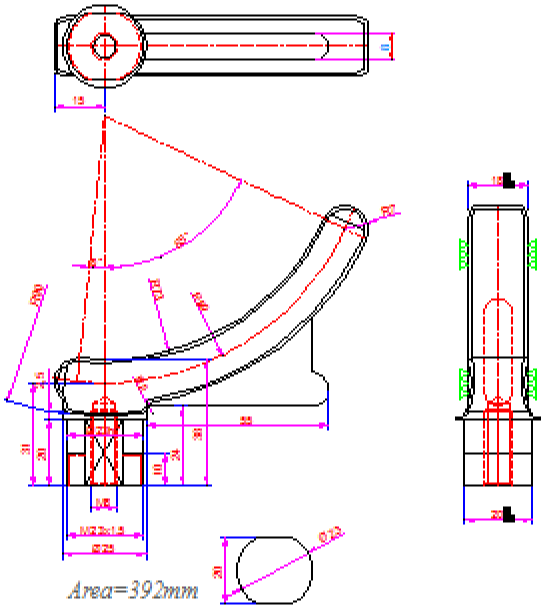


Figure 29: The output contact

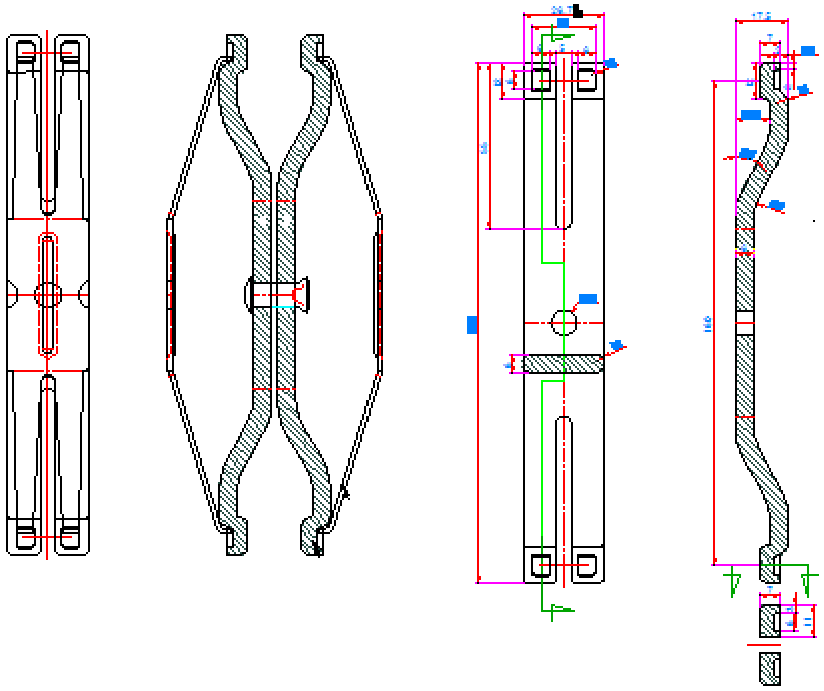


Figure 30: The rotating contacts

The magnet embedded into the busbar contact is the most important element especially for the arc pushing and extinguishing mechanism. The selection of this magnet is very important in terms of its B-H characteristic that determines the magnetic force effect on the arc applied by the magnet during opening on load. This magnetic force effect is the cause of arc stretching and finally arc extinguishing. As the contribution of this thesis to the design, the magnet selection and related parameters are investigated.

Because of the SF_6 gas dielectric property, we determine in the Section 3.6 The arc will be extinguished at 0.51 cm of linear distance between busbar contact and rotating contacts. It is reasonable to state that since the magnet has a diameter of 3 cm, from the center of the magnet, the length parameter for arc diminishing is calculated as following:

dl=0.51+1.5=2,01 cm from the center of magnet. With these results, it is possible to measure the field strength during the arc extinguishing period as an average by assuming the current is constant until the arc extinguishing instant, but only the direction of the arc is changed due to the magnetic force effect applied by the magnet on the arc.

$$MMF = i \ _{c} \ H \ x \ dl = N \times i \qquad [3.6]$$

At nominal ratings;

$$H = \frac{i}{dl} = \frac{630A}{(2{,}01 \times 10^{-2)} m} = 31.35 \ kA/m \qquad [3.7]$$

For the worst case design parameters of the magnet that is the field strength at the short circuit current value that the contacts should withstand for 1 second;

$H = \frac{16 \ kA}{(2{,}01 \times 10^{-2)} m} = \mathbf{796 \ kA/m}$ **, will be used as the design parameter for the selection of the magnet type.** [3.8]

The Maxwell simulation results related to H distribution inside of the vessel in 2 cases which are the busbar contact without magnet application as a sole copper and the busbar contact with magnet embedded into the sole copper are given as Figure 31 and 32. Since the Maxwell system design can be applied in 2D drawing, the direction of H can not be visualised. As expected, the magnetic field strength is concentrated between the busbar and rotating contact while the magnet is used in the busbar contact due to the magnetic effect of the magnet. The simulation of H is obtained from the Maxwell program solution type of Magnetic/ Magnetostatic with the application of rated phase current of 630 A to the busbar contcact while the earthing contact is grounded. The x and y axis unit is cm with 1 cm unit increment for both x and y axis.

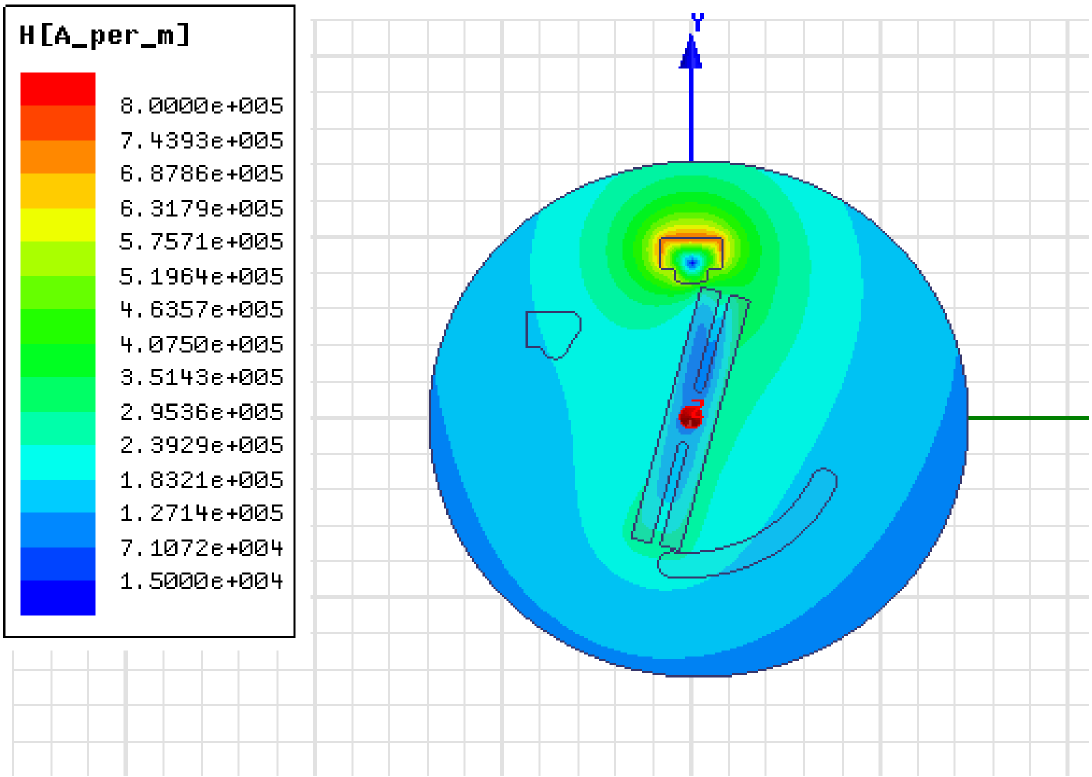


Figure 31: Maxwell simulation results for magnetizing force while the busbar contact is made of sole copper without any magnet

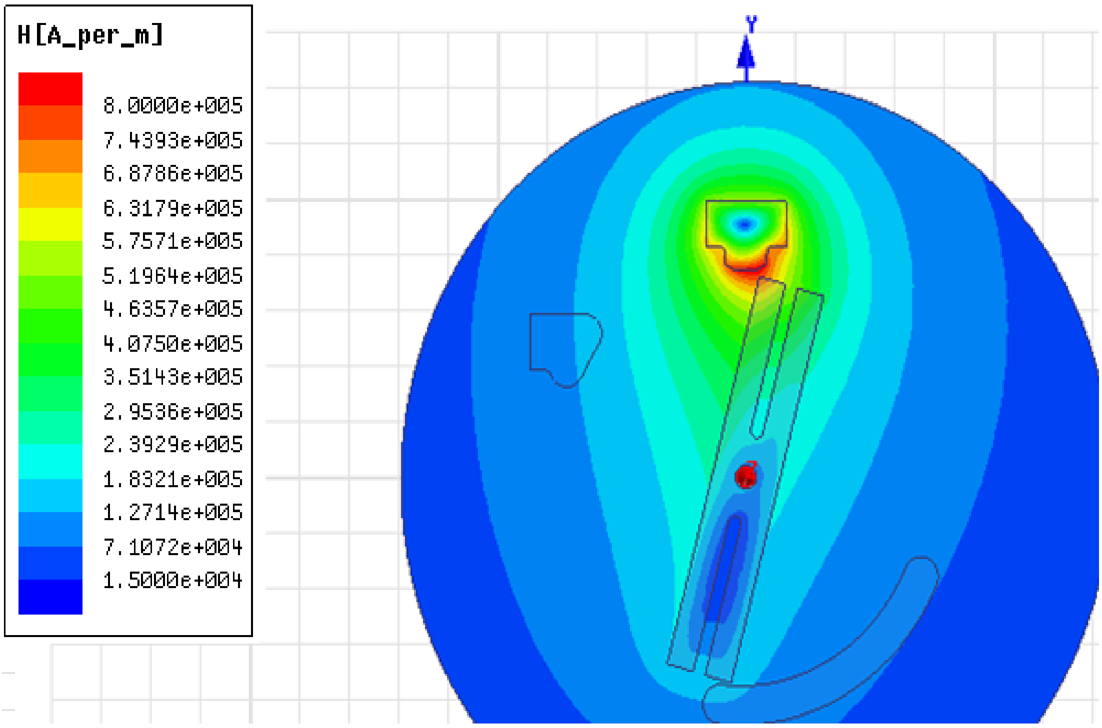


Figure 32: Maxwell simulation results for magnetizing force while the busbar contact is made of copper with embedded magnet which will apply magnetic effect

For calculating the flux density we need to investigate the electron movement during the arc extinguishing and so the drift velocity of the electrons. To understand the magnet effect on arc extinguishing, Hall effect needs to be taken into account. According to the Hall effect, due to the application of magnetic field and so magnetic force of the magnet on the electrons, the electrons of the arc are curved out of the direct current path between busbar and rotating contacts which leads to vertical charge imbalance than produces electric field on the system. This electric field opposes with the magnetic force.

$$F = q \times \; Vdr \; \times B \; = q \; \times E \qquad [3.9]$$

where Vdr is the drift velocity and e is the electron charges drifting from the current path. The electric field which occurs due to the impact of the magnetic force on the arc can be calculated as below:

$$E = \frac{\Delta V}{\Delta d} = \frac{(7\times 10^3)}{1.5+0.51\ \times 10^{-2}} = 3.48\ \times 10^5\ V/m \qquad [3.10]$$

In normal system conditions, the electric field is applied on a zone, not in a single direction. However, since Maxwell can compute our system on 2 D simulation, we simplify the calculation and electric field effects on one direction instead of computing 3D components.

From the simulation results of E vector, it is seen that at the instant of arc occurance , 3.4 ^{o} rotation from the fully closed structure, the electric field is strong and has a direction through the rotating contact. After 20^{o} rotation of the rotating contact from the edge point of arc extinguishing region, the electric field vector amplitude is getting decreased and the direction is changed. The Maxwell simulation results are obtained in the program solution type of Electrical/ AC Conduction with the application of rated phase voltage 7 kV applied to the busbar contcact while the earthing contact is grounded so 0 V.

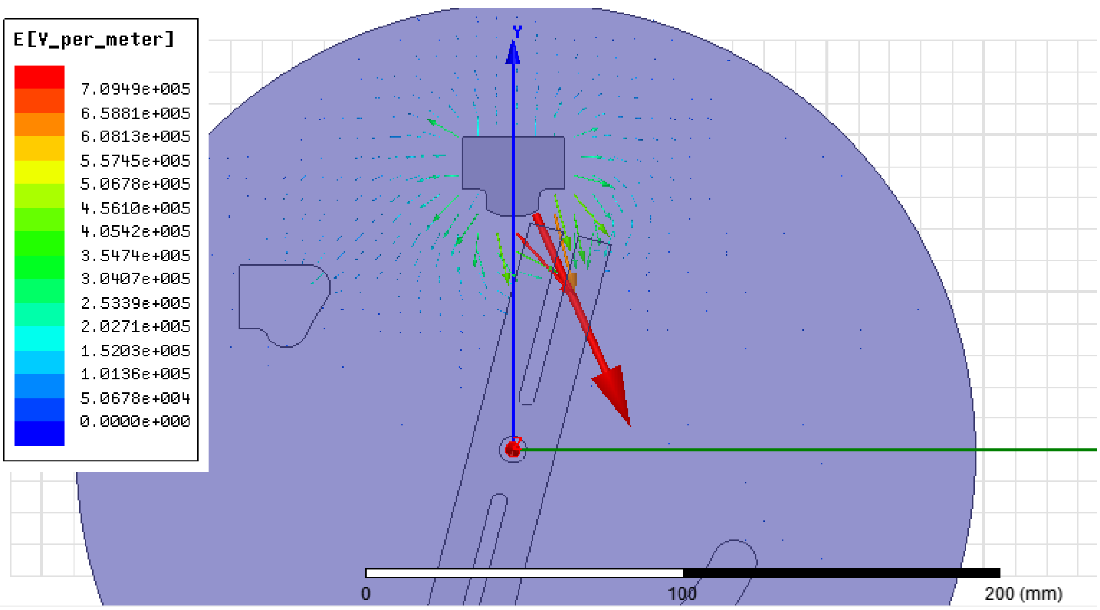


Figure 33: Maxwell simulation results for electric field vector distribution at the instant of arc extinguishing. Electric field amplitude and direction shows the arcing through the contacts.

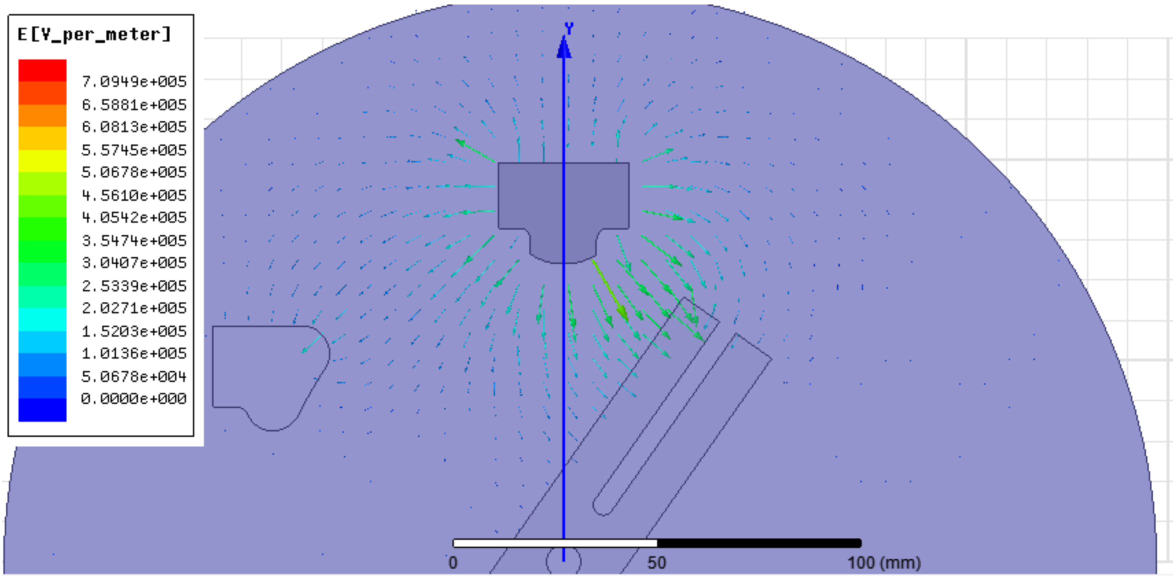


Figure 34: Maxwell simulation results for electric field vector distribution after 20^{o} rotation of the rotating contact. The arc extinguishing is already completed.

According to the Hall effect and the relation between the magnetic flux density and electric field:

$$F = q \times \ V_{dr} \ \times B \ = q \ \times E \qquad [3.11]$$

$$E = \ V_{dr} \ \times B \qquad [3.12]$$

The drift velocity of the electrons is the main point needs to be clarified to find the electric field on the arc region. We will assume that the drift velocity and the electric field is constant during the arc extinguishing. The drift velocity in SF_6 gas chamber can be calculated by assuming the occurrence of the Hall effect on the arc. The drift velocity formula with respect to time is:

$$V(t) = \frac{e \times E \times cos(wt)}{m \times v_{en}} \quad [3.13]$$

Corresponding maximum drift velocity until the arc extinguishing will be taken as the basis to determine the minimum B at the arc extinguishing region. v_{en} is the frequency of electron- neutral collisions while w=2πf is the cyclic frequency of the field.[40]

$V_{dr} = \frac{e \times E}{m \times v_{en}}$ is the amplitude of the drift velocity formula. [3.14]

By integrating both sides of the V(t) formula , we obtain the formula as below:

$$A = \frac{e \times E}{m \times v_{en} \times w} = \frac{V_{dr}}{w} \quad [3.15]$$

From this formula with the approximation of Levitskii, is assumed that the amplitude of the electron displacement increases which leads A to get closer to L/2 while L is the inter-electrode gap at the turning point of breakdown curve. Therefore it is assumed that while the arc is extinguished, the electron displacement increases and the Levitskii approximation will be an issue. We assume that the drift velocity is constant at that instant of arc extinguishing and the electric field is distributed almost uniform at that region where arc is extinguished which means the sharp points which might lead non homogenous electric field distribution is negligible. This estimations and assumptions come with the result that;

$$V_{dr} = \frac{L \times w}{2} = L \times \pi \times f \qquad [3.16]$$

The f can be calculated from the Matlab arc simulation results. According to the track of the arc, the frequency of the arc at the arc extinguishing instant could be accepted as 0.02 s with the division effect of the time parameter 10^{-9}. L, inter electrode gap at the turning point of breakdown curve, is accepted as 0.52 cm. Normally, it is supposed to be less than 0.52 cm since arc is extinguished before reaching to the rotating contact.

$$V_{dr} = \frac{L \times w}{2} = 0.52 \times 10^{-2} \times \pi \times \frac{0.02}{1 \times 10^{-9}} = 3.26 \times 10^{5} m/s \qquad [3.17]$$

$B = \frac{E}{V_{dr}} = \frac{3.48 \times 10^5}{3.26 \times 10^5} = \mathbf{1.067\ T}$ **, will be used as the design parameter for the selection of the magnet type.** [3.18]

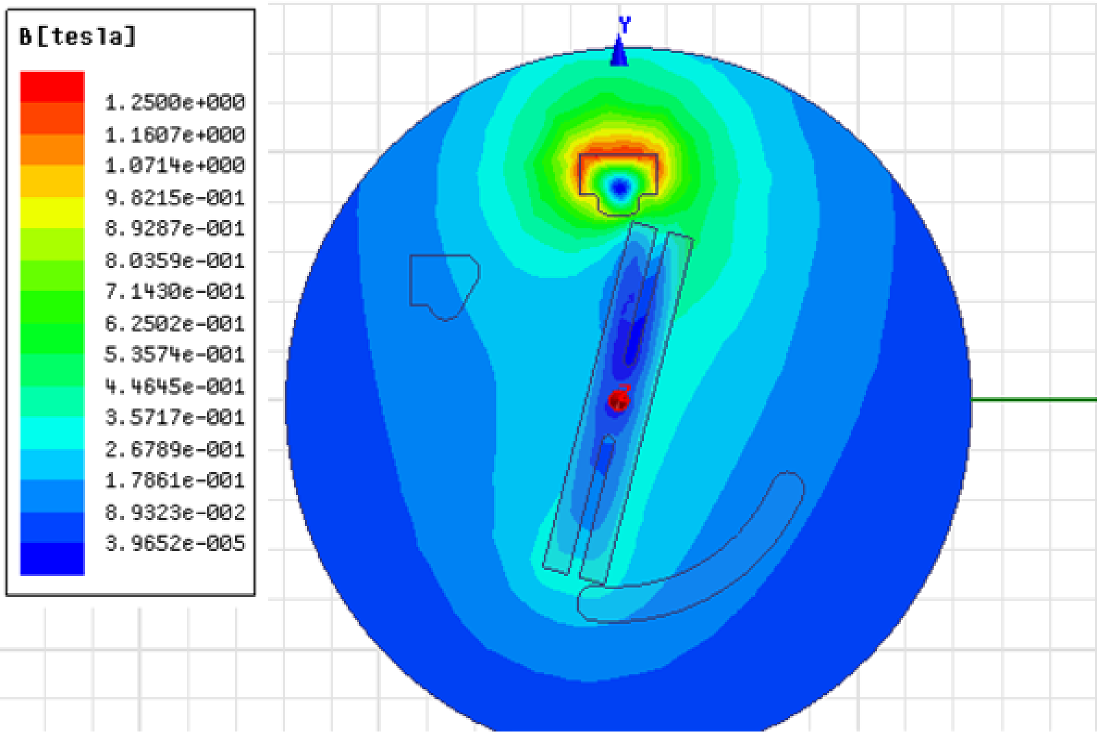


Figure 35: Maxwell simulation results for magnetic flux density while the busbar contact is made of sole copper without any magnet

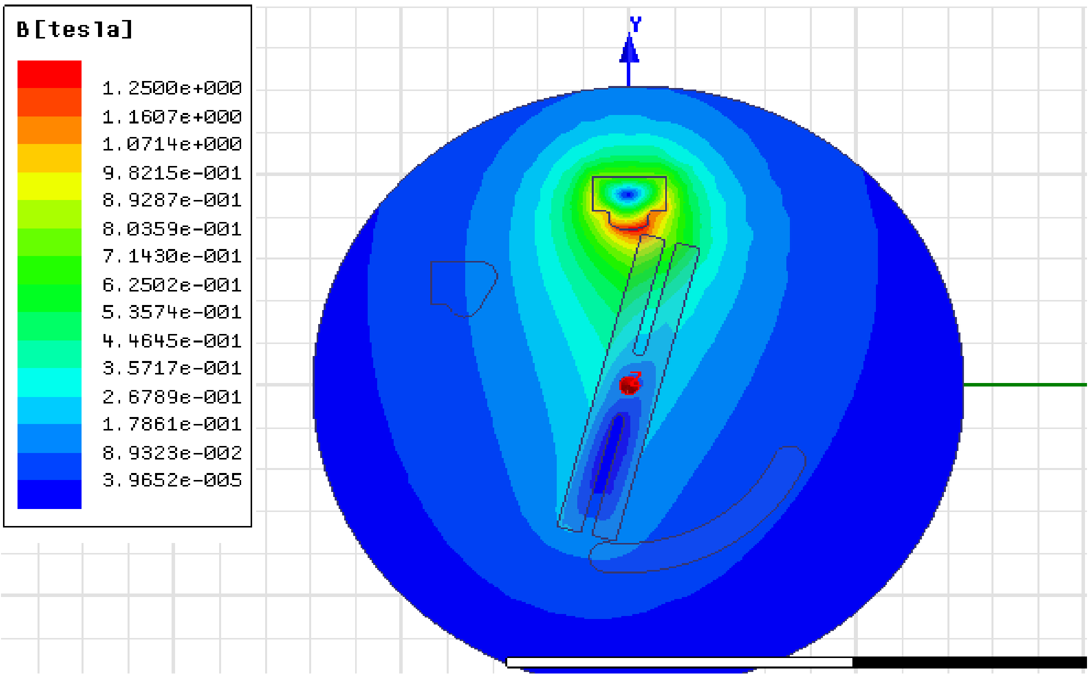


Figure 36: Maxwell simulation results for magnetic flux density while the busbar contact is made of copper with embedded magnet that will apply magnetic effect

The simulation of B is obtained from the Maxwell program solution type of Magnetic/ Magnetostatic with the application of rated phase current of 630 A to the busbar contcact while the earthing contact is grounded. The x and y axis unit is cm with 1 cm unit increment for both x and y axis. Since the Maxwell drawing can be applied in 2D drawing, the direction of B can not be visualised. As expected, the magnetic flux density is concentrated between the busbar and rotating contact if the magnet is applied on the system due to the magnetic affect of the neodymium magnet.

These B and H values indicates the magnet selection parameters. The magnet needs to have high magnetic field strength. This significat property indicated the magnet selection as a rare- earth magnet. Regarding to calculated values, magnet is selected as NEODYMIUM MAGNET- (sintered).

It is a permanent magnet with tetragonal $Nd_2Fe_{14}B$ crystal structure which leads a high saturation magnetization. This magnet has a potential of high storage magnetic energy which leads the action of arc extinguishing.

This magnet is obtained from the company Mıknatıs Teknik with the model name of NMPOT Q30.

Which has the parameters as following:

Table 6: B and H values of the Neodymium magnet

Magnet	B (T)- max	H (kA/m)- max
$Nd_2Fe_{14}B$ (sintered)	1.0–1.4	750–2000

To analyse the magnet and its magnetic characteristis, it is necessary to acquire the load line characteristic of the neodymium used in our design. First of all, because of its magnetic properties, it is expected to have the BH characteristic in the second quandrant. Regarding to our measurement taken from Gaussmeter, the BH values of the magnet is recorded as the table given below. The load line curve related to the positive application on 0.51 cm away from the magnet surface is acquired.

With the assumption of cylindrical arc plasma as the arc conducting region, it is possible to calculate the force applied on the arc plasma for stretching the arc and finally extinguish it. The base asumption is that, the arc plasma has the density of SF_6

gas which is 6,2563 kg/m^3. As the asumption of arc plasma diameter as 8 mm, we can calculate the maximum arc stretching length via ineartia and the magnetic force applied.

The mass of the arc plasma is calculated as following:

$$m = d \times v \qquad [3.17]$$

$$m = 6.2563 \times \pi \times r^2 \times L \qquad [3.18]$$

$$m = 6.2563 \times \pi \times (0.4 \times 10^{-2})^2 \times L \qquad [3.19]$$

$$m = (0{,}31453 \times L)\ \text{kg} \qquad [3.20]$$

where m is mass, l is the length of the plasma cylinder, r is the radius of the cylinder and v is the volume of the arc plasma.This arc plasma can carry 630 A current as maximum.

The inertia of the plasma cylinder in the z direction, perpendicular to the force applied on the plasma needs to be calculated to acquire the magnetic force applied.

$$I_z = \frac{m \times r^2}{2} = \frac{0.31453 \times L \times (0.4 \times 10^{-2})^2}{2} = \frac{0.025}{10^4} \times L \qquad [3.21]$$

The plasma can be accepted as a mass that has an accelerateed motion which results in stretching of arc and extinguishing it totally. We assume the cross section of arc is contant until it extinguishes which leads the consequence that the arc current is constant with the cross section until the arc is totally diminished. In this assumption, the mass is taken by assuming the plasma as a homogenous SF_6 gas cylindrical path. With this cylindrical path stretching, the arc is diminished in 20 ms, within 0.51 cm linear distance between the contacts. The aim is to calculate the stretching length of the arc via the application of the magnetic force established by the magnet. For calculating this value, the force calculations will be used. In these force calculations, real B value measured by gaussmeter in 0.5 cm away of the surface which is 42 mT is used. The F formula obtained from accelerated motion of the arc plasma by assuming the constant deceleration and the F formula obtained from current and magnetic flux density is used and the streching effect of the magnet is calculated in terms of stretching lenght.

$$V_{dr} = \frac{L \times w}{2} = \text{ L } \times 10^{-2} \times \pi \times \frac{\frac{0.02}{1 \times 10^{-9}} m}{s} \qquad [3.22]$$

$$\text{F} = \text{B} \times \text{I} \times \text{L} \times \cos Q = B \times 630 \times \text{L} \qquad [3.23]$$

$$\text{F} = \text{m} \times \text{a} = \text{m} \times \frac{V_{dr}}{t} \qquad [3.24]$$

$$0.31453 \times L \times \frac{L/20 \times 10^{-3}}{20 \times 10^{-3}} = 0.042 \times 630 \times L \qquad [3.25]$$

$$0.31453 \times L \times \frac{L/20 \times 10^{-3}}{20 \times 10^{-3}} = 0.042 \times 630 \times L \qquad [3.26]$$

$$L = 3.2047\ cm \qquad [3.27]$$

This L value corresponds to the arc stretching length valculated from the system to diminish the arc within the SF_6 gas medium.

Therefore;

$$m = \ 0{,}31453 \times L \ = 0{,}31453 \times \frac{3{,}2047}{100} = 10{,}08\ microgram \qquad [3.28]$$

Table 7: The recorded BH values of the neodymium magnet

NO	B (mT)				H (kA per m)			
	Positive		Negative		Positive		Negative	
	0.5 cm from the surface of the magnet	1 cm from the center of the magnet	0.5 cm from the center of the magnet	1 cm from the center of the magnet	0.5 cm from the center of the magnet	1 cm from the center of the magnet	0.5 cm from the center of the magnet	1 cm from the center of the magnet
1	43,5	16,5	36,5	14,5	35,1	13,2	30,7	11,7
2	42,7	16,6	36,8	14,4	34	13,4	30	11,7
3	44,9	17,1	37	14,5	34,2	12,7	30	11,5
4	45	17,6	37,8	14	34,7	12,2	30,4	11,7
5	45,3	17,4	38,6	14,6	35,9	13,2	30	11,7
6	39,8	16	43,3	16	31,8	11,7	35,8	12,8
7	45,8	17,4	38	14,6	36	13,3	30,2	12
8	38,5	16,5	38,5	14,7	35,2	13,4	30,5	12,2
9	38,6	15,3	43,8	16,2	29,7	11,5	35	13
10	45,2	17	38	14,2	35,7	13,6	30,5	11,6
11	39,9	16,7	44,9	16,9	32,2	12,7	35,5	13
12	46,2	16,4	39,1	15,42	36	13,6	31,2	12,2
13	38,7	15,24	44,6	16,31	31,2	12,21	35,2	12,9
14	45,3	16,76	37,5	14,9	36	13,72	30	11,4
15	38,3	15,5	44,2	16,4	30,7	12,23	35,1	12,7
16	45,6	17,3	38,7	14,5	35,5	13,7	30,5	12
17	39,3	15,9	44,4	16,62	30,08	12,7	35,7	13,15
18	40	15,9	45,4	17	30,8	12,61	35,8	13,52
19	39,6	16	44,7	16,7	31,6	12,62	35,3	13,4
20	40	15,9	45,2	17	31,6	12,68	36,1	13,4
21	39,4	15,9	45,4	16,9	31,8	12,45	35,8	13,17
22	40,01	16	41,4	16,6	31,6	12,9	35,9	13
23	44,9	16,8	38,4	15,17	36,2	13,9	30,4	11,08
24	43,3	16,9	37,8	14,87	34,4	13,5	30,7	11,9
25	45,2	16,9	38,9	15,07	35,2	13,8	30,3	11,8
26	38,9	15,3	42,6	15,08	31,1	14,4	35,1	12,86
27	45,8	17,43	39,5	15,29	35,9	13,9	31,2	11,9
28	42,1	16,8	38	14,96	35,3	13,4	30,3	11,9
29	39,9	16	43,4	15,7	31,2	12,35	34,3	12,91
30	39,2	15,8	44,8	16,6	31,6	12,5	34,1	12,9
31	39,5	15,6	43,8	15,8	30,1	11,9	34	13,04
32	37,2	14,7	41,8	13,8	31	12,48	35	13

33	46	17,78	38,1	14,9	36,5	13,76	30,9	12,08
34	46,6	17,8	38,5	14,9	36	13,8	31,5	12,08
35	40	16,7	44,4	16,25	31,7	12,7	35,3	13,3
36	39,7	15,9	44,5	16,34	31,6	12,4	35,6	13
37	40,3	16,15	45,7	17,1	31,9	12,86	36,2	13,5
38	40,8	16,16	43,9	16,24	32,2	12,55	34,8	13,15
39	45,9	17	38,4	14,96	36,9	13,26	30,2	11,94
40	45,2	16,85	38,2	14,62	36	13,4	30,4	11,8
41	40	16,06	44,3	16,57	30,9	12,67	35,3	13,23
42	40,5	16,23	45,1	16,8	31,9	12,5	35,1	13,11
43	45,2	17,3	38	14,9	35,1	13,78	30,7	11,8
44	40,1	16,2	44,3	16,75	32	12,79	36,2	13,5
45	40,7	16,3	43,5	16,29	32	12,96	35,6	13,28
46	45,2	17,3	38,3	14,8	35,7	13,7	27,1	11,9
47	45,2	17,3	38,1	14,8	36,4	13,6	30,7	11,9
48	39,2	16,04	44,3	16,6	30,6	12,7	35,8	12,9
49	45,6	17,6	40	15,04	36,6	14,04	31,9	11,85
50	45,7	17,6	38,5	14,7	36,6	14,12	30	11,85
AVG	42,1902	16,508	41,178	15,557	33,4796	13,0408	32,878	12,464

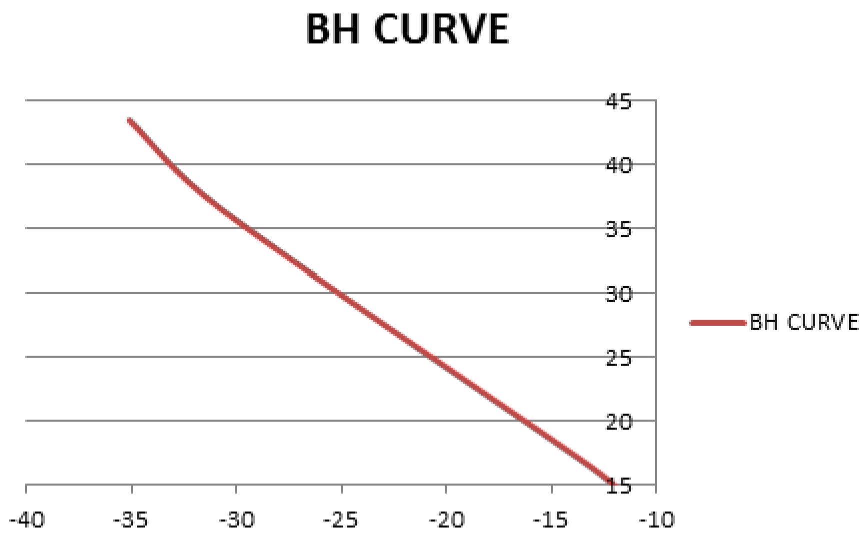


Figure 37: The load line related to BH values taken from 0.5 cm away from the surface of the magnet.

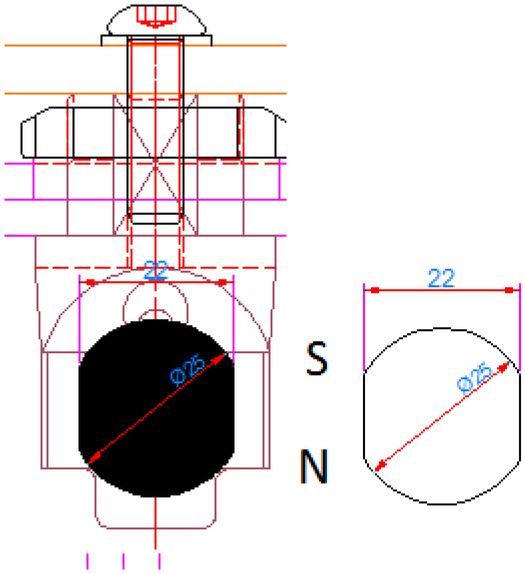


Figure 38: The magnet embedded inside the busbar contact

To justify the selection of Neodymium as the magnet to acquire sufficient magnetic force on arc to diminish it,the Maxwell simulation results with magnet application of Alnico5 is acquired. Alnico5 has much lower magnetic field strength and magnetix flux density compared with Neodymium. Moreover, Alnico5 can not provide sufficient magnetic effect with respect to arc extinguish parameters of linear distance between contacts to be limited as 0.52 cm and the duration of arc extinguishing as 20 ms. In Figure 37, it is seen that Alnico5 can not lead satisfactory magnetic fkux density at the arc extinguishing region that will meet the arc diminish milestones of the load breaker design

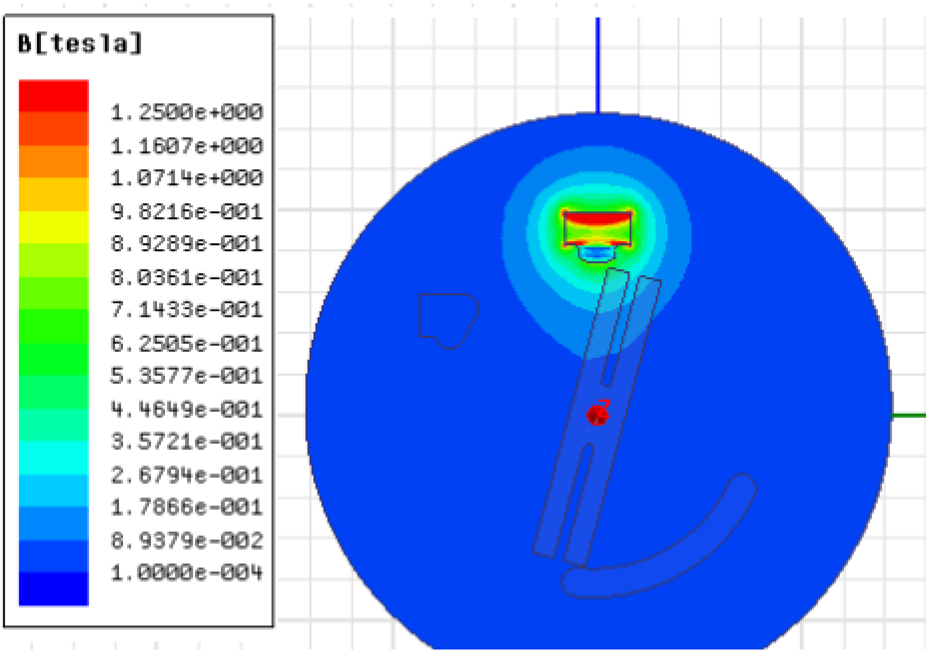


Figure 39: Maxwell simulation results for magnetic flux density distribution while the magnet is selected as Alnico5, instead of Neodymium.

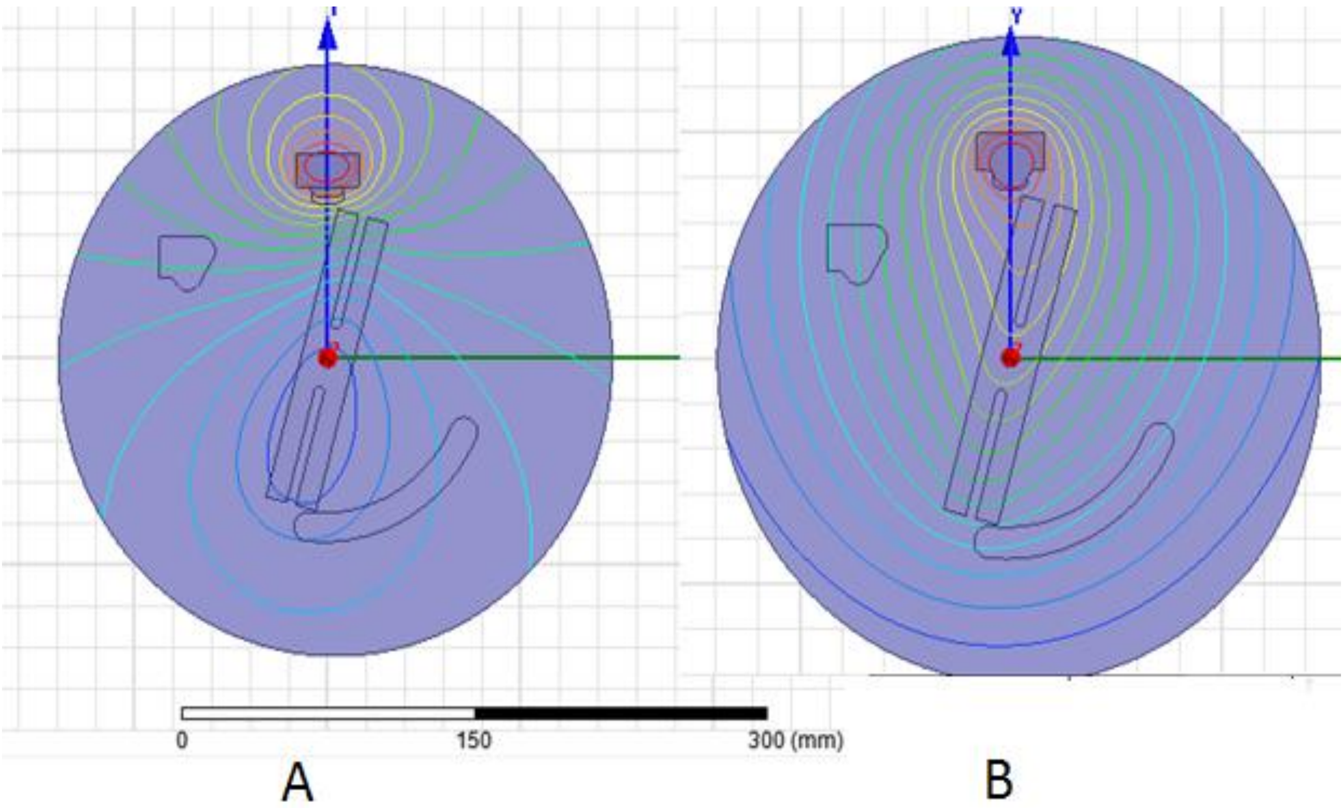


Figure 40: Maxwell simulation results for magnetic flux density distribution as incremental change perspective.

According to the magnetic flux density simulation results view from incremental change perspective as given at Figure 37, the comparison between magnet applied and pure copper busbar contact could be visualized. The magnetic flux is concentrated between the contacts at the arc extinguishing instant with the application of the magnet. The x and y axis unit is cm with 1 cm unit increment for both x and y axis.

According to the right hand rule; while the current passing through the magnetic field, the electrons face with a magnetic force depending on the current value, magnetic flux density and the length of the current carrying path. The main milestone on arc breaking or extinguishing is the applied magnetic force on the ions (arc), which leads the arc path to get stretched. This magnetic force is directly related to the magnetic induction, B which is induced by the magnet embedded inside of the contact. This condition finally leads to the breaking of the arc via effect of the magnetic force applied. Therefore, this magnet embedded in busbar contacts works as magnetic field source to apply magnetic force on electrons to diminish the arc line.

Arc is not distributed uniform. Electrons have different behavior and face with different magnetic and electrical effects. The electron’s mean path determines arc path regarding the pre request of the points where magnetic force equals to electric force applied on the magnet. The arc stretching occurs actually because of the increasing magnetic force applied on arc electrons compared with the electric force applied at opposite direction. The cause of the increased magnetic force on arc compared with the electric force is selection of proper magnet with satisfactory magnetic strength and magnetic field density. Arc stretching is caused by the cross section decrease of the arc path because of the magnetic force effect of the neodymium. The cross section of the arc is directly related to the current of the arc. The decreased cross section comes with the result of the decreased arc current. As the consequence, the resistance of the arc is increased and the arc is extinguished. The Figures 38, 39,40 and 41 show the electric field and magnetic flux density distribution between the contacts while the rotational contact has 20^o and 40^o from its totally closed position. It is seen that with the increased rotational angle, the electric field and magnetic flux density is getting decreased with different rates. Because of the more rapid decrease in electric field drift velocity is getting decreased with the increase in the rotation angle.

Figure 41: The photo of the busbar contacts and magnet for arc extinguishing

Figure 42: The photo of the earthing contacts

Figure 43: The photo of the output contacts

Figure 44: The photo of the rotating contacts

In Section 2.3, three type of switching apparatus mechanism is defined as the hinge type, linear type and the rotating on central axis type, while the design work subjected in this thesis adopts the rotating on the central axis mechanism.

3.5 Arc Modeling and the Arc Extinguishing Mechanism

Arc modelling is a frequently used method of symbolizing the high voltage arc effect before verification at international laboratories. The arc modelling is used for simulating the switching process with arc extinguishing by deriving formulas as taking some parameters into account which are arc voltage, post arc current and transient recovery voltage and other parameters.

As the arc extinguishing mechanism there are 3 main mechanisms. The first one is called the rotating puffering which is more applicable to rotating central mechanism and the hinge type operation mechanism. This system is based on the extinguishing the arc by concentrating SF_6 gas on the arc beginning point. With the special design of the contacts, the system leads SF6 gas to be puffered on the arc area with the open and close movement of the contacts. Currently most of the load break switches are used with rotating puffering arc extinguishing mechanism while the mechanisms are generally hinge type or rotating on the central axis.

Another, rarely used method is the limiter model. In the limiter model the end of the output contact has a shape of hook, so that at the loading period the current is passing in the opposite direction at the output contact. In the limiter model, the contacts have opposite direction of current flow at the contact touching points which leads the pushing magnetic force to occur on the contacts. Therefore in the limiter model, the difficult point is not to open the contacts, but to keep the contacts at the close position due to the magnetic force issue. But the verification of an apparatus matters the safe tripping at the short circuit current, the closing at the short circuit current in not an issue.

The final arc extinguishing model is the magnetic force effect by using the proper magnet on the contacts. This system is more adopted in the circuit breakers working with the mechanism of linear movement. The contribution of this thesis to the design parameter of the load break switch is that even the mechanism is based on rotation around the central axis, the method of arc extinguishing is the magnet effect on the contacts. The busbar contact has the magnet embedded in the contact and covered by silver plated copper. This method leads more basic manufacturing steps on the contacts and it is a more secure solution on arc extinguishing. This contribution on the thesis leads arc extinguishing in a small period with a small rotation angle. All load break applications use puffering of SF_6 gas on the arc source point to increase the dielectric strength on the source point of arc to diminish the arc. However, SF_6 gas is insulation medium whose dielectric properties get weaker in time because of contaminations and corona ionization effect seen during arc extinguishing. Therefore, counting on puffering mechanism as arc extinguishing leads shorter life cycle, longer arc extinguishing duration with longer required distance between contacts to diminish the arc. With the magnet embedded in the busbar contact, the arc is repelled and spitted. The material that extinguishes the arc is not the SF_6 gas based insulating material but the magnetic force occurred at the magnetic area created by the magnet if the busbar contact. This study contributes to the design of the switchgear by acquiring better arc extinguishing method with optimum distance between contacts, optimum rotation on the central axis and longer life time.

Between the rotating and busbar contact, arc is occurred as current conducting gas plasma. In this plasma, there are electrons and also other ions and molecules that lead a conducting path within SF_6 medium. The arc is stretched and follows a path regarding the balance between magnetic and electrical force. Electrical force in the system is acquired by the existence of current conducting, so the arc. Magnetic force is acquired because of the magnetizing force effect of the magnet embedded in the busbar contact. As an example, the arc can be assumed to be a thin conductor between rotating and busbar contacts. But of course, applying magnetic and electrical force on a conductor and on a conducting gas plasma have different consequences and parameters that need to be encountered. The arc stretching is related to the balance between magnetic and electrical forces. While arc is stretched and pushed away from the magnet high magnetic strength region, tha magnetic force on the arc will be decreased. In the system , the arc cannot be assumed as homogenous plasma, the contact geometry itself does not lead a purely linear magnetic region . Moreover, the arc plasma contains electrons and many other ions, molecules that lead a heterogeneous plasma structure.

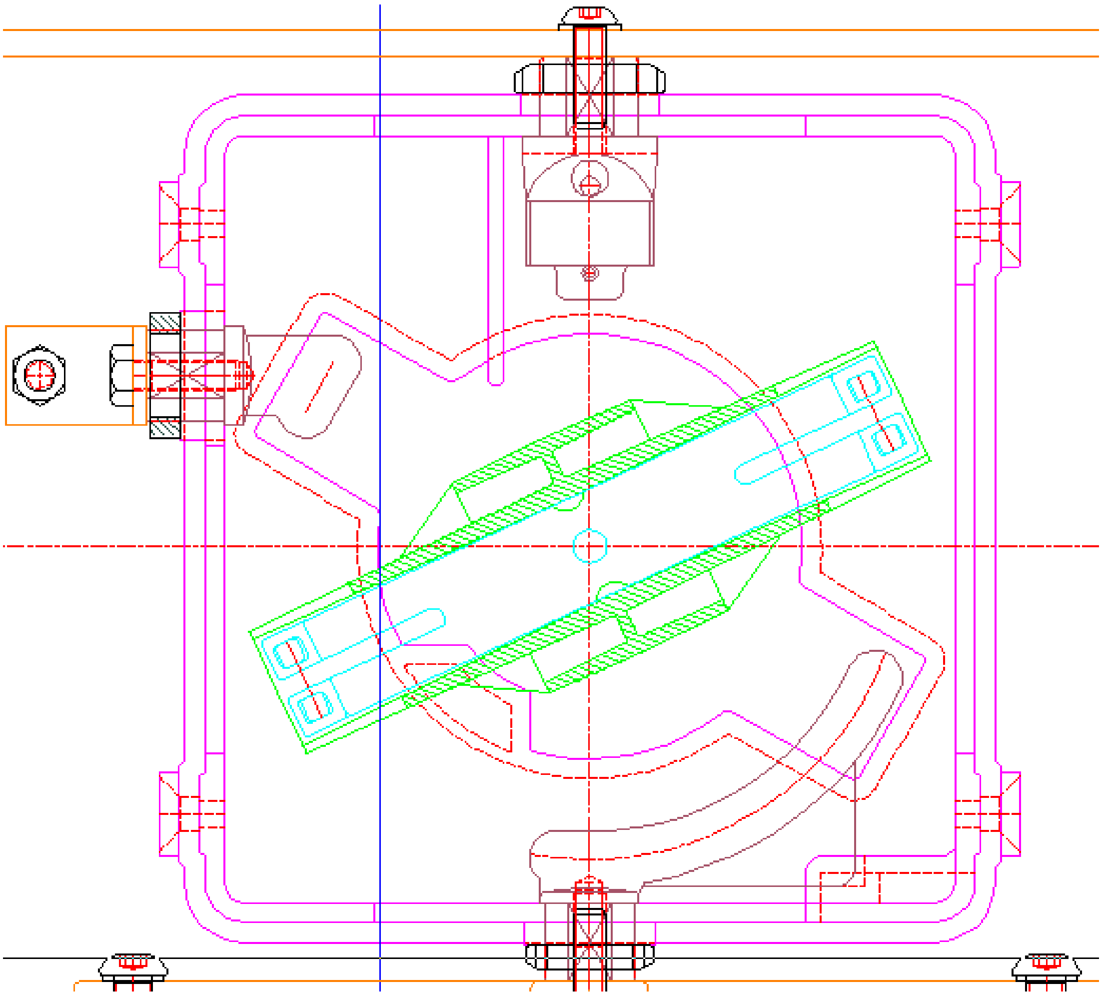


Figure 45: The contact geometry

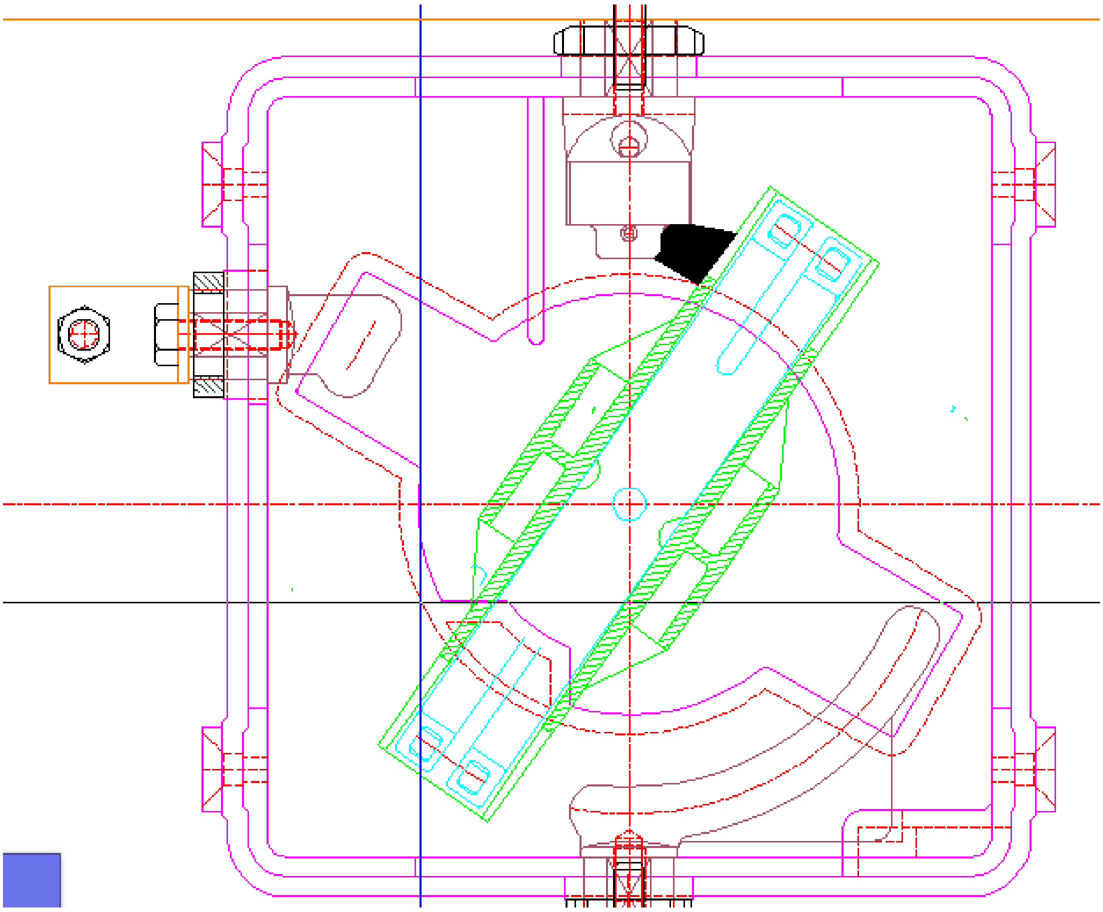


Figure 46: Arc occurrence region

Many application and theory was used on arc modelling at literature. The literature survey is completed to investigate the current arc models and the most suitable model to be adopted as the contribution of this study to the design. . The Cassie and Mayr models are the first methodologies on arc modelling at the literature that leads to many further works to be obtained. It is necessary to understand the milestones of these 2 fundamental models and the future models that are derived from Cassie and Mayr models with different modelling methodologies and with additional electrical parameters included. Cassie model is more applicable on high currents like between 100A- 100 000 A, while the Mayr model is a better approximation for small currents near 0. Therefore, since our main focus on load breaking switch has nominal current of 630A, in this thesis Cassie arc modeling is selected for arc characteristic investigation. Before starting the milestones of the arc modeling of the thesis subject, it is necessary to understand the available arc modeling methods [36].

Cassie model is mainly focus on the high current modelling by proposing that the potential difference between the source and final point of the arc is constant while the cross section area of the arc has a direct proportion with the current. Moreover, Cassie model declares the arc temperature as constant [35]. Since Cassie model states the linear relation between the arc conductance and the stored energy, it refers the arc dynamism with the following equation [38].

$$\frac{1}{G} \times \frac{dG}{dt} = \frac{1}{\tau} \times \frac{u^2}{U_A^2} - 1 \qquad [3.29]$$

At this equation, G is the dynamic conductance of arc, U_A is the arc voltage which is assumed as constant is Cassie model, τ is the time constant of the arc at arc voltage and maximum current parameters, u is the system voltage or in other words the voltage drop across the arc until the arc is extinguished and the voltage drops to 0 volt.

Mayr arc model gives better approximation for small currents. In this model, it is assumed that the cross section area of the arc is constant.

$$\frac{1}{G} \times \frac{dG}{dt} = \frac{1}{\tau} \times \frac{U_A \times i}{P} - 1 \qquad [3.30]$$

In this equation, G is the arc conductance, P is the cooling power, U_A is the arc voltage, i is the arc current, τ is the time constant. P and τ are functions of conductance, current and voltage [37].

Cassie and Mayr arc models are the milestones on arc modelling. All other modeling methods related to arc modelling are generally takes Cassie or Mayr as the starting point and have an average of 5 or more parameters taken as variable.

Schwartz arc model is a modified Mayr arc model that demonstrated on the dependence of arc conductance with the time constant and the cooling power. Schwartz model proposed very short post arc current with transient recovery voltage with high damping factor and a significant arc voltage variation between the measured and calculated one just before current zero moment [36].

Habendack arc model is effective for both arc with high current and current zero since it considers the electric arc conductance as a Cassie conductance and a Mayr conductivity in series connection. Haberdack model calculates shorter post arc current that measured on experiments [36].

Schavemaker model is based on constant time parameters by taking Mayr as the starting point. It also takes cooling power as a function of electrical power [35]. Schavemaker arc model proposes that the arc voltage remains almost constant, with little peak before current zero moment [36].

Kema model is the combination of 3 Mayr model with its series conductance calculated from different modified Mayr equations.

In this thesis, since the test current under work during load breaking is 630A, Cassie model is adopted (more precise solution at modeling at high current). Also, since the arc extinguishing method has no relation with arc puffering, cooling power is totally neglected and assumed that it has no effect on arc extinguishing. To work on the method and model of arc extinguishing, Matlab Simulink results and Maxwell simulations are used. To verify Cassie model and compute the parameters related to Cassie formula is necessary to compare and prove the Simulink simulation results. Therefore, the steps to derive the Cassie Arc formula need to be investigated in detail.

The total power of arc can be calculated as the sumation of power loss on arc and the heat content of the ar [39].This situation can be formulated as:

$$P = u \times i = P_{loss} + \frac{dQ}{dt} \qquad [3.31]$$

where u is the voltage drop across the arc region until the arc is extinguished and the voltage drops to 0 volt (the system voltage), P_{loss} is the power loss of the arc, i is the system current and Q is the heat content.

These calculations lead the solution of the heat content as;

$$\frac{dQ}{dt} = P - P_{loss} \qquad [3.32]$$

So;

$$Q = (\quad P - P_{loss}) \qquad [3.33]$$

Conductance of arc is actually a function of heat content so we can state :

$$G = G(\quad P - P_{loss}) = G(Q) \qquad [3.34]$$

Differentiate both side:

$$\frac{dG}{dt} = \frac{dG(Q)}{dQ} \times \frac{dQ}{dt} = \frac{dG(Q)}{dQ} \times (P - P_{loss}) \qquad [3.35]$$

$$\frac{1}{G} \times \frac{dG}{dt} = \frac{G\prime(Q)}{G(Q)} \times (P - P_{loss}) \qquad [3.36]$$

From ohm law's:

$$P = U \times I \qquad [3.37]$$

$$U = R \times I \qquad [3.38]$$

$$G = 1/R \qquad [3.39]$$

$P = U^2 \times G$ [3.40]

In Cassie model we assume, arc tempreature is constant so the cross section of arc is propotional with the current. The arc voltage is constant until it extinguishes.

$P_{loss} = U_c^2 \times G$ and $P = u^2 \times G$ [3.41]

$\frac{1}{G} \times \frac{dG}{dt} = \frac{G\prime(Q)}{G(Q)} \times \ u^2 \times G - U_c^2 \times G \quad =$ [3.42]

$\frac{U_c^2 \times G}{Q} \times \ \frac{u^2}{U_c^2} - 1 \ = \frac{1}{\mathrm{T}} \times \ \frac{u^2}{U_c^2} - 1$ [3.43]

T is the time contant arising from the change in the arc cross section. This time constant is also set in IEC 60265 regarding by only taking current as a variable since change in arc contant is only depended on the current.

The program used for the arc modeling is Matlab/Simulink via “power_arcmodels” tool. This tool constructs the Cassie and Mayr arc model circuitry as given below Modeling parameters are calculated by the program after the entry of calculated parameters.

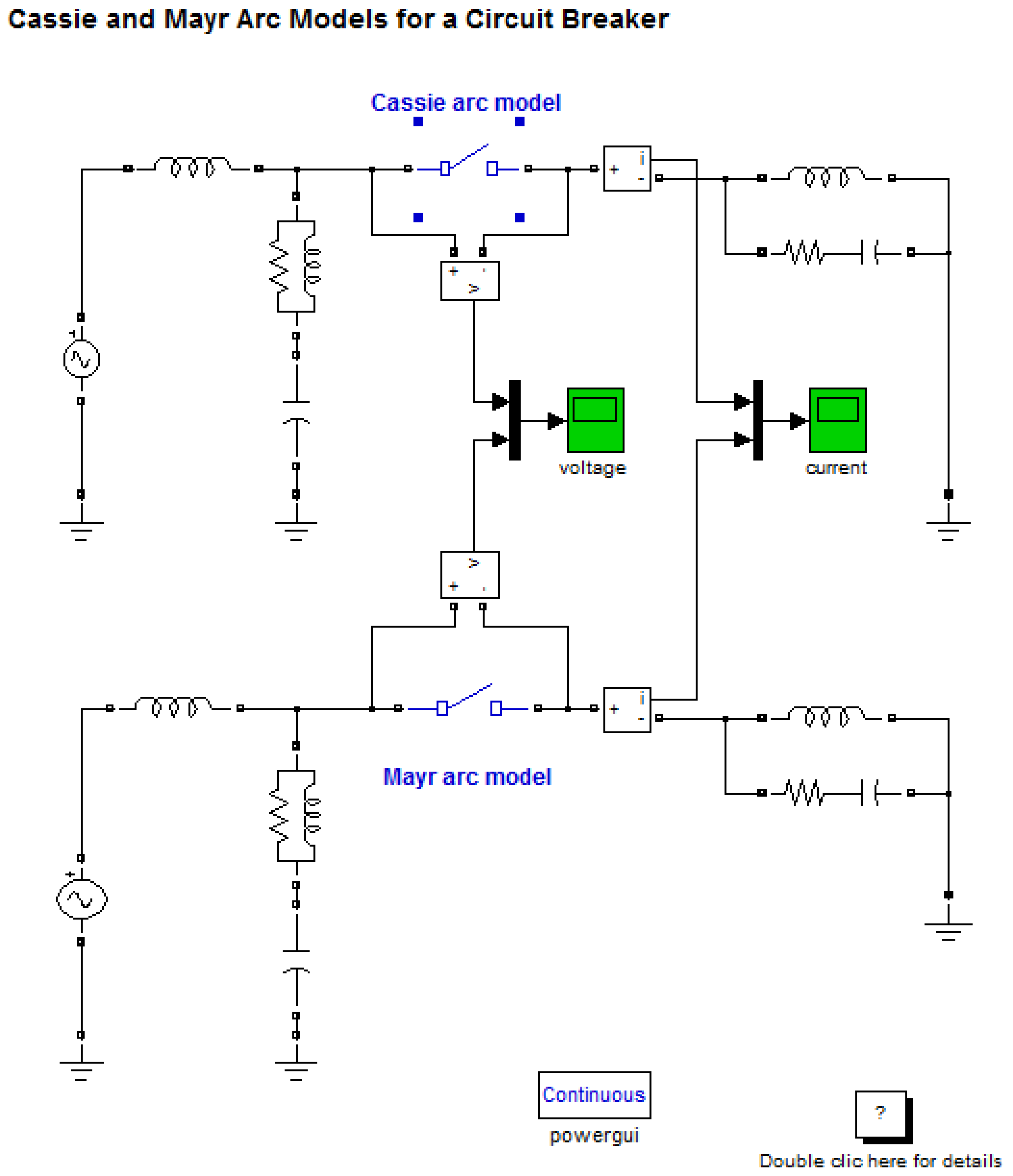


Figure 47: Arc modelling circuitry via Mayr and Cassie arc models on Simulink

The transient recovery voltage and time constants are determined with respect to IEC 60265. These values determine the arc model parameters.

$$U_c = U\sqrt{\tfrac{2}{3}} \times 1.4 \times K_{\emptyset} \qquad [3.44]$$

In this equation, U_c is the transient recovery voltage while U is the rated voltage of the system. $K_\emptyset$ is the first pole to clear factor that is accepted as 1 for rated voltages equal or higher than 245 kV, 1.5 for the rated voltage lower than 245 kV. For our case $K_\emptyset$ is 1.5. 1.4 is the amplitude factor as constant [33]. Even the prototype is designed as 12 kV nominal voltage. The voltage and making/ breaking tests are completed as per 24 kV voltage level. As normal, any equipment that passes 24 kV voltage tests are also perceived successful for 12 kV voltage tests. Therefore the calculations are based on that U is 24 kV.

$$U_c = 24kV\sqrt{\tfrac{2}{3}} \times 1.4 \times 1.5 \quad [3.45]$$

$$U_c = 40.8\ kV \quad [3.46]$$

The time parameter is calculated according to IEC 60265.

$$\tau = \frac{K}{I} \quad [3.47]$$

Where K is the time coordinate factor and I is the nominal current of the system. In our case, I is 630A at the instant of starting of arc occurrence while K is given as Table V in IEC 60265 as 70

$$\tau = \frac{70}{0.63} \quad [3.48]$$

$$\tau = 87.5\ \mu s \quad [3.49]$$

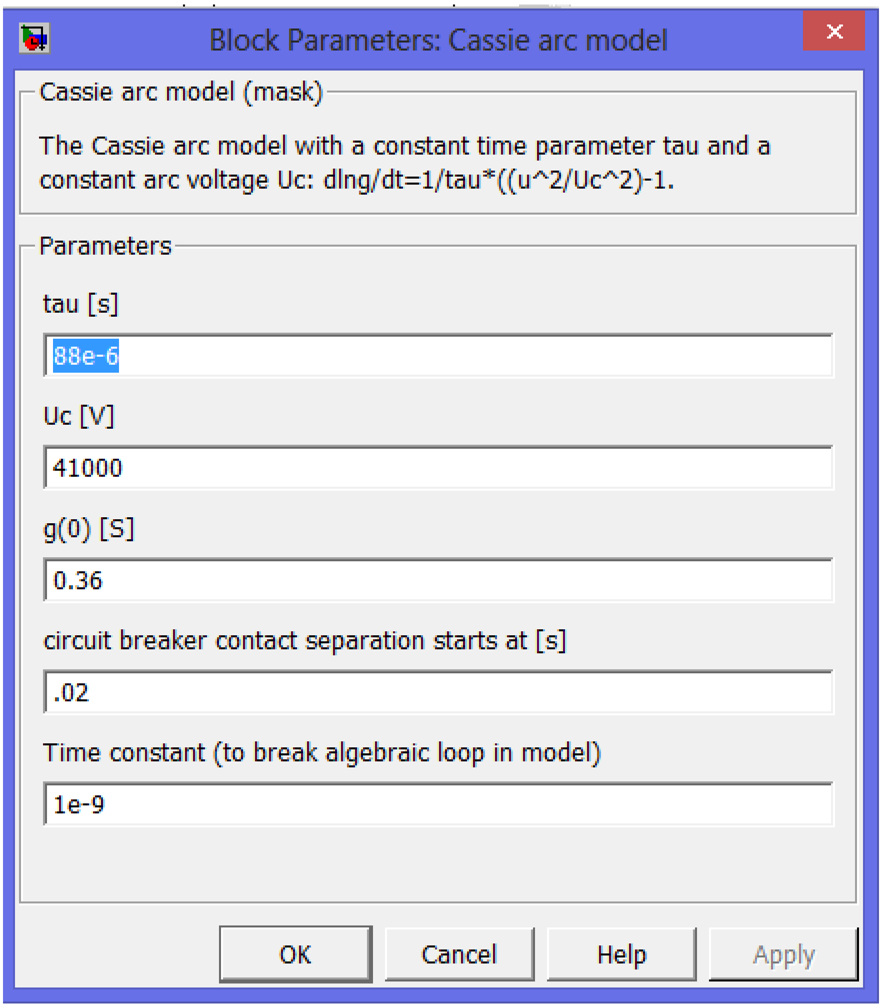


Figure 48: The Cassie arc model parameters obtained from Simulink after entering calculated time constant and arc voltage values

The calculated arc voltage and the time constant values are set to the Matlab input parameters which leads to the other arc model parameters to be calculated from the program. The Simulink simulation computations provide the information related to the arc conductance at the x=0 point as 0.36 siemens and dt value as 0.02 sn which is 20 ms, corresponds to the total time period for arc extinguishing. For the purpose of arc model and Simulink computation verification with the design contributions, the Simulink computation outcomes and the calculated τ and U_c values are applied to the derivated Cassie model formula.

The accepted and adopted arc extinguishing period is 20 ms. Therefore dt is 0.02 s. The other parameters as computed. By using these parameters, we can calculate

$$\frac{1}{G} \times \frac{(G-0.36)}{(0.02\times10^{-3})} = \frac{1}{(87.5\times10^{-6})} \times (\frac{24^2}{40.8^2} - 1) \qquad [3.50]$$

So;

G=0.042 S [3.51]

This means the arc resistance at the beginning of arc occurrence is 2.77 ohm while it increases to 23.8 ohm until the point where arc is extinguished. As expected arc conductance is getting lower so the arc resistance is getting higher which leads to the extinguish of arc.

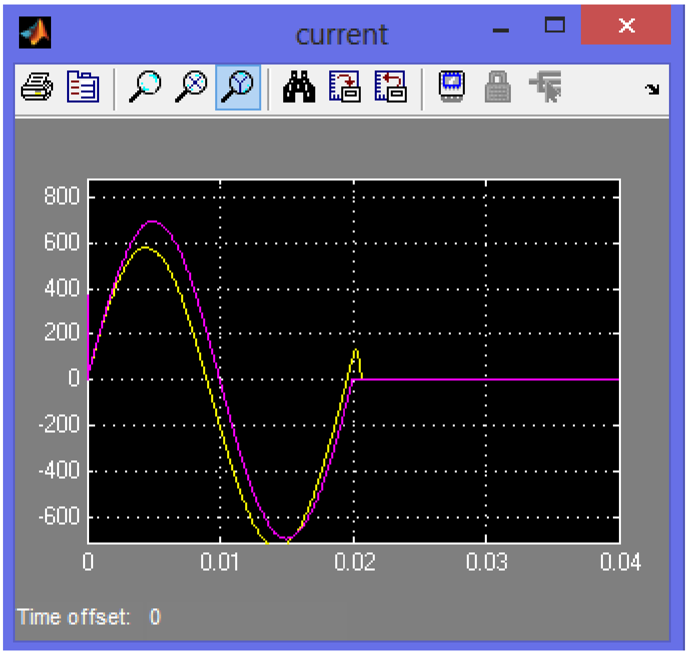


Figure 49: The current graph of the system Cassie arc model from the Simulink

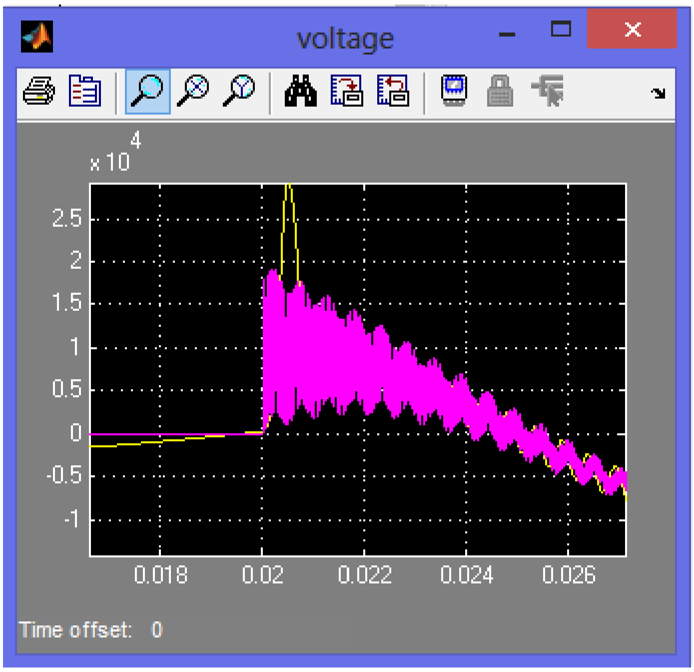


Figure 50: The voltage graph of the system Cassie arc model from the Simulink

The Matlab simulation results with the application of the calculated values show the voltage and current value changes at the arc instant. As expected, at the arc occurrence, the change in the current and voltage follow an exponential decay before reaching to the steady state condition. Also the results of the voltage and current values are similar with the real life graphs. The current is diminished in a small period, while from the voltage characteristics, it is seen that a great deal of oscillation prolongs for a long period. The reason of this oscillation is the stray capacitances. The stray capacitances are in picofarad value which leads arc extinguishing of high current values at high frequency. In the voltage characteristic both 50 Hz and also high frequency oscillations are observed. These voltage waves passing through the RLC circuit meets at a steady state position after a while. The frequency of the stray capacitance oscillations cannot be measured clearly because of the picofarad value of the stray capacitance. At the verification of the design stage the calculated values are used as the standard test values at the international laboratory which gave the simulation results same with the ones that are simulated at the modeling stage. Therefore the modelling is accepted as successful.

3.6 SF_6 Gas Implementation on the Prototype

The SF_6 gas properties are defined in the Chapter 2. The prototype design is based on SF_6 properties on thermal cooling effect, its heavy structure and its high insulation level. After the contacts, the internal mechanism of the load breaker, the metallic vessel and mechanism are prepared, the installation of the system into the prepared metallic vessel will be completed. After the completion of the metallic vessel with all contact and load breaker installed, the gas insulation medium preparation is the final task. After the gas implementation is finalized, the switchgear electrical vessel implemented on mechanical parts will be completed

As it is stated at the design criteria, the relative pressure inside of the vessel is 50 kPa as nominal. This pressure cannot decrease below of 30 kPa. Because below of 30 kPa , the gas insulation loses its effectiveness on the rated power frequency withstand voltage that it needs to endure for 1 minute.

This minimum 30 kPa relative pressure value is defined according to the 1.2 / 50 μs lightning impulse across the isolating devices that is defined by IEC 60060-1 standard. Even the nominal voltage parameter of the prototype is 12 kV, all the design parameters and high voltage tests applied are to ensure the safe operation of the equipment for voltage levels below 24 kV.

From the graphics related to the insulation characteristic of the SF_6 gas given in Figure 10 and 11, the design milestone is keeping the distance to every conducting point at least 7 cm. Calculations given in [3.1]- [3.2] and graphical comparisons in Figure 11 prove that the expected design parameters satisfy the lightning impulse withstand test requirement of 1.2/50 μsn.

In Figure 11, the pd value is the multiplication of the distance between isolating points and the relative pressure inside of the vessel.

$$pd = (30 \times 10^{-3}) \text{ M Pa} \times (7 \times 10^{-2}) \text{ m} \quad [3.52]$$

pd= 2.1 kPa m. [3.53]

According to the breakdown characteristic of the SF_6 gas given in Figure 20, the PD value of 2.1 kPa.m assures the breakdown voltage of SF_6 at 30 kPa relative voltage to be no lower than 150 kV. By this manner the voltage tests of power frequency voltage withstand and lighting impulse withstand test as well as nominal voltage application is verified. There is seen no breakdown as expected as the design milestone. As a result, the testing on the prototype manufactured regarding the milestone will pass the test successfully that will be explicitly explained in Chapter 4.

The room conditions (under standard temperature and pressure) requires 1 bar pressure to be applied from the outside of the vessel, in order to obtain the relative pressure of the vessel in between 30 kPa to 50 kPa, 1.3 bar to 1.5 bar SF_6 gas needs to be injected into the vacuumed vessel.

The breakdown field relative to pressure of SF_6 is 89 V m-1 Pa-1as seen in Table 4 which provides the related parameters of SF_6.

The lowest SF_6 gas pressure inside of the vessel is 30 kPa.

$$89 \times 30 \times \frac{10^3}{10^2} = 26.7\ kV/cm \qquad [3.54]$$

The voltage level between 3 contact during the arc extinguishing needs to be more than 24 / V3 = 13,58 kV to ensure that the distance between the busbar and rotating contact is sufficient to ensure the satisfactory dielectric strength that leads no breakdown of the insulation medium. This corresponds to the linear distance between the busbar contact and the rotating contact for arc extinguishing is to be minimum 0.51 cm which corresponds to 0.52 cm of arc length that is 3.40 central rotation angle. Therefore it is accepted that the arc extinguishing is handled in a region where the rotating contact is rotated 3.4 cm from its vertical position. This contribution to the design parameter leads the arc extinguishing at smallest possible distance between contacts.

To visualize the effect of SF_6 gas as an insulation medium compared with air by perceiving the design parameter of this thesis contribution on minimum distance between the contacts to extinguish the arc, the Maxwell voltage simulation is used. As the simulation outcomes the potential distribution inside of the vessel are taken for both SF_6 gas vessel medium and air vessel medium.

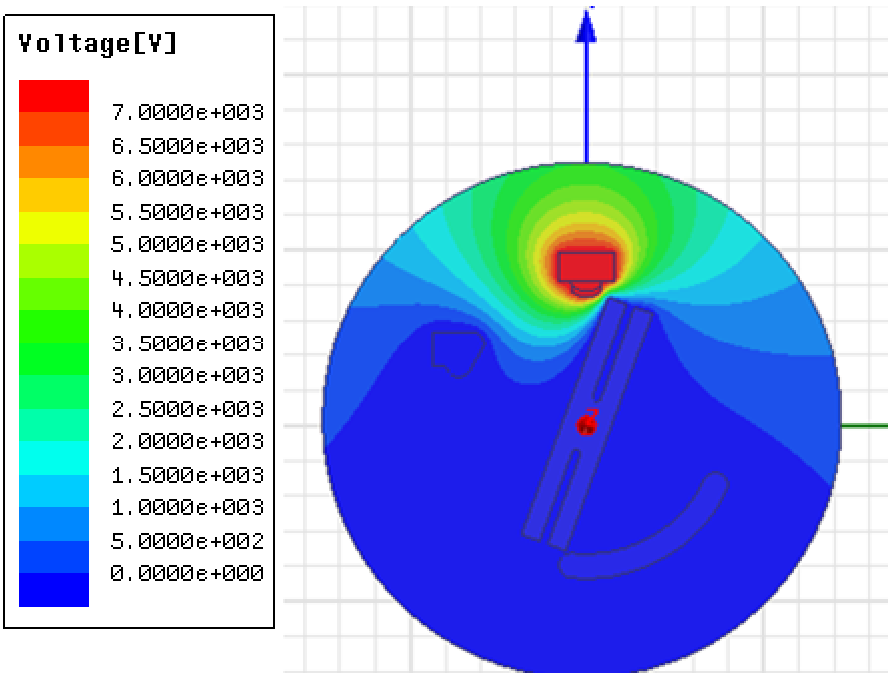


Figure 51: The Maxwell simulation of the potential distribution results while insulation medium is SF_6, the applied voltage on the busbar contact is 12 $\overline{3}$ 7 kV, the applied voltage on the earthing contact is 0 V

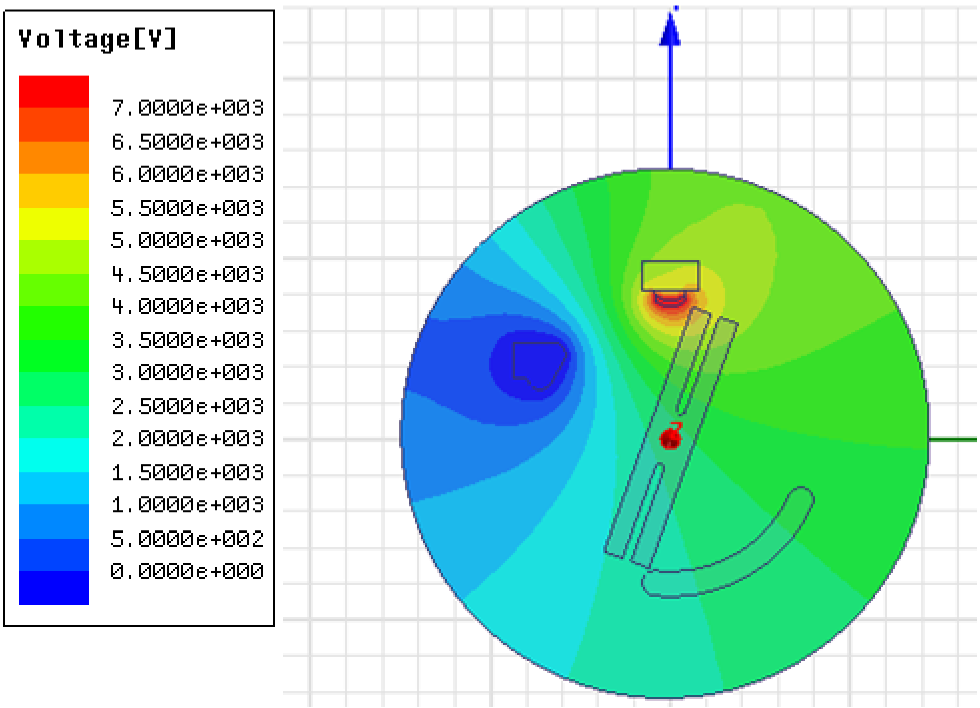


Figure 52: The Maxwell simulation results of the potential distribution while insulation medium is air, the applied voltage on the busbar contact is 12 $\overline{3}$ 7 kV, the applied voltage on the earthing contact is 0 V

The steps listed below are applied to prepare the SF_6 gas insulation medium of prototype;

1. After the mechanical vessel design and manufacturing is completed, the first task is to vacuum the mechanical vessel.
2. The second step is to inject Helium gas into the vacuumed vessel. The reason of this task is that Helium is the smallest molecule after Hydrogen gas molecule which is not preferred in these applications because of its combustive nature. This Helium injection procedure is just applied to verify whether there is any hole on the vessel after the welding procedure. So it is reasonable to say that this step is done only for controlling the welding quality. This is very important since the gas insulated switchgear has to have a relative pressure inside of the vessel in between 50 kPa to 30 kPa. Any

possible hole might lead the leakage of SF_6 gas out of the vessel which will lead the gas insulated switchgear to lose its insulation property after a while. Since Helium is a very small molecule, verifying no leakage at the Helium filled vessel ensures that no leakage will happen with SF_6 gas. The spectrometer is used to detect any possible Helium leakage.

3. After verifying that there is no leakage on the welded vessel, the helium inside will be vacuumed.
4. The vacuumed vessel is filled with Nitrogen gas for the purpose of cleaning the vessel from any kind of contaminates. The reason of why Nitrogen gas is preferred for this cleaning process is that the Nitrogen itself is an insulating gas. Figures 10 and 11 shows its high breakdown properties even lower than SF_6 gas.
5. Then the Nitrogen filled vessel is vacuumed again. Even there is Nitrogen particles remained in the vessel after vacuuming process, since it is a non - conducting material, it does not lead to any insulation problems.
6. As the final step, SF_6 gas will be filled to the vacuumed vessel and the vessel gas gate will be sealed.

Crucial design milestones regarding the SF_6 gas properties and SF_6 gas filling occupation is that the vessel material needs to be selected as 3 mm stainless and non-magnetic steel sheet, since this kind of steel sheet is much smooth compared with regular steel sheet. This leads a great advantage on the Nitrogen gas cleaning.

Another important design milestone is that while the outside pressure is constantly 1 bar, vacuuming the vessel might lead the vessel cage to be deformed. To prevent this kind of mechanical impact on the vessel, some supporting mechanical pieces are welded on the vessel that will lead the vessel to withstand 1 bar relative pressure.

Also during the load break switch operation, the arc and its thermal effects will lead the decomposition of the SF_6 gas and some unwanted gasses such as S_2F_{10}, SF_4… etc are occurred at the SF_6 insulation medium. Therefore an amount of active alumina is added to the SF_6 gas medium which is used for unwanted gasses to be collected at a certain region. Active Alumina works similar to the silica gel behavior on humidity for a transformer.

CHAPTER 4

VERIFICATION OF THE PROTOTYPE SWITCHGEAR

4.1. Test Methods

The verification of the prototype switchgear is based on the international standards and general technical specifications of the target country's distribution utilities.

The adopted international standards used for MV gas insulated switchgear and load break switches are IEC 62271-200, IEC 62271-100, IEC 62271-102, IEC 60060, IEC 60265 and IEC 60076-4 for High voltage test methods applied of the switchgear, IEC 60076-3 for the dielectric tests

According to the Turkish regulations, the technical specification used as the base for the gas insulated switchgear manufacturing is TEDAS MYD 95-002.

According to the IEC 62271-200 which defines the mandatory tests as;

- Tests to verify the insulation level of the equipment
- Tests to prove the temperature rise of any part of the equipment and measurement of the resistance of circuits
- Tests to prove the capability of the main and earthing circuits to be subjected to the rated peak and the rated short-time withstand currents
- Test to prove the making and breaking capacity of the included switching devices
- Tests to prove the satisfactory operation of the included switching devices and removable parts

- Tests to verify the protection of persons against access to hazardous parts and the protection of the equipment against solid foreign objects

Mandatory type tests, where applicable:

- Tests to verify the protection of persons against dangerous electrical effects
- Tests to verify the strength of gas-filled compartments
- Tightness tests of gas- or liquid-filled compartments
- Tests to assess the effects of arcing due to an internal fault (for switchgear and controlgear classification IAC)
- Electromagnetic compatibility tests (EMC)

For Turkish regulations, the defined type tests that are satisfying for verification of the switchgear reliability on the network are listed in the TEDAŞ MYD 95-002 as:

- Dielectric tests (regarding IEC 62271-200 clause 6.2)
- Temperature rise test (regarding IEC 62271-200 clause 6.5)
- Measurement on resistance at the main circuit test (regarding IEC 62271-200 clause 6.4)
- Short-time withstand current and peak withstand current tests (regarding IEC 62271-200 clause 6.6)
- Mechanical tests (regarding IEC 62271-200 clause 6.102)
- Verification of the protection class (regarding IEC 62271-200 clause 6.7)
- Tightness test (regarding IEC 62271-200 clause 6.8)
- Internal arc test (regarding IEC 62271-200 clause 6.106)
- Making and breaking test (regarding IEC 62271-200 clause 6.101)
- Pressure test capacity (regarding IEC 62271-200 clause 6.103)

4.2 Dielectric Tests on Main Circuit and Auxiliary Circuits

The dielectric test is a voltage test that verifies that the equipment insulation can withstand against electrical shocks. The dielectric test failure is inherently the breakdown of the insulation. During the breakdown, an abnormal and sudden current flow increase can be noted by the test simulator. The actual breakdown can be visualized as a strong sound or seen as a light flashover

The Dielectric Test is applied on 12 kV 630A 16 kA SF_6 gas insulated compact type switchgear. The pressure of SF_6 gas during the test was 0,4bar (absolute) at 10,2 Celcius. The connection to the live part of the switching device in the switchgear is done by YE3SV type 1 x 95 mm^2 XLPE insulated cable per phase.

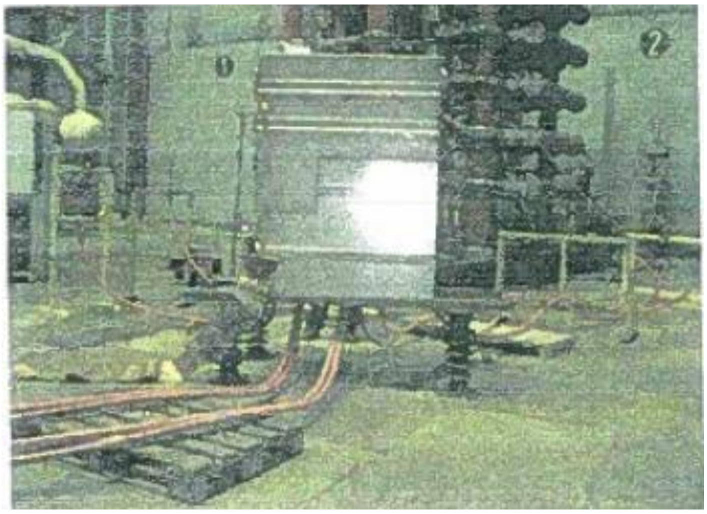


Figure 53: The photo related to test set up of Dielectric Tests on Main Circuit and Auxiliary Circuits

4.2.1 Lightning Impulse Voltage Test

Switchgear and controlgear is subjected to lightning impulse voltage tests in dry conditions only. IEC 60060-1 is applied using the standard lightning impulse 1.2/50 µs. Fifteen consecutive lightning impulses at the rated withstand voltage are applied for each test condition and each polarity. Instrument transformers, power transformers or fuses may be replaced by replicas reproducing the field configuration of the high-voltage connections. Overvoltage protective devices are disconnected or removed. Current transformer secondary are short-circuited and earthed. Current transformers with a low ratio may have their primaries short-circuited too. During the lightning impulse voltage tests, the earthed terminal of the impulse generator is connected to the enclosure of the switchgear, except that during the tests the switchgear is insulated from earth in order that the voltage appearing between any of the live parts and the switchgear will not exceed the test voltage

During this test for each phase, 15 times the defined lightning voltage is applied. No more than 2 breakdowns are accepted to verify the equipment as passed the test.

According to Impulses with the front duration of 1.2 μs are called lightning impulses while impulses with longer front duration are called switching impulses. As it is referred above the impulse type that used in the test is a full lightning impulse with 1.2 μs front duration and 50 μs time to reach the half value. During the test, the maximum amplitude of the impulse obtained from oscillogram is the peak value of the defined test voltage [13].

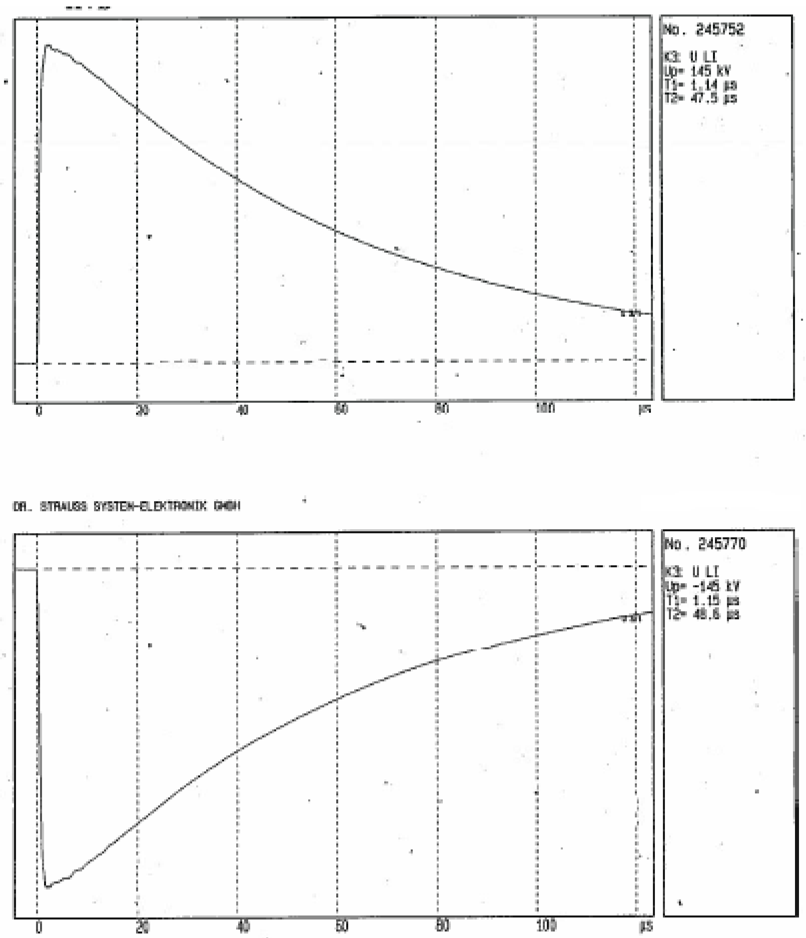


Figure 54: The oscillogram results of lightning voltage withstand test taken from page 6 of the test report 42912

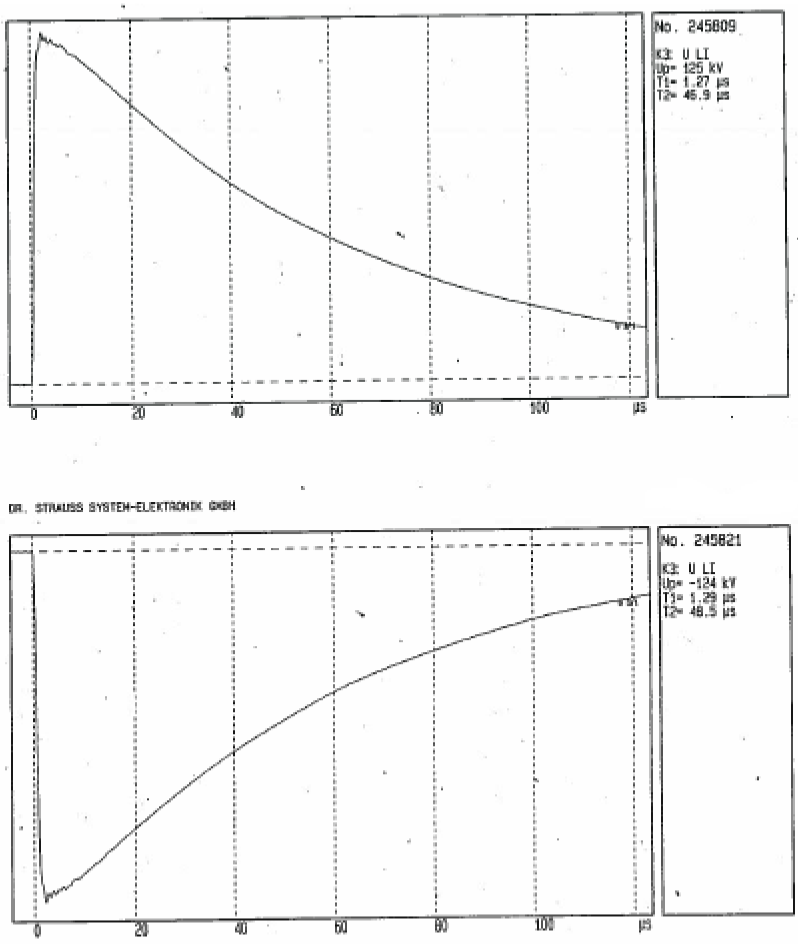


Figure 55: The oscillogram results of lightning voltage withstand test, taken from page 7 of the test report 42912

As seen from the oscillogram plot in Fig.51, The test object can withstand the impulse voltage up to 145 kV. As explained before, even the product is produced with the purpose of 12 kV nominal voltage level, because of the design parameters, all voltage tests are done according to the 24 kV voltage level. As the result, the product passed the test successfully regarding the Table 1a of IEC 60694 which states that if the equipment has 24 kV (rms) rated voltage value, the rated lightning impulse withstand voltage (peak value) has to meet 125 kV as the common value and 145 kV across the isolating distance [31].

4.2.2 Power Frequency Voltage Test

Switchgear and controlgear is subjected to short-duration power-frequency voltage withstand tests in accordance with IEC 60060-1. The tests are performed in dry conditions with the period of period is 1 minutes. Instrument transformers, power transformers or fuses may be replaced by replicas reproducing the field configuration of the high-voltage connections. Overvoltage protective devices may be disconnected or removed. A transformer, a coil, or a similar device normally connected between phases is disconnected from the pole stressed with test voltage. During the power-frequency voltage tests, one terminal of the test transformer is connected to earth and to the enclosure of the metal-enclosed switchgear and control gear. Except that during the tests, the mid-point or another intermediate point of the voltage source should be connected to earth and to the enclosure in order that the voltage appearing between any of the live parts and the enclosure will not exceed the test voltage. If this is not practicable, one terminal of the test transformer may, with the agreement of the manufacturer, be connected to earth and the enclosure is, if necessary insulated from earth [30].

Test method states that neither of the two voltage values applied to the two terminals shall be less than one-third of the rated withstand voltage phase-to-earth [31]. Therefore the rated power frequency voltage across isolating device is 60 kV to earth and between poles it is 50 kV. The test results that is shown below indicates that the test is passed.

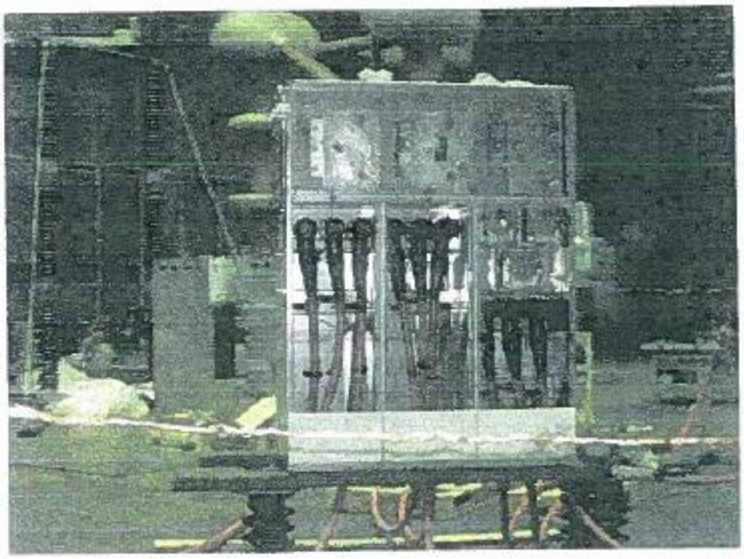


Figure 56: The photo of the test set up for power frequency voltage test

The testing result table of power frequency voltage test, taken from page 10 of the test report 42912 is given as Appendix-B

4.3 Verification on the Degree of Protection

IP classification of the gas insulated switchgear is defined according to the IEC 62271-200, IEC 60529,IEC 60694.

According to the IEC 60694, MV and HV equipment defined as internal does not have any protection from water. This is the reason of the second digit on IP value to be 0. And according to the IEC60529, even the RMU is an internal equipment, it needs to have the protection degree of 3 to ensure that an operator can not reach to the internal pieces of equipment via a work tool while the system is under energy. Also it is ensured that any animal / insect that might cause any disorder on the system cannot enter to the internal area of the RMU. Therefore the required IP classification is IP30. This means;

“3” as; protection against access to hazardous parts and protection against the penetration of solid foreign objects which corresponds to the protection against the particles that has diameter equal or more than 2,5 mm. So an access probe with 100 mm length and 2,5 mm diameter is used as testing apparatus . The switchgear passed the test.

“0” as; no protection on water.

The test results indicate that the RMU is passed the test regarding the international standards.

4.4 Temperature Rise Test and Measuring the Main Circuit Resistance

This test are applied regarding of IEC 61271/200 clause 6.4 and 6.5.

The test procedure is as following:

1) Measurement of the resistance of the main circuit before and after the test.
2) Temperature rise test on cubicle type on incoming and outgoing feeders with load break switch as LBS-S1 and LBS-S2 at I= 630A/ 50 Hz and to the transformer protection feeder with load break switch and fuse combination as LBS-S3 I= 200A/ 50 Hz

The temperature rise test is performed with all components and arrangements are mounted as its original form. The system needs to be constructed in normal service position with all normal enclosures, doors, shutters, partitions and covers are closed. In the system the rated number of phase and rated current needs to be applied. So in the test system, 3 phase incoming unit is used as the entrance. The current of 630A is applied to switchgear for 12 hours. The current enters to the incoming feeder, leaving the system from outgoing unit and transformer protection unit. The temperature sensors are connected to the current passing crucial nodes to be able to record the temperature value instantly. The temperature rise of the different components is referred to the ambient air temperature outside the enclosure and should not exceed the values specified for them in the relevant standards. If the ambient air temperature is not constant, the surface temperature of an identical enclosure under the same ambient conditions may be taken as reference.

When testing individual functional units, the neighboring units should carry the current which produce the power loss corresponding to the rated conditions. It is admissible to simulate equivalent conditions by using heaters or heat insulation, if the test cannot be performed under actual conditions. Where there are other main functional components installed within the enclosure, they shall carry the currents which produce the power loss corresponding to the rated conditions. Equivalent procedures to generate the same power dissipation are acceptable. The temperature rise of the different components shall be referred to the ambient air temperature outside the enclosure and should not exceed the values specified for them in the relevant standards.

The resistance measurement on the main circuit is done by digital ohmmeter OMICRON CPM 500 before and after the application of the temperature rise test.

Table 8: The test result of main circuit resistance before and after the temperature rise test

Resistance	Phase R	Phase S	Phase T	
R_1 [$\mu\Omega$]	187	188	201	Resistance before temperature rise test
R_2 [$\mu\Omega$]	186	186	199	Resistance after temperature rise test
ΔR[%]	-0,5	-1	-1	

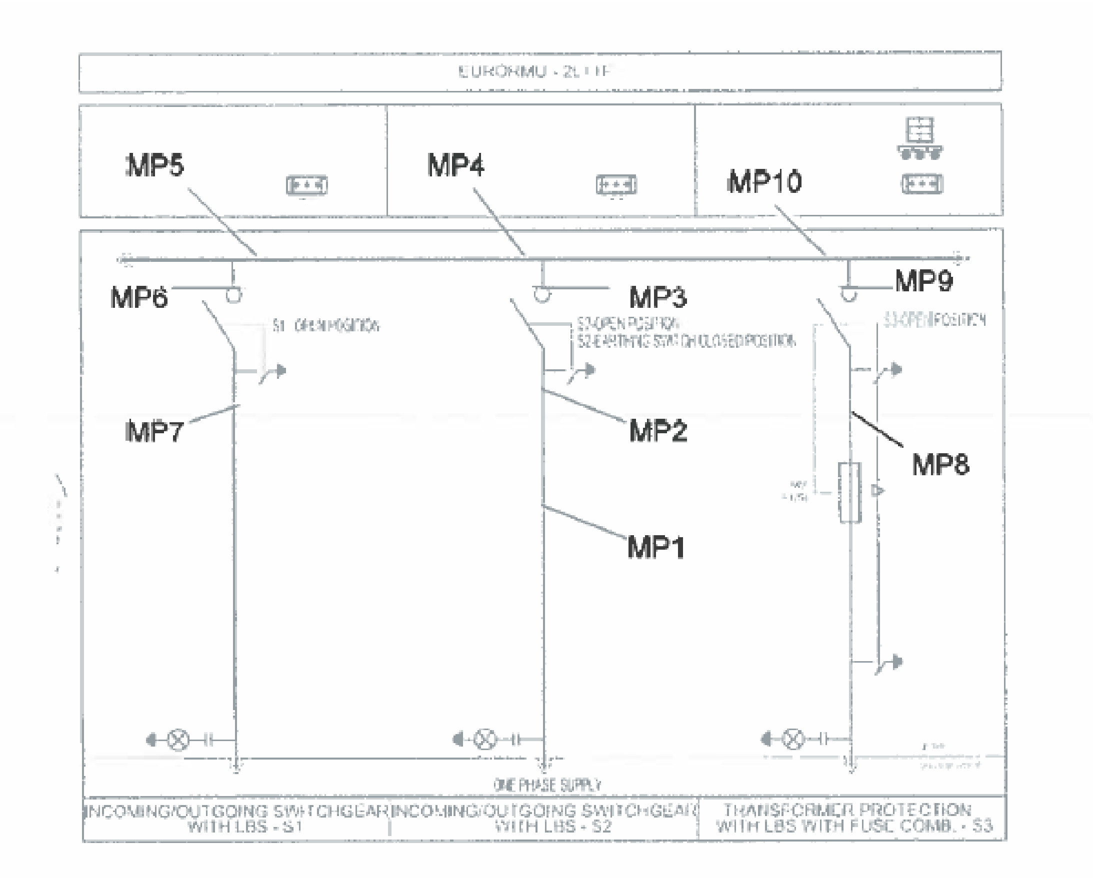


Figure 57: The placement of temperature rise test measuring sensors

Temperature values were measured using the temperature computerized system type multimeter. Measurement points are given in the Figure 55. The environment temperature before the temperature rise test is 12 Celsius while the environment temperature after the temperature rise test became 12,3 Celsius.

No. of MP	Phase	Place of the measurement points MP	Nature of the part	Material	Maxim value of temperature rise at ambient air temperature air not exceeding 40°C [K]	Final tempera-ture for Δt≤1K/h [°C]	Tempe-rature rise [K]	Tempe-rature rise reserve [K]
MP1	R	Incoming	Connection	Cu / Cu	50	60.35	46.60	3.40
	S	Terminals				60.14	47.39	2.61
	T					58.47	45.72	4.28
MP2	R	Input	Contact	Cu Ag /Cu	65	71.38	58.63	6.37
	S	contacts				73.47	60.72	4.28
	T	from LBS S2				73.64	60.89	4.11
MP3	R	Output	Connection	Cu / Cu Ag	75	77.54	64.79	10.21
	S	terminals				75.28	62.53	12.47
	T	from LBS S2				76.44	63.69	11.31
MP4	R	Bus bars	Connection	Cu /Cu	50	60.24	47.49	2.51
	S	From LBS S2				59.64	46.89	3.11
	T					60.27	47.52	2.48
MP5	R	Bus bars	Connection	Cu / Cu	50	59.31	46.56	3.44
	S	fom				60.32	47.57	2.43
	T	LBS-S1				60.47	47.72	2.28
MP6	R	Input	Contact	Cu Ag /Cu	65	72.35	59.60	5.40
	S	contacts				74.54	61.79	3.21
	T	from LBS-S1				73.66	60.91	4.09
MP7	R	Output	Connection	Cu /Cu Ag	75	75.36	62.61	12.39
	S	terminals				77.24	64.49	10.51
	T	from LBS-S1				75.17	62.42	12.58
MP8	R	Input	Connection	Cu Ag /Cu	75	64.34	51.59	23.41
	S	terminals				64.47	51.72	23.28
	T	from LBS-S3				65.12	52.37	23.63
MP9	R	Output	Connection	Cu /Cu Ag	75	45.68	32.93	42.07
	S	terminals				46.32	33.57	41.43
	T	from LBS-S3				45.77	33.02	41.98
MP10	R	Bus bars	Connection	Cu / Cu	50	40.27	27.52	22.48
	S	fom				40.38	27.63	22.37
	T	LBS-S3				41.20	28.45	21.55
MP11	-	Handle	Insulator	-	30	18.37	5.62	24.38
MP12	-	Environmet temperature	Environment	-	-	12.75[1]	-	

Figure 58: The testing result of temperature rise measured from temperature sensors on 10 crucial point of switchgear, taken from page 60 of the test report 11053

The 3 phase temperature rise test was performed by passing current of 630 A/ 50 Hz on the incoming and outgoing feeders with load break switch as LBS-S1 and LBS-S2 until the temperature variation did not exceed 1°C per hour. At the same time with another source the temperature rise test was performed by passing a current of 200

A/ 50 Hz on the transformer protection feeder with load break switch and fuse combination as LBS-S3. Same successful results are obtained. As the result, since all temperature rise recorded by the sensors is lower that allowed temperature rise value, the prototype passed the test.

4.5 Mechanical Operation Test

The Mechanical operation test is applied regarding the IEC 61270-200 clause 6.102 which states that for the switches and the removable parts : Switching devices and withdrawal parts shall be operated 50 times, and removable parts inserted 25 times and removed 25 times to verify satisfactory operation of the equipment [30].

The function of the test verifies especially the mechanical switching elements durability after a certain period of operation time. Also this test verifies the functionality of the interlocks. The interlocks shall be set in the position intended to prevent the operation of the switching devices and the insertion or withdrawal of removable parts. During these tests only normal operating forces shall be employed and no adjustment shall be made to the switching devices, removable parts or interlocks. In case of manually operated equipment, the normal manual operation handle shall be used to perform the tests. The interlock test is accepted as satisfactory if during the interlock is active; the insertion of the removable parts are prevented, the switching device cannot be operated, the effort to operate them is practically the same before and after the tests [30].

The test procedure is handled in 2 stages.

The first stage is for switching devices with the following steps:

- 50 close- open operations on Load Break Switch in Switchgear with LBS-S1
- 50 close- open operations on Load Break Switch in Switchgear with LBS-S2
- 50 close- open operations on Load Break Switch in Switchgear with fuse combination as LBS-S3
- 50 close- open operations on Earthing Switch of LBS-S1
- 50 close- open operations on Earthing Switch of LBS-S2

- 50 close- open operations on Earthing Switch of LBS-S3
- 50 close- open operations on Earthing Switch cable side in EURORMU_LLF

The second stage is for interlocks with the following steps:

- 50 attempts to operate the Load Break Switch in Switchgear with LBS-S1
- 50 attempts to operate the Load Break Switch in Switchgear with LBS-S2
- 50 attempts to operate the Load Break Switch in Switchgear with fuse combination as LBS-S3
- 50 attempts to operate the Earthing Switch of LBS-S1
- 50 attempts to operate the Earthing Switch of LBS-S2
- 50 attempts to operate the Earthing Switch of LBS-S3
- 50 attempts to operate the Earthing Switch cable side in EURORMU_LLF

Interlock tests are applied as follows:

1. The interlock was set in the position intended to prevent the operation of the Load Break Switch in Switchgear with LBS-S1
   The following operations were performed;

- 50 attempts to close the Load Break Switchwith Earthing Switch of Load Break Switch in close position

2. The interlock was set in the position intended to prevent the operation of the Earthing Switch of Load Break Switch in Switchgear with LBS-S1
   The following operations were performed;

- 50 attempts to close the Earthing Switch of Load Break Switch with Load Break Switch in close position

3. The interlock was set in the position intended to prevent the operation of the Load Break Switch in Switchgear with LBS-S2
   The following operations were performed;

- 50 attempts to close the Load Break Switchwith Earthing Switch of Load Break Switch in close position

4. The interlock was set in the position intended to prevent the operation of the Earthing Switch of Load Break Switch in Switchgear with LBS-S2

   The following operations were performed;

- 50 attempts to close the Earthing Switch of Load Break Switch with Load Break Switch in close position

5. The interlock was set in the position intended to prevent the operation of the Load Break Switch in Switchgear with LBS-S3

   The following operations were performed;

- 50 attempts to close the Load Break Switch with Earthing Switch of Load Break Switch in close position
- 50 attempts to close the Load Break Switch with Earthing Switch on cable side in close position

6. The interlock was set in the position intended to prevent the operation of the Earthing Switch of Load Break Switch in Switchgear with LBS-S3

   The following operations were performed;

- 50 attempts to close the Earthing Switch of Load Break Switch with Load Break Switch in close position

7. The interlock was set in the position intended to prevent the operation of the Earthing Switch on the cable side

   The following operations were performed;

- 50 attempts to close the Earthing Switch on cable side with Load Break Switch in close position
- 50 attempts to close the Earthing Switch on cable side with Earthing Switch of Load Break Switch in close position

As the test results of the interlock tests, the load break switch cannot operate at the test procedure of 1, 3and 5. The earthing switch of load break switch cannot be operated at the test procedure of 2, 4 and 6

4.6 Making and Breaking Tests

The Making and Breaking tests are applied regarding the IEC 61270-200 clause 6.101 to verify the switchgear rated making and breaking capacities under the proper conditions of installation and use. As it is not possible to cover all possible configurations and designs of switching devices, the following procedures shall be followed, the precise combination of tests being determined by the characteristics and location of the particular switching device being considered [30].

a) The complete appropriate making and breaking current test sequences are made with the switching device in one of the compartments. lf other compartments are similar in design, and also the switching device intended for use in the compartment is identical, then the tests referred to above are also valid for these compartments [30].

b) Where the compartments are not similar but are designed to accept the same switching device, the following tests/test duties are to be repeated in each of the other compartments, as appropriate to the requirements of the relevant standard:

IEC 62271-100 test duty T100s, T100a, and critical current tests (if any) also taking into account the requirements of 6.103.4 of the standard for the test connection arrangement, where applicable [30].

IEC 62271-102 short-circuit making operations according class E1 or E2, as applicable.

IEC 60265-1: 10 CO-operations with rated mainly active load breaking current (Test duty 1). Test duty 5 according to class E1, E2 or E3, as applicable, unless the switch does not have a rated short-circuit making capacity.

IEC 62271-105:Test duties TDIsc, TDIWmax and TDItransfer.

IEC 60470: Verification of coordination with SCPDs to 6.106 of IEC 60470.

c) Where compartments are designed to accept more than one particular type or design of switching device, each variant of switching device shall be fully tested.

4.6.1 Making and Breaking Test on Load Break Switch

This test mainly covers close loop distribution line circuit current test, mainly active load current test, cable- charging current test, line charging current test, earth fault current test , cable- charging and line- charging under earth fault current test. The test program is made of 6 main steps. These test duties are defined with technical points as below:

1) Test duty1- mainly active load current test;

a) One hundred close- open (CO) operations applied at the parameters of U_r= 24 kV, I_1= 630A, cos φ_l = 0,7, Uc= 41 kV, U_0/t_3= 0,466 kV/ µs

b) Twenty close-open (CO) operations applied at the parameters of U_r= 24 kV, I_1= 31,5 A, cos φ_l = 0,7

2) Test duty2a- Close loop distribution line circuit current test;

   Twenty close-open (CO) operations applied at the parameters of U_r= 4,8 kV, I_{2a}= 630 A, cos φ_l = 0,3

3) Test duty4a- cable charging current test;

a) Ten close- open (CO) operations applied at the parameters of U_r= 24 kV, I_{4a}= 16A

b) Ten close-open (CO) operations applied at the parameters of U_r= 24 kV, I= (0,2-0,4) I_{4a} A=3,2 A

4) Test duty4b- Line charging current test;

   Ten close-open (CO) operations applied at the parameters of U_r= 24 kV, I_{4b} A=1,5 A

5) Test duty6a- earth fault current test;

   Ten close-open (CO) operations applied at the parameters of U_r= 24 kV, I_{6a} A=48 A

6) Test duty6b- cable charging and Line charging under earth fault current test;

Ten close-open (CO) operations applied at the parameters of U_r= 24 kV, I_{6b} A=28 A

Test duty		1 (100 %I_1)	1 (5 %I_1)	2a
Number of phases		3	3	3
Power supply/ Connection		G1/Δ	G1/Y	G1/Y
Transformer/Ratio		TR 4, 5, 6/7.42	TR 4, 5, 6/7.42	TR 4, 5, 6/1.07
Earthing	Power supply	600 Ω	600 Ω	600 Ω
	Apparatus	The metal enclosure was connected to earth through current transformer		
Reactor [Ω]		0.18	0.6	0.4
Power factor		< 0.15		
Load circuit	Reactor L [mH]	83	1660	10
	Resistor R [Ω]	26	534	1.12
	Capacitor C [μF]	-	-	-
	Power factor	0.7	0.7	0.3
T.R.V. adjustment	Capacitor [μF]	-	-	-
	Resistor R [Ω]	-	-	-
M2 - Test current - Shunt		2kA/2V	-	2kA/2V
- Current transformer		-	50A/5A	-
M3 - Leakage current - Current transformer 5 A/5 A				
M4, M5 – Power supply voltage - Voltage transformer 15000 V/100 V				
M6 - Voltage on supply circuit - Voltage divider 120 kV / 60 V				
M8 - Data acquisition system TRAS 1 – 16 bit / 16 channels				

Test duty		4a (I_{4a})	4a (0.2-0.4)I_{4a}	4b	6a	6b
Number of phases		3	3	3	3	3
Power supply/ Connection		T	T	T	T	T
Transformer/Ratio		TR 7, 8, 9/7.42		TR 4, 5, 6/7.42	TR 7, 8, 9/7.42	
Earthing	Power supply	–		-		
	Apparatus	The metal enclosure was connected to earth through current transformer				
Reactor	[Ω]	0.4	0.4	0.4	0.4	0.4
Power	factor	< 0.15				
Load circuit	Reactor L [mH]	-	-	-	-	-
	Resistor R [Ω]	15	150	461	15	15
	Capacitor C [μF]	3.87	0.8	0.29	3.2	3.2
	Power factor	-	-	-	-	-
T.R.V.	Capacitor [μF]	-	-	-	-	-
adjustment	Resistor R [Ω]	-	-	-	-	-
M2 - Test current - Shunt		-	-	-	-	-
- Current tranformer		50 A/5 A		50 A/5 A	50A/5A	
M3 - Leakage current - Current transformer 5 A/5 A						
M5 - Power supply voltage - Voltage transformer 15000 V/100 V						
M6 - Voltage on supply circuit - Voltage divider 120 kV / 60 V						
M7 - Voltage across poles – Capacitive divider 50 kV/7 V						
M8 - Data aquisition system TRAS 1 – 16 bit / 16 channels						

Figure 59: Test duty cycles technical specs

The transient recovery voltage properties is given as belo with its oscilloscope view.

Characteristics	Symbol		Values Test duty 1
T.R.V. peak value	U_C	kV	41
Time corresponding to U_C	t3	μs	88
Rate of rise	U_C/t3	kV/μs	0.466
Frequency	f	Hz	-
Amplitude factor	-	-	1.4
Power frequency recovery voltage	Ur	kV	13.86
First pole to clear factor	-	-	1.5

Figure 60: The properties of the transient recover voltage

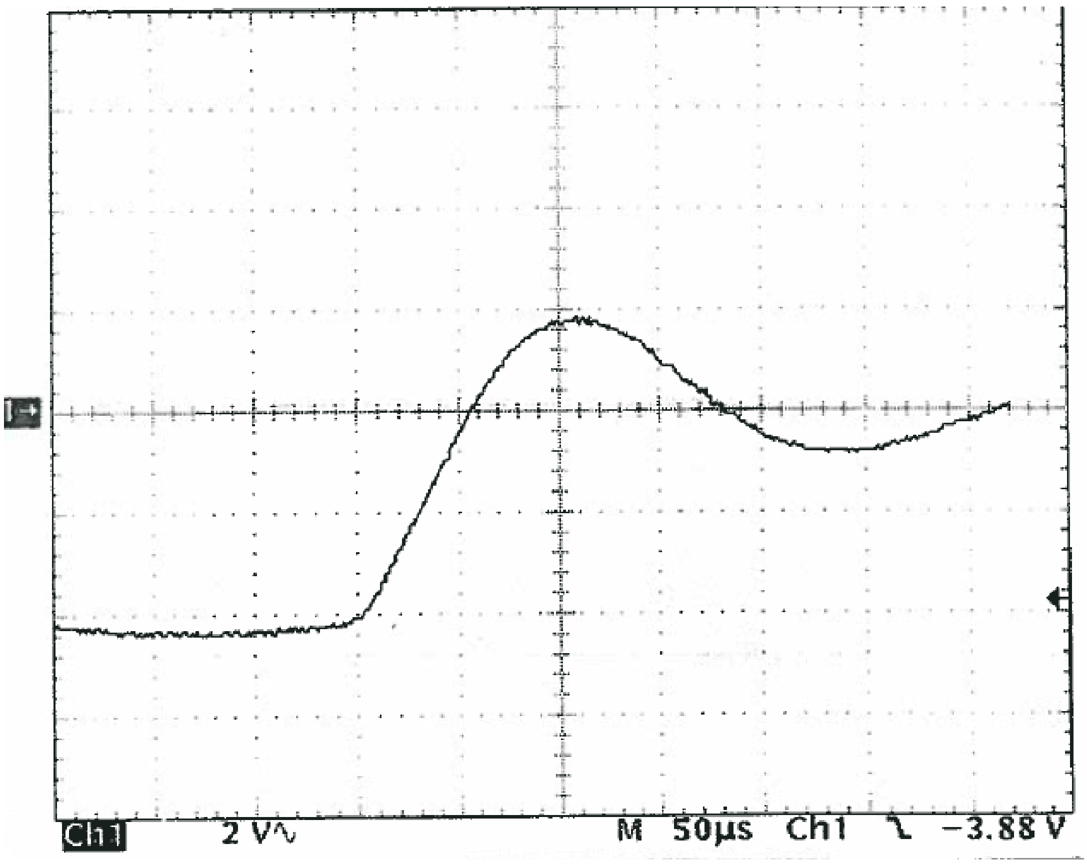


Figure 61: The TRV (the transient recovery voltage) oscilloscope view

The data obtained from the test is provided as Appendix- A. The test results are controlled and it is observed that with the making and breaking test at different conditions, does not lead any serious contact default or any arc problem after different applications. Also according to the Cassie arc model applied at Section 3.5 theoretical results of test parameters and the simulation results met with the test parameter defined in IEC 62271. This situation proves the arc model consistency.

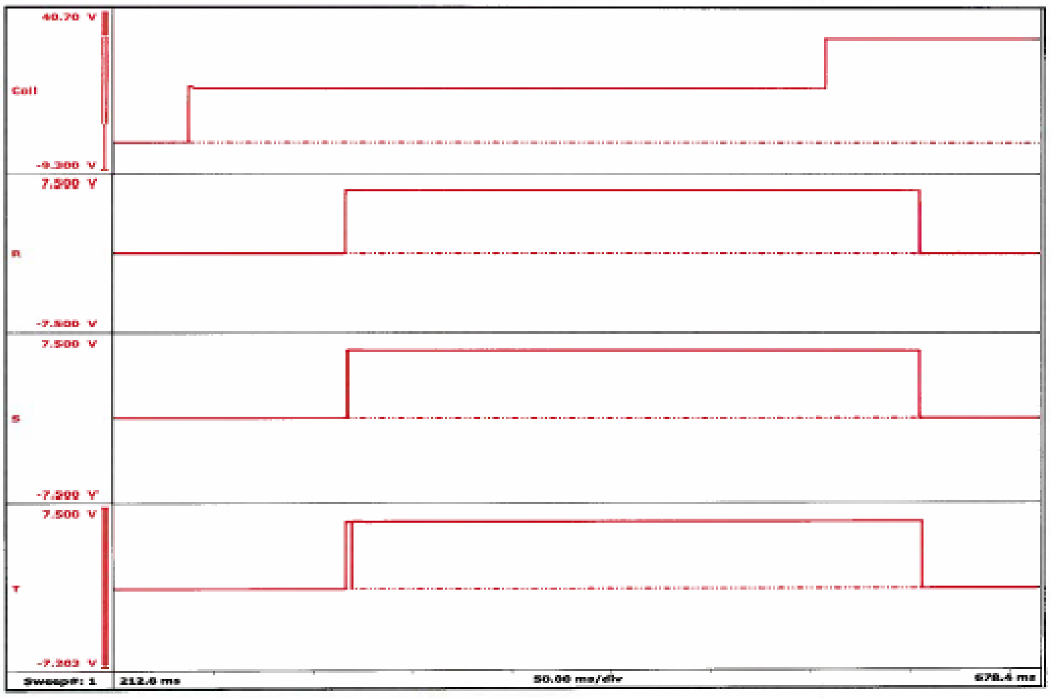


Figure 62: The oscilloscope view at the initial condition

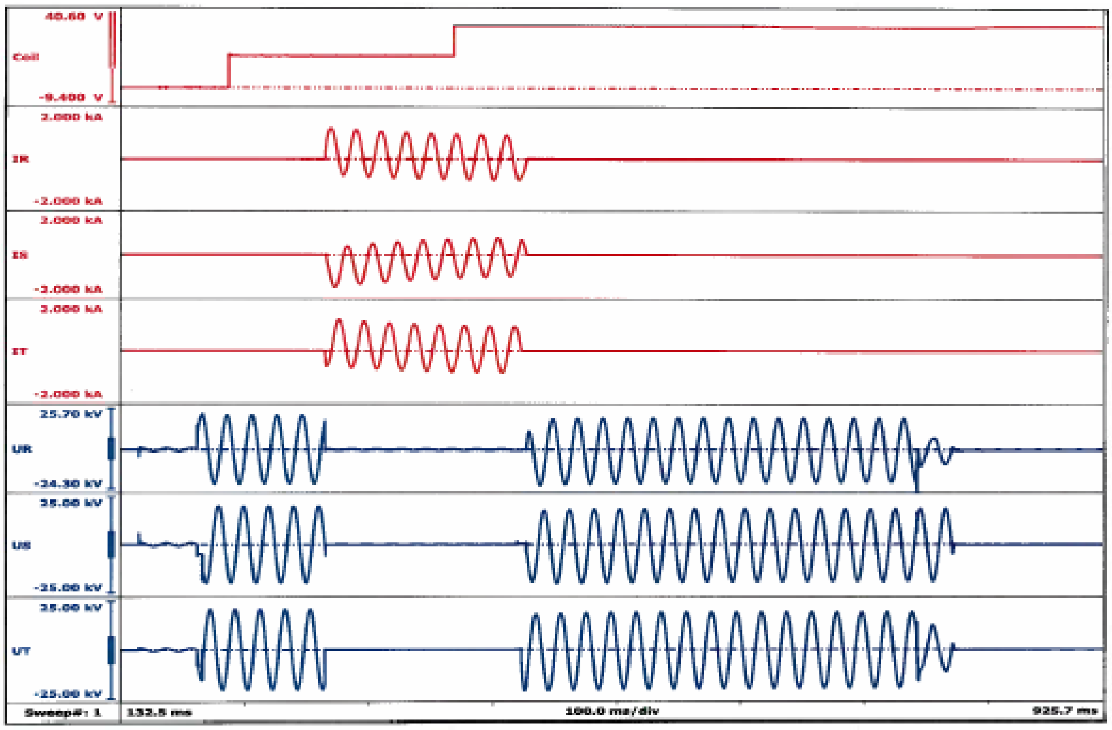


Figure 63: The oscilloscope view after first 10 open and close action

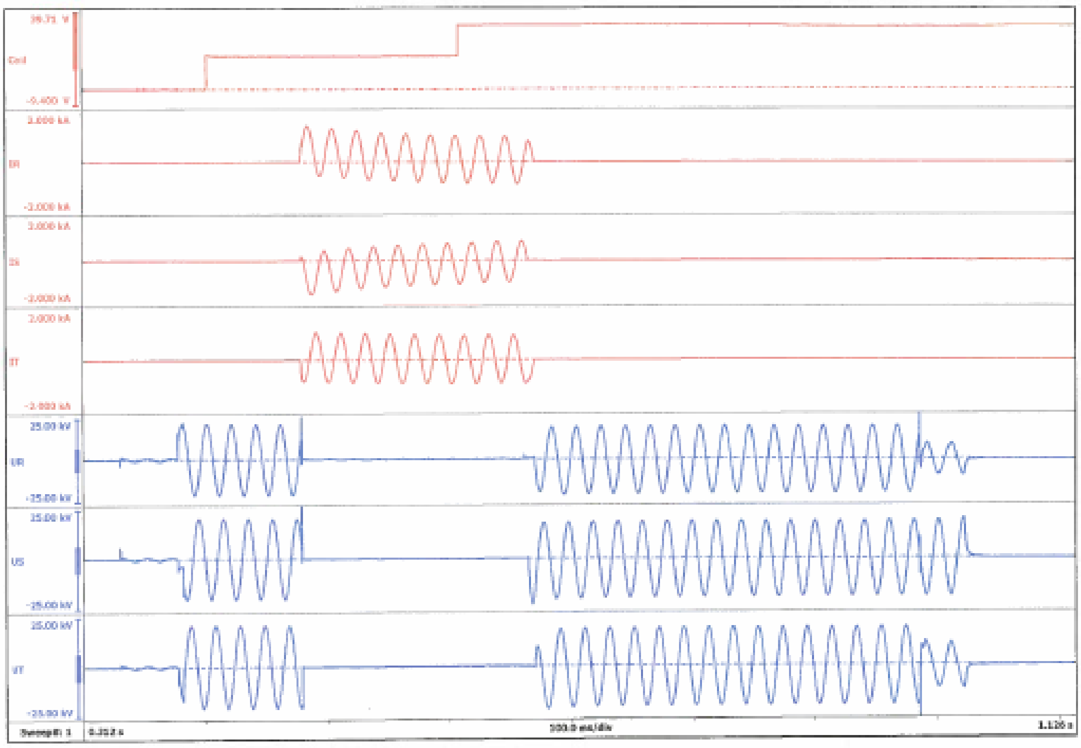


Figure 64: The oscilloscope view after last 10 open and close action

4.6.2 Making and Breaking Test in Test Duties TDISC, TDIWmax, TDItransfer

The test procedure can be summariesed as below

1) Test Duty TD_{ISC}

   One calibration test

   One open (O) operation at the following parameters: U= 24 kV, I_{sc}= 16 kA, cos φ_1 < 0,15, U_c= 41 kV, t_3 = 88 μs

   One close-open (CO) operation at the following parameters: U= 24 kV, I_{sc}= 16 kA, cos φ_1 < 0,15, U_c= 41 kV, t_3 = 88 μs

2) Test Duty TD_{IWmax}

   One calibration test

   One open (O) operation at the following parameters: U= 24 kV, Iwmax= 3,22 kA, cos φ_1 < 0,15, Uc= 44 kV, t3 = 264-352 μs

   One close-open (CO) operation at the following parameters: U= 24 kV, Iwmax= 3,22 kA, cos φ_1 < 0,15, Uc= 44 kV, t3 = 264-352 μs

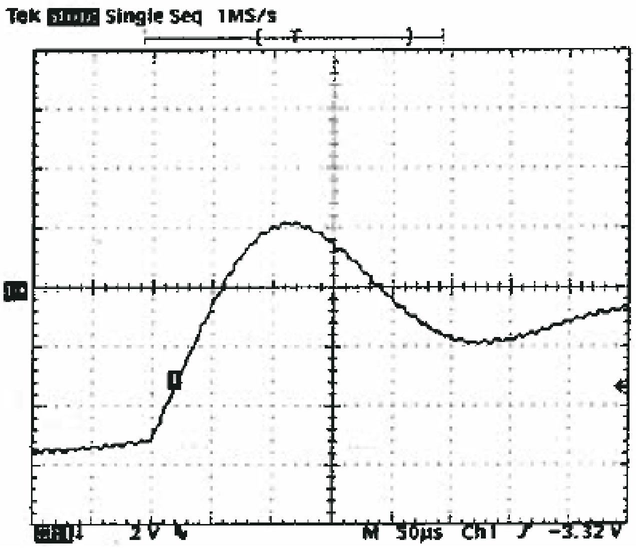
3) Test Duty $TD_{Itransfer}$,

   One calibration test

   Three open (O) operations at parameters U= 24 kV, $I_{transfer}$= 630 A, cos φ_1 = 0,3, U_c= 41 kV, t_3 = 176 μs. During the tests the fuse link was placed on a phase and the other phases were short-circuited with rigid connections. For each test the fuse was places on other phase. One power frequency withstand voltage test in dry conditions at 48 kV.

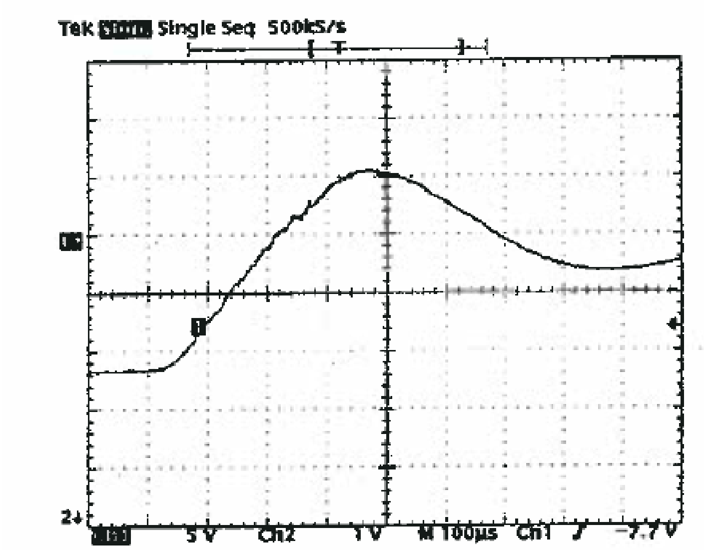
Characteristics	Symbol		Values		
			Test duty		
			TD_{Isc}	$TD_{IW\ max}$	$TD_{I\ transfer}$
T.R.V. peak value	U_C	kV	41	44.7	42.9
Time corresponding to U_C	t_3	μs	89	282	190
Rate of rise	U_C/t_3	kV/μs	0.46	0.159	0.224
Frequency	f	Hz	-	-	-
Amplitude factor	k_{af}	-	1.4	1.52	1.45
Power frequency recovery voltage	Ur	kV	13.86	13.86	13.86
First pole to clear factor	k_{pp}	-	1.5	1.5	1.5

Figure 65: Prospective tansient recovery voltage (TRV) in Test Duties TDISC, TDIWmax, TDItransfer



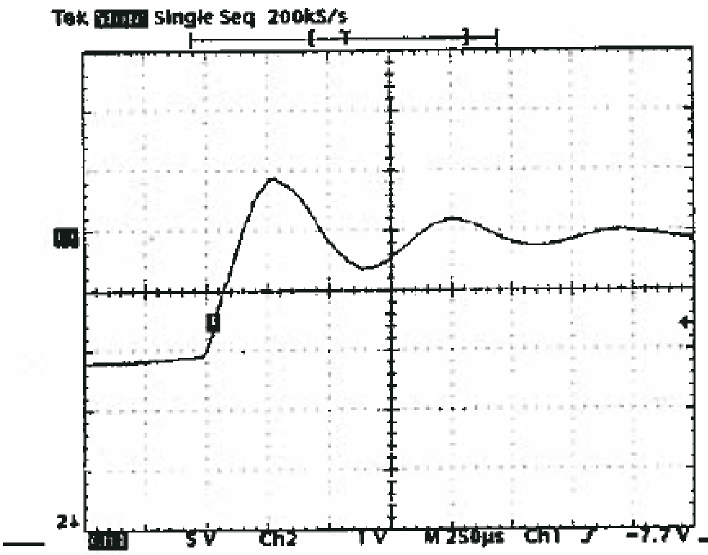
Test duty TD_{Isc}

Figure 66: Oscillogram on TRV in Test Duty TD_{ISC}



Test duty TD_{IWmax}

Figure 67: Oscillogram on TRV in Test Duty TD_{IWmax}



Test duty $TD_{Itransfer}$

Figure 68: Oscillogram on TRV in Test Duty $TD_{Itransfer}$

1. After tests SF6 Insulated Compact Extensible type RMU has been submitted to dielectric tests according to IEC 62271-1/2007 clause 6.2.6.1 by applying a voltage of 48 kV/50 Hz during 1 minute between the contacts and between phases and ground. During the dielectric tests there were observed no breakdown or flashover.

As the test result, RMU has been submitted to dielectric tests by applying 48 kV/ 50 Hz during 1 minute between the contacts and between phases and ground. During the dielectric tests, there were no breakdown or flashover observed.

Apparatus condition before the test: New															
Test No.	Oscillogram No.	Operation and time interval	U_{RS} U_{ST} U_{TR} [kV]	U_{0R} U_{0S} U_{0T} [kV]	I_R I_S I_T [A]	T [s]	φ/ρ °el	I_{DR} I_{DS} I_{DT} [kA]	U_R U_S U_T [kV]	t_{oR} t_{oS} t_{oT} [ms]	t_{eR} t_{eS} t_{eT} [ms]	t_{aR} t_{aS} t_{aT} [ms]	t_{fR} t_{fS} t_{fT} [ms]	t_{iR} t_{iS} t_{iT} [ms]	Remarks
0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.
Test duty TD_{Isc}															
	80102/2011	-	7.5 7.5 7.5	- - -	5000 5000 5000	- - -	- - 65/-	- - -	- - -	- - -	- - -	- - -	- - -	- - -	Calibration test
1	80103/2011	O-3min	- - -	- - -	16100 16200 16300	- - -	- 60/78 -	5 8.05 3.5	14 14 14	48 48 48	- - -	1 1 1.5	8 6 5	49 49 49.5	All fuses worked and switch disconnector opened
2	80104/2011	CO	24.2 24.2 24.2	14 14 14	16100 16200 16300	- - -	- - -	3.3 8.3 4.5	14 14 14	48 48 48	76 76 76	1 1.5 1	10 6 9	49 49.5 49	All fuses worked and switch disconnector opened
Test duty TD_{IWmax}															
	80105/2011	-	24.5 24.5 24.5	- - -	3200 3200 3200	- - -	- - 5/-	- - -	- - -	- - -	- - -	- - -	- - -	- - -	Calibration test
3	80106/2011	O-3min	- - -	- - -	3220 3220 3220	- - -	18/72 - -	3.3 2.1 3.1	14.2 14.2 14.2	48 48 48	- - -	5.5 3.5 3.0	9.3 6.5 9.3	53.5 51.5 51.0	All fuses worked and switch disconnector opened
4	80107/2011	CO	24.6 24.6 24.6	14.2 14.2 14.2	3220 3220 3220	- - -	- - -	3.2 1.5 3.0	14.2 14.2 14.2	48 48 48	76 76 76	3 3 3	10 - 10	51 51 51	Fuses on R and T worked and switch disconnector opened
	80125/2011	-	24.3 24.3 24.3	- - -	640 635 637	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	Calibration test
5	80126/2011	O-3min	24.3 24.3 24.3	- - -	640 557 557	- - -	- - -	- - -	14.02 14.02 24.30	30 30 30	- - -	8.4 8.4 -	- - 71	100 100 -	Fuse on T phase
6	80127/2011	O-3min	24.3 24.3 24.3	- - -	552 635 552	- - -	- - -	- - -	24.30 14.02 14.02	30 30 30	- - -	- 9.6 9.6	65 - -	- 94 94	Fuse on R phase
7	80128/2011	O	24.3 24.3 24.3	- - -	554 554 637	- - -	- - -	- - -	14.02 24.30 14.02	30 30 30	- - -	2 - 2	- 37 -	66 - 66	Fuse on S phase

Figure 69: The table of the test results for making and breaking test in test duties TD_{ISC}, TD_{IWmax}, $TD_{Itransfer}$, , taken from page 7-8 of the test report 11051

4.7 Internal Arc Test

The switchgear internal arc classification is defined at the design criteria Section as IAC. This internal arc class offers a tested level of protection to persons in the vicinity of the equipment in normal operating conditions and with the switchgear and controlgear in normal service position, in the event of internal arc.

The test is applied according to IEC 61271-200 Annex A. The test is performed at the normal operation conditions of the switchgear. The removing or replacing of the active components like fuses or removable parts are not considered to be normal operations, neither those required to carry out maintenance works.The normal operation activities means the conditions of metal enclosed switchgear and controlgear required to carry out operations such as opening or closing HV switching devices, connecting and disconnecting withdrawal parts, reading of measuring instruments and monitoring equipment, etc. If the test defined needs to be carried out as any cover removed and/or any door has to be opened, the test is carried out with the cover and/or door removed.

Internal faults inside metal-enclosed switchgear and controlgear can occur in a number of locations and can cause various physical phenomena. For example, the arc energy resulting from an arc developed in any insulating fluid within the enclosure will cause an internal overpressure and local overheating which will result in mechanical and thermal stressing of the equipment. Moreover, the materials involved may produce hot decomposition products, either gaseous or vaporous, which may be discharged to the outside of the enclosure. The internal arc is intended to verify the effectiveness of the design in protecting people in case of an internal arc. It does not cover all the effects which may constitute a hazard, such as the presence of gases with potential toxic characteristics that can be present after the fault. The Internal Arc Classification IAC makes allowance for internal overpressure acting on covers, doors, inspection windows, ventilation openings, etc. It also takes into consideration the thermal effects of the arc or its roots on the enclosure and of ejected hot gases and glowing particles, but not damage to internal partition and shutters not being accessible in normal operating conditions [30].

The test is handled in a few steps. Firstly 3 phase current calibration test is done. The internal arc test is applied by 3 phase arc initiation point on the lower terminals of load break switch inside of tank of incoming/ outgoing switchgear with LBS-S1 and 3 phase applied voltage on the input terminal of incoming/ outgoing switchgear with LBS-S2. The arc initiation is done by the customer. The supply is made with copper cables of 3 x 240 mm^2. The test parameters were I_p=55kA, Ik=22kA, tk=1 s and f=50Hz.

As the second stage, 2 phase current calibration test is applied. The internal arc test is applied by 2 phase arc initiation point in the cable compartment on input terminals of incoming/ outgoing switchgear with LBS-S1 and 3 phase applied voltage on the input terminal of incoming/ outgoing switchgear with LBS-S1. The arc initiation is done with copper wire,0,5 mm diameter. The supply is made with copper cables of 3 x 240 mm^2. The test parameters were I_p=47,85kA, Ik=19,14kA, tk=1 s and f=50Hz.

As the second stage, 2 phase current calibration test is applied.

The compact RMU is placed in a special room/ chamber with floor, two perpendicular walls and ceiling settled on a cable channel with dimensions of 950 mm x 980 mm x 600 mm. The dimensions between RMU, walls and ceiling were 100 mm from the laterial right wall, 1200 mm from the ceiling, 100 mm from the rear wall. The combined vertical and horizontal simulator made og 140 g/m^2 cotton fabrics were placed in the front and the left side of the switchgear assembly at 300 mm distance corresponding to accessibility class A.

The internal arc test is the most important test in terms of the safety of the operator to be maintained at the operation period. Most of the injuries and accident in switchgear operations are happened because of internal arc. The test is applied at the arc chamber with the arc simulator that creates the internal arc for the switchgear

The result of test is prepared as a summary table as following:

Table 9: Results of the internal arc test

Criterion	**Remark**
The doors, covers etc… correctly secured do not open	Satisfactory
All earthing connections are still effective	Satisfactory
Arcing does not cause holes yto develop in the freely accessible external parts of the enclosure as a result of burning or other effects	Satisfactory
No fragment of the enclosure occurs within the time specified for the test. Projections of small parts, up to an individual mass of 600 kg are accepted	Satisfactory
The indicators arranged vertically and horizontally do not ignite	Satisfactory

As the test result, during the test doors did not open, the indicators arranged vertically and horizontally did not ignite, no detached parts of the SF_6 insulated compact RMU were observed, the midriffs for the pressure relief worked correctly at the test inside of the tank. The result table of the test completely consistent with the parameters defined at IEC 61271-200 Annex A which is totally dedicated to internal arc test.

4.8 Short Time Withstand Current and Peak Withstand Current Test on Main Circuit and Earthing Circuit

Short time and peak current withstand test are performed according to the IEC 61271-200 clause 6.6 which is consistent with IEC 60694.

The test is applied on main circuit and earthing circuits both according to the standard. For the test on the main circuit, the test applied to verify the capability of the main circuit to withstand the rated short time and peak withstand current under the normal conditions of installation and use. The test needs to be performed such that all associated components influencing the performance or modifying the short circuit current. The short circuit tests carry out according to the rated number of phases.

Equipment which does not include any current-limiting device may be tested at any convenient voltage. Equipment which incorporates with a current-limiting device shall be tested at the rated voltage of the switchgear and controlgear. Other test voltages can be used, if it can be demonstrated that both the applied peak current and resulting thermal effects are equal to, or higher than, those with rated voltage. For equipment including current-limiting devices the prospective current (peak, r.m.s value and duration) shall not be less than the rated value. Self-tripping circuit-breakers, if any, shall be set on their maximum tripping values. Current-limiting fuses, if any, shall be provided with fuse-links having the maximum rated current specified. After the test, no deformation or damage to components or conductors within the enclosure, which may impair good operation of the main circuits, shall have been sustained [30].

For the test on the earthing circuit, the test applied to verify the capability of the earthing conductors, earthing connections and earthing devices to withstand the rated short time and peak withstand current under the neutral earthing condition of the system. The test needs to be performed such that all associated components influencing the performance or modifying the short circuit current. The short-circuit current tests with earthing devices shall be carried out according to the rated number of phases. Further single-phase tests may be necessary in order to verify the performance of all the circuits that are intended to provide the connection between the earthing device and earthing point provided. Whether there are any removable earthing devices, the earthing connection between the fixed part and the removable part shall be tested under earth-fault conditions. The earth-fault current may flow among the earthing conductor of the fixed part and the earthing point of the removable part. After the test some deformation and degradation of the earthing conductor, earthing connections or earthing devices is permissible, but the continuity of the circuit shall be preserved. Visual inspection is sufficient to check the continuity of the circuit.

The test procedure is as following:

1) Measurement of the main circuit resistance.
2) 3 phase short time withstand current and peak withstand current test on the main circuit at parameters: Ip= 50 kA, Ik= 20 kA, tk= 1 s. The supply was connected with 3x1x240 mm2 copper XLPE cable.
3) Measurement of the main circuit resistance.
4) 1 phase tests on Earthing Connections of LBS-S2 at parameters: Ip= 50 kA, Ik= 20 kA, tk= 1 s. The supply was made with 2x1x240 mm2 copper XLPE cable between the ends of the earthing connection.

The base of the testing process is to arrange the test object in a way that the most onerous condition. The test connections to the terminals of the switchgear and controlgear shall be arranged such a way as to avoid unrealistic stressing to the terminals. The switching devices shall be in the closed position and fitted with clean contacts in a new condition. Each test shall be preceded by a no-load operation of the mechanical switching device and, with the exception of earthing switches, by measurement of the resistance of the main circuit [30].

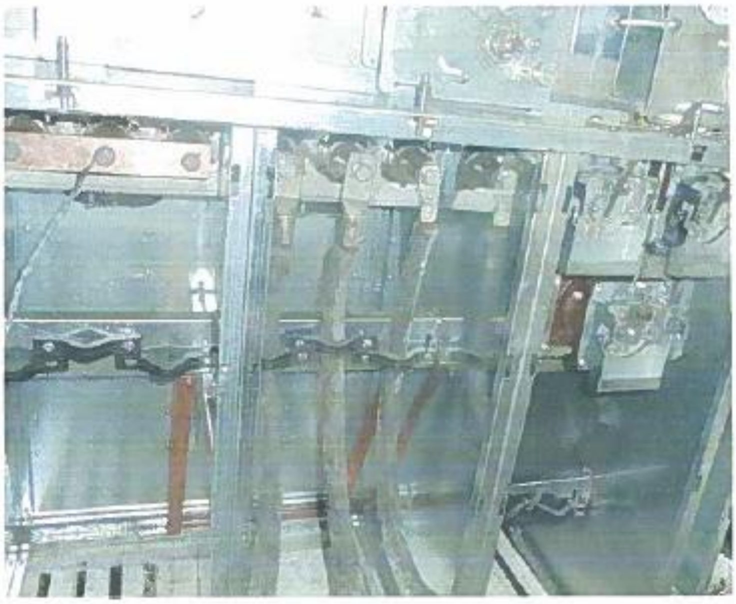


Figure 70: The test set up photo for short time withstand current and peak withstand current test

The tests are performed and the RMU passed the test. After tests load break switch and earthing switch opened at first attempt and no visible damages were observed. The resistance measured on main circuit after tests did not exceed %4,21 of the resistance measured before tests. After tests no deformation or interruption of current paths were observed.

The test result can be summarised as following table;

Table 10: Results for the short time withstand current and peak withstand current test

Requirements	**Remark**
A no load operation of the mechanical switching devices shall be performed immediately after the test, and the contacts shall open at the first attempt.	Satisfactory
The resistance shall be measured after test and shall not increase by more than %20 the resistance measured before the	Satisfactory

test	
After test on earthing circuit some deformation and degradation of the earthing connection or earthing devices is permissible, but the continuity of the circuit shall be preserved.	Satisfactory
After the test, no deformation or damage of the components and conductor within enclosure, which may impair good operation of the main circuits, shall have been sustained.	Satisfactory

The test results obtained from the 3 phase test are tabulated as following:

Oscillogram No.	I_{pR} I_{pS} I_{pT} [kA]	I_{tR} I_{tS} I_{tT} [kA]	t_t [sec.]	$I_{t.med}$ [kA]	$I_{t.med.equiv.tk}$ [kA]	DU_R DU_S DU_T [V]	Remarks
80132/2011	50.8 - -	20.5 20.8 21.0	1.0	20.76	20.76	18 18 16	Test on main circuit

Figure 71: The table related to test results acquired from the short time withstand current and peak withstand current test on 3 phase

The oscillogram plot related to the test result is given as below;

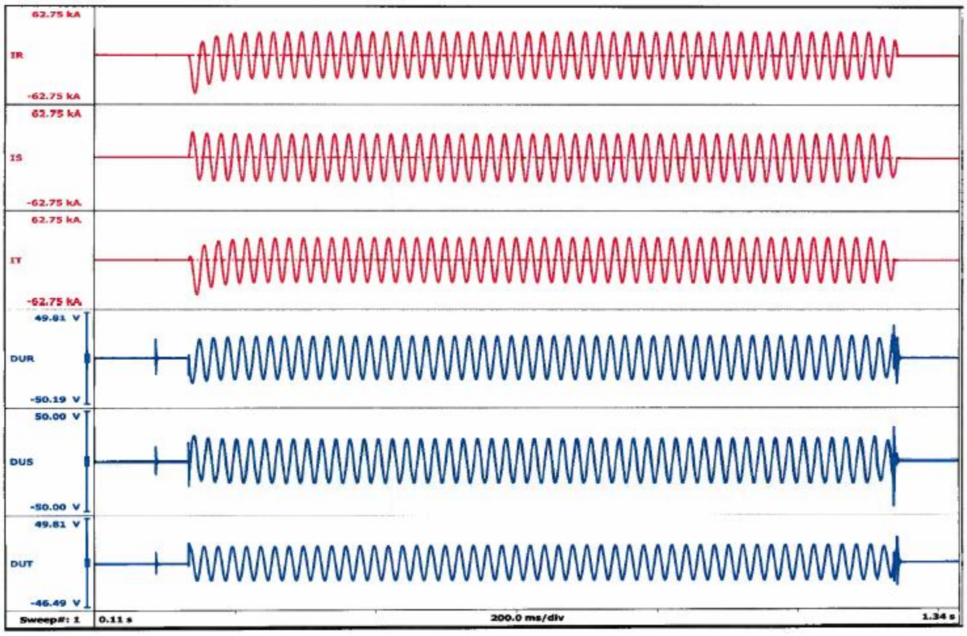


Figure 72: The oscillogram plot for short time withstand current and peak withstand current test on 3 phase

The result is consistent with the calculated equivalent value of the short time withstand current:

$$I_{t\ med\ equiv.\ tk} = I_{t\ med} \times \sqrt{\frac{t}{tk}} \qquad [4.1]$$

Where I_{tmed} is the effective current mean value, $I_{tmed\ equiv\ tk}$ is the equivalent value of short time withstand current on t_k= 1s, t is the duration of the short circuit.

The test results obtained from the 1 phase test are tabulated as following:

Oscillogram No.	I_p [kA]	I_t [kA]	t_t [sec.]	$I_{t\ equiv.\ t_k}$ [kA]	Remarks
79908/2011	50.1	21.5	0.96	21.06	Test on Earthing Connection from incoming / outgoing switchgear with LBS-S2

Figure 73: The table related to test results acquired from the short time withstand current and peak withstand current test on 1 phase

The oscillogram plot related to the test result is given as below;

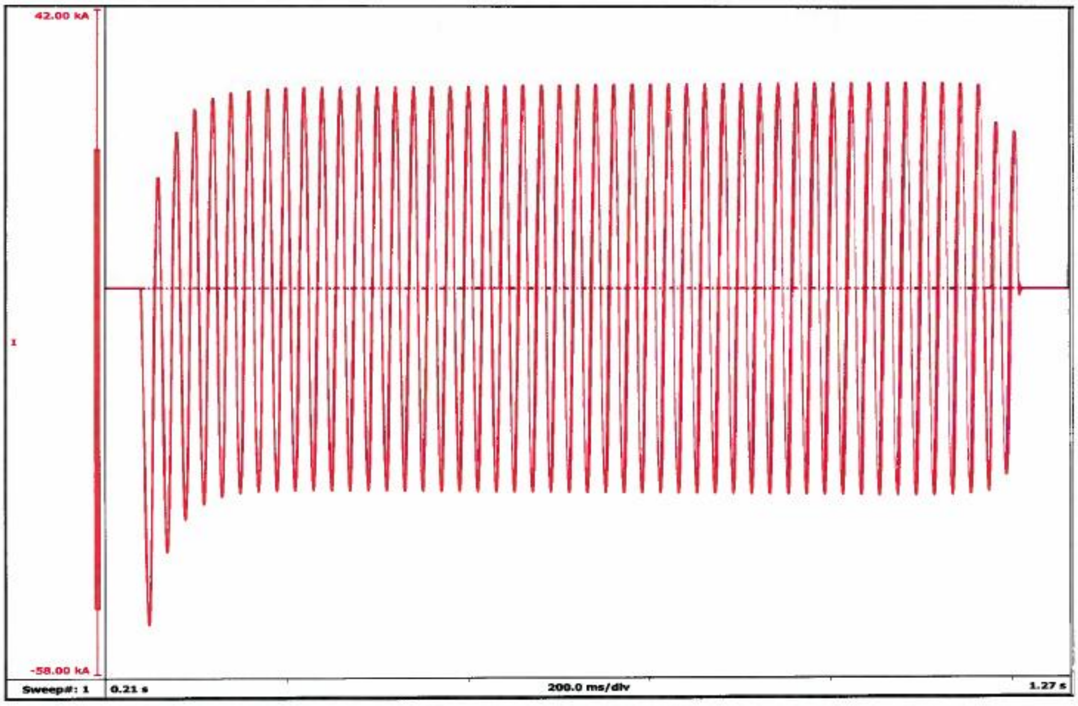


Figure 74: The oscillogram plot for short time withstand current and peak withstand current test on 3 phase

The result is consistent with the calculated equivalent value of the short time withstand current:

$$I_{k\ equiv.\ tk} = I_t \times \sqrt{\frac{t}{t_k}} \qquad [4.2]$$

Where I_{tmed} is the effective current mean value, $I_{k\ equiv.\ tk}$ is the equivalent value of short time withstand current on tk= 1s, t is the duration of the short circuit .

CHAPTER 5

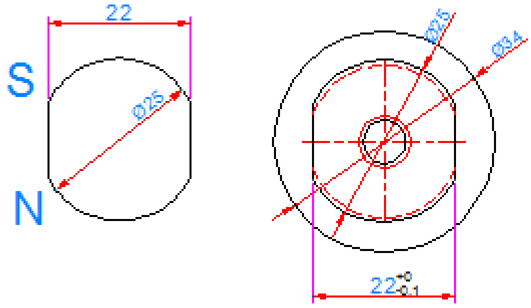
CONCLUSIONS AND FUTURE WORK

Design, implementation and prototype testing of 12 kV gas insulated load break switch and its enclosure has been successfully completed with the engineering contribution of this thesis work. This load break switch is based on the needs of industry and related international technical standards. Prior design phase of literature survey, market research have been carried out considering not only domestic market but also international target markets.

In the design phase, the arcing nature of medium voltage has been thoroughly analyzed and several methods for mechanical opening and closing operations are investigated. Regarding the literature and market survey, as the engineering contribution, the target is defined as designing a load breaker with safer and more reliable arc extinguishing methodology with its supplementary design segments that leads less arc extinguishing duration with less required separation between contacts during arc diminishing which means smaller rotation angle for our case. Firstly arc modeling and arc extinguishing type is investigated. Many arc models are studied starting with the Mayr and Cassie models. According to the system parameters, due to the high rated current, Cassie model is adopted for modeling. Arc simulations are obtained from the Maxwell and Matlab programs. The derivation of the Cassie arc formula is studied and the derived formula is applied to our system to get arc conductance/ resistance calculated at the arc starting and arc extinguishing instants. Arc model parameters are computed from Matlab and simulated with Maxwell program. After determination of the arc model parameters, it is seen that the defined parameters met with the test parameters used in making/ breaking tests. Also, the simulations related to the arc modeling shows the voltage and current behavior after the breaking action. The mathematical calculations compared with the simulation results and the system behavior is verified.

In order to extinguish the electrical arc, many methodologies are investigated. It is seen that from the literature, the common arc extinguishing method is based on rotational puffering or any other methodology used with the support of rotational puffering. As the contribution of this thesis on the load breaker design parameter is that, the arc extinguishing mechanism is totally based on magnetic force effect without any impact of puffering. Rotational puffering is simply blowing the SF_6 gas as the insulation material with high dielectric property to the source point of the arc to suppress the arc formation. This method is not a safe method for arc extinguishing since SF_6 gas dielectric property will reduce due to the contaminations and ionization due to the effect of arc or other causes in time. Therefore, depending on insulation material suppression effect on arc which will lose its dielectric strength and also might face with change on its pressure is not an acceptable arc extinguishing method according to the design limits of our load breaker. Also, puffering arc extinguishing method requires longer duration for arc extinguishing with longer contact separation for ultimate arc extinguishing. Therefore as a conclusion, the adopted arc extinguishing method investigated with this study is based on magnetic force effect created by the magnet embedded into the busbar contact. By neglecting the effect of rotational puffering of SF_6 on arc, the Cassie model selection is also justified which perceives the cooling effect of SF_6 gas medium as negligible for the arc extinguishing method.

The magnet character is determined regarding of the B and H calculations which lead to the best selection as the magnet to be neodymium from the group of rare earth magnets because of its magnetic characteristics. By this way, selection of the magnet is verified with the calculations based on system parameters. This arc extinguishing method is a novel technic which diverts the electrical arc and extends the arcing distance by the Hall effect on the arc plasma and electrons. The Hall effect is studied and the drift velocity of the arc plasma and electrons due to the magnetic force applied by the magnet is calculated. Such an increasing distance results in higher impedance and inherently forces on the arc to extinguish it. The SF_6 gas and the mechanism had to be put in a special vessel, therefore this vessel and its surrounding auxiliary subsystems have been also designed. The technical drawings for prototype production are prepared.



The design of the mechanism is based on rotating around the central axis, which is one of the 3 methods that could have been implemented. Rotational central axis method is the safer method which also requires minimum energy to be applied for open or close operation that leads to the design contribution called less linear distance between the contacts, so smaller rotational angel for arc extinguishing. This mechanism is to break 630A current at 12 kV voltage range. These technical requirements are also selected for standard current and voltages that are commonly used in the electrical market. According to the market survey, the contacts in other market products are made from tungsten material. However, tungsten is an expensive material compared to other conductive material. Since the arcing stress is reduced on the contacts by using magnetic force effect, it enabled the usage of cheaper material such as silver plated copper. The contact structure is investigated. Also the mechanical parameters related to the load tripping are calculated. Spring parameters and the spring usage on the system are studied. The k constant of the springs which are important for spring selection are calculated.

The vessel implemented according to the initial design is tested with the required relative pressure (between 30-50 kPa) and it has been seen that it has failed to withstand the requirements. Therefore, the design of the vessel is revised with the external reinforcements. The internal reinforcements are avoided because welding process introduces irregularities and contaminations which defects the homogeneity of the internal electrical field distribution. Regarding the minimum distance between live end grounded parts within SF_6 gas medium is verified to pass the necessary voltage tests of 24 kV system by necessary calculations. Maxwell simulation results are used to compare the insulation effect of air and SF_6 gas.

Even this thesis witness to a whole design process of 12 kV rated compact type gas insulated load breaker application; the main engineering contributions of this thesis are listed as below with the objective of arc extinguishing at less duration with less rotational angle as safer and more reliable arc diminishing method. These topics are simulated, calculated and verified in detail throughout the Chapter 3.

- Arc modelling and arc extinguishing methodology
- Parameters related to SF_6 gas as the insulation medium
- Contact structure and magnet selection parameters
- Mechanical design parameter as spring selection parameter

The verification of electrical switchgear has to be certified by internationally accredited laboratories in order to be sold in the market. The prototype load break switch that has been produced according to the design is first tested in Europower Energy factory in Kazan, Ankara. After it is seen that the prototype is ready for the type test, it has been taken to Icmet Laboratory in Romania. The IEC 62271-1, IEC 62271-101, IEC 62271-103, IEC 62271-200 which are also based on IEC 60060-1 clearly states the required type tests for such a product. The following tests have been carried out:

- Dielectric Tests on Main Circuit and Auxiliary Circuits: Lightning Impulse Voltage Test and Power Frequency Voltage Test
- Verification on the degree of protection
- Temperature rise test and Measuring the main circuit resistance
- Mechanical Operation Test
- Making and Breaking Tests: Making and Breaking Test on Load Break Switch and Making and Breaking Test in Test Duties TDISC, TDIWmax, TDItransfer
- Internal Arc Test
- Short time withstand current and peak withstand current test on main circuit and earthing circuit

The prototype has proved successful in each and every test mentioned above. The details of the test are explained in Chapter 4 and appendices in detail. The design of insulation system with SF_6 material has verified successful in the dielectric tests. The auxiliary systems have also verified successful in their individual dielectric tests. The prototype withstands all the voltage requirements. The current flowing through the main circuit does not cause an additional heating more than 30-75 K according to the temperature sensor location. The rated current of 630A can also be safely switched in the making and breaking tests under regular load conditions. The prototype can also satisfy the peak current conditions specified in IEC standards. The panel enclosure verified to be compliant with IP3x.

The prototype design has been slightly modified and introduced to mass production. The produced RMU systems has been first exported to Nigeria and then to Kosovo. These units has been successfully commissioned and in service.

The magnetic force method based RMU that is implemented within the scope of this thesis work shall lead the design of new products with extended current and voltage levels. As a further work, these arc extinguishing method and models can also be implemented to other types of switchgear such as air insulated metal enclosed switchgear. The magnet optimization can also be carried out in new projects. The arc model used in the design stage is also proved by the verification of test method. The simulation results taken from Simulink are consistent with the real test outcomes which show that the arc modeling parameters calculated leads successful results.

As a conclusion, with this thesis it is verified that the designed 12 kV compact type gas insulated switchgear with load breaker as incoming/ outgoing and load break switch+ fuse combination as transformer protection is designed convenient to international standard verification parameters. In other words, the design parameters met the planned verification limits and the product has satisfactory design limitations. During the design stage, arc modeling is used for simulating the test effect on design parameters. The crucial methodologies used as design milestones is the load break mechanical structure as the rotating switching apparatus around the central axis, arc extinguishing method via magnetic force effect with the magnets placed on busbar contacts. The simulation results show that the arc extinguishing and mechanical design parameters will give satisfactory results. Also the type tests that are defined at the international standards are applied for the verification of the design. The test results are consistent with the international acceptable limits. Therefore the design contribution on the 12 kV gas insulated switchgear with load breaker and the complete design is successfully accomplished.

APPENDIX-A : THE TEST DATA OF MAKING AND BREAKING TEST ON LOAD BREAK SWITCH

TEST DUTY 1:

%100 of the I_1 while, I=630 A

9.1 Test duty 1 (100% I1) I = 630 A												Table 4
Apparatus condition before the test: New												
Test no. /test duty	Oscillogram no.	Operation and time interval	U1R U1S U1T [kV]	IR IS IT [A]	DC [%]	U2R U2S U2T [kV]	URS UST UTR [kV]	TCR TCS TCT [ms]	TOR TOS TOT [ms]	TaR TaS TaT [ms]	TbR TbS TbT [ms]	REMARKS
0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
	79909/2011	CO	- - -	- - -	-	- - -	- - -	78 78 78	48 48 48	- - -	- - -	No load closing- opening times
1/1	79910/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	11 11 6	59 59 54	Load Break Switch closed and opened
2/1	79911/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	11 11 6	59 59 54	Load Break Switch closed and opened
3/1	79912/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	11 11 6	59 59 54	Load Break Switch closed and opened
4/1	79913/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	11 11 6	59 59 54	Load Break Switch closed and opened
5/1	79914/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	5 10 10	53 58 58	Load Break Switch closed and opened
6/1	79915/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	13 8 13	61 56 61	Load Break Switch closed and opened
7/1	79916/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	15 10 15	63 58 63	Load Break Switch closed and opened
8/1	79917/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	5 10 10	53 58 58	Load Break Switch closed and opened
9/1	79918/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	5 10 10	53 58 58	Load Break Switch closed and opened
10/1	79919/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	13 8 13	61 56 61	Load Break Switch closed and opened

Figure 75: The results of test on "Test Duty 1" %100 of the I1, taken from the test report 11049

0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
11/1	79920/2011	CO-3min	14	640	< 20	13.9	24	78	48	13	61	Load Break Switch closed and opened
			14	635		13.9	24	78	48	8	56	
			14	638		13.9	24	78	48	13	61	
12/1	79921/2011	CO-3min	14	640	< 20	13.9	24	78	48	14	62	Load Break Switch closed and opened
			14	635		13.9	24	78	48	9	57	
			14	638		13.9	24	78	48	14	62	
13/1	79922/2011	CO-3min	14	640	< 20	13.9	24	78	48	6	54	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	11	59	
14/1	79923/2011	CO-3min	14	640	< 20	13.9	24	78	48	6	54	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	11	59	
15/1	79924/2011	CO-3min	14	640	< 20	13.9	24	78	48	6	54	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	11	59	
16/1	79925/2011	CO-3min	14	640	< 20	13.9	24	78	48	14	62	Load Break Switch closed and opened
			14	635		13.9	24	78	48	9	57	
			14	638		13.9	24	78	48	14	62	
17/1	79926/2011	CO-3min	14	640	< 20	13.9	24	78	48	6	54	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	11	59	
18/1	79927/2011	CO-3min	14	640	< 20	13.9	24	78	48	8.5	56.5	Load Break Switch closed and opened
			14	635		13.9	24	78	48	3.5	51.5	
			14	638		13.9	24	78	48	8.5	56.5	
19/1	79928/2011	CO-3min	14	640	< 20	13.9	24	78	48	11.5	59.5	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11.5	59.5	
			14	638		13.9	24	78	48	6.5	54.5	
20/1	79929/2011	CO-3min	14	640	< 20	13.9	24	78	48	8	56	Load Break Switch closed and opened
			14	635		13.9	24	78	48	3	51	
			14	638		13.9	24	78	48	8	56	
21/1	79930/2011	CO-3min	14	640	< 20	13.9	24	78	48	11	59	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	6	54	
22/1	79931/2011	CO-3min	14	640	< 20	13.9	24	78	48	8	56	Load Break Switch closed and opened
			14	635		13.9	24	78	48	3	51	
			14	638		13.9	24	78	48	8	56	

Figure 76: The results of test on the “Test Duty 1” , taken from the test report 11049

0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
23/1	79932/2011	CO-3min	14	640	< 20	13.9	24	78	48	18	66	Load Break Switch closed and opened
			14	635		13.9	24	78	48	13	61	
			14	638		13.9	24	78	48	18	66	
24/1	79933/2011	CO-3min	14	640	< 20	13.9	24	78	48	10	58	Load Break Switch closed and opened
			14	635		13.9	24	78	48	15	63	
			14	638		13.9	24	78	48	15	63	
25/1	79934/2011	CO-3min	14	640	< 20	13.9	24	78	48	11	59	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	6	54	
26/1	79935/2011	CO-3min	14	640	< 20	13.9	24	78	48	12	60	Load Break Switch closed and opened
			14	635		13.9	24	78	48	12	60	
			14	638		13.9	24	78	48	7	55	
27/1	79936/2011	CO-3min	14	640	< 20	13.9	24	78	48	11	59	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	6	54	
28/1	79937/2011	CO-3min	14	640	< 20	13.9	24	78	48	11	59	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	6	54	
29/1	79938/2011	CO-3min	14	640	< 20	13.9	24	78	48	10	58	Load Break Switch closed and opened
			14	635		13.9	24	78	48	15	63	
			14	638		13.9	24	78	48	15	63	
30/1	79939/2011	CO-3min	14	640	< 20	13.9	24	78	48	11	59	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	6	54	
31/1	79940/2011	CO-3min	14	640	< 20	13.9	24	78	48	10	58	Load Break Switch closed and opened
			14	635		13.9	24	78	48	15	63	
			14	638		13.9	24	78	48	15	63	
32/1	79941/2011	CO-3min	14	640	< 20	13.9	24	78	48	14	62	Load Break Switch closed and opened
			14	635		13.9	24	78	48	9	57	
			14	638		13.9	24	78	48	14	62	
33/1	79942/2011	CO-3min	14	640	< 20	13.9	24	78	48	14	62	Load Break Switch closed and opened
			14	635		13.9	24	78	48	9	57	
			14	638		13.9	24	78	48	14	62	
34/1	79943/2011	CO-3min	14	640	< 20	13.9	24	78	48	12	60	Load Break Switch closed and opened
			14	635		13.9	24	78	48	7	55	
			14	638		13.9	24	78	48	12	60	

Figure 77: The results of test on the "Test Duty 1" , taken from the test report 11049

0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
35/1	79944/2011	CO-3min	14	640	< 20	13.9	24	78	48	16	64	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	16	64	
36/1	79945/2011	CO-3min	14	640	< 20	13.9	24	78	48	5	53	Load Break Switch closed and opened
			14	635		13.9	24	78	48	10	58	
			14	638		13.9	24	78	48	10	58	
37/1	79946/2011	CO-3min	14	640	< 20	13.9	24	78	48	4	52	Load Break Switch closed and opened
			14	635		13.9	24	78	48	9	57	
			14	638		13.9	24	78	48	9	57	
38/1	79947/2011	CO-3min	14	640	< 20	13.9	24	78	48	14	62	Load Break Switch closed and opened
			14	635		13.9	24	78	48	9	57	
			14	638		13.9	24	78	48	14	62	
39/1	79948/2011	CO-3min	14	640	< 20	13.9	24	78	48	13	61	Load Break Switch closed and opened
			14	635		13.9	24	78	48	8	56	
			14	638		13.9	24	78	48	13	61	
40/1	79949/2011	CO-3min	14	640	< 20	13.9	24	78	48	15	63	Load Break Switch closed and opened
			14	635		13.9	24	78	48	10	58	
			14	638		13.9	24	78	48	15	63	
41/1	79950/2011	CO-3min	14	640	< 20	13.9	24	78	48	6	54	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	11	59	
42/1	79951/2011	CO-3min	14	640	< 20	13.9	24	78	48	5	53	Load Break Switch closed and opened
			14	635		13.9	24	78	48	10	58	
			14	638		13.9	24	78	48	10	58	
43/1	79952/2011	CO-3min	14	640	< 20	13.9	24	78	48	13	61	Load Break Switch closed and opened
			14	635		13.9	24	78	48	8	56	
			14	638		13.9	24	78	48	13	61	
44/1	79953/2011	CO-3min	14	640	< 20	13.9	24	78	48	13	61	Load Break Switch closed and opened
			14	635		13.9	24	78	48	8	56	
			14	638		13.9	24	78	48	13	61	
45/1	79954/2011	CO-3min	14	640	< 20	13.9	24	78	48	14	62	Load Break Switch closed and opened
			14	635		13.9	24	78	48	9	57	
			14	638		13.9	24	78	48	14	62	
46/1	79955/2011	CO-3min	14	640	< 20	13.9	24	78	48	7	55	Load Break Switch closed and opened
			14	635		13.9	24	78	48	12	60	
			14	638		13.9	24	78	48	12	60	

Figure 78: The results of test on the "Test Duty 1" , taken from the test report 11049

0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
47/1	79956/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	7 12 12	55 60 60	Load Break Switch closed and opened
48/1	79957/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	7 12 12	55 60 60	Load Break Switch closed and opened
49/1	79958/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	15 10 15	63 58 63	Load Break Switch closed and opened
50/1	79959/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	6 11 11	54 59 59	Load Break Switch closed and opened
51/1	79960/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	8 3 8	56 51 56	Load Break Switch closed and opened
52/1	79961/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	12 12 7	60 60 55	Load Break Switch closed and opened
53/1	79962/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	8 3 8	56 51 56	Load Break Switch closed and opened
54/1	79963/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	11 11 6	59 59 54	Load Break Switch closed and opened
55/1	79964/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	7 2 7	55 50 55	Load Break Switch closed and opened
56/1	79965/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	18 13 18	66 61 66	Load Break Switch closed and opened
57/1	79966/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	10 15 15	58 63 63	Load Break Switch closed and opened
58/1	79967/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	11 11 6	59 59 54	Load Break Switch closed and opened

Figure 79: The results of test on the "Test Duty 1" , taken from the test report 11049

0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
59/1	79968/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	11 11 6	59 59 54	Load Break Switch closed and opened
60/1	79969/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	11 11 6	59 59 54	Load Break Switch closed and opened
61/1	79970/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	11 11 6	59 59 54	Load Break Switch closed and opened
62/1	79971/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	10 15 15	58 63 63	Load Break Switch closed and opened
63/1	79972/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	11 11 6	59 59 54	Load Break Switch closed and opened
64/1	79973/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	10 15 15	58 63 63	Load Break Switch closed and opened
65/1	79974/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	14 9 14	62 57 62	Load Break Switch closed and opened
66/1	79975/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	14 9 14	62 57 62	Load Break Switch closed and opened
67/1	79976/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	14 9 14	62 57 62	Load Break Switch closed and opened
68/1	79977/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	14 9 14	62 57 62	Load Break Switch closed and opened
69/1	79978/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	14 9 14	62 57 62	Load Break Switch closed and opened
70/1	79979/2011	CO-3min	14 14 14	640 635 638	< 20	13.9 13.9 13.9	24 24 24	78 78 78	48 48 48	10 15 15	58 63 63	Load Break Switch closed and opened

Figure 80: The results of test on the "Test Duty 1" , taken from the test report 11049

0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
71/1	79980/2011	CO-3min	14	640	< 20	13.9	24	78	48	11	59	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	6	54	
72/1	79981/2011	CO-3min	14	640	< 20	13.9	24	78	48	10	58	Load Break Switch closed and opened
			14	635		13.9	24	78	48	15	63	
			14	638		13.9	24	78	48	15	63	
73/1	79982/2011	CO-3min	14	640	< 20	13.9	24	78	48	12	60	Load Break Switch closed and opened
			14	635		13.9	24	78	48	12	60	
			14	638		13.9	24	78	48	7	55	
74/1	79983/2011	CO-3min	14	640	< 20	13.9	24	78	48	12	60	Load Break Switch closed and opened
			14	635		13.9	24	78	48	12	60	
			14	638		13.9	24	78	48	7	55	
75/1	79984/2011	CO-3min	14	640	< 20	13.9	24	78	48	11	59	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	6	54	
76/1	79985/2011	CO-3min	14	640	< 20	13.9	24	78	48	11	59	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	6	54	
77/1	79986/2011	CO-3min	14	640	< 20	13.9	24	78	48	10	58	Load Break Switch closed and opened
			14	635		13.9	24	78	48	15	63	
			14	638		13.9	24	78	48	15	63	
78/1	79987/2011	CO-3min	14	640	< 20	13.9	24	78	48	18	66	Load Break Switch closed and opened
			14	635		13.9	24	78	48	13	61	
			14	638		13.9	24	78	48	18	66	
79/1	79988/2011	CO-3min	14	640	< 20	13.9	24	78	48	8	56	Load Break Switch closed and opened
			14	635		13.9	24	78	48	3	51	
			14	638		13.9	24	78	48	8	56	
80/1	79989/2011	CO-3min	14	640	< 20	13.9	24	78	48	11	59	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	6	54	
81/1	79990/2011	CO-3min	14	640	< 20	13.9	24	78	48	7	55	Load Break Switch closed and opened
			14	635		13.9	24	78	48	2	50	
			14	638		13.9	24	78	48	7	55	
82/1	79991/2011	CO-3min	14	640	< 20	13.9	24	78	48	11	59	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	6	54	

Figure 81: The results of test on the “Test Duty 1” , taken from the test report 11049

:

0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
83/1	79992/2011	CO-3min	14	640	< 20	13.9	24	78	48	8	56	Load Break Switch closed and opened
			14	635		13.9	24	78	48	3	51	
			14	638		13.9	24	78	48	8	56	
84/1	79993/2011	CO-3min	14	640	< 20	13.9	24	78	48	5	53	Load Break Switch closed and opened
			14	635		13.9	24	78	48	10	58	
			14	638		13.9	24	78	48	10	58	
85/1	79994/2011	CO-3min	14	640	< 20	13.9	24	78	48	14	62	Load Break Switch closed and opened
			14	635		13.9	24	78	48	9	57	
			14	638		13.9	24	78	48	14	62	
86/1	79995/2011	CO-3min	14	640	< 20	13.9	24	78	48	6	54	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	11	59	
87/1	79996/2011	CO-3min	14	640	< 20	13.9	24	78	48	6	54	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	11	59	
88/1	79997/2011	CO-3min	14	640	< 20	13.9	24	78	48	6	54	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	11	59	
89/1	79998/2011	CO-3min	14	640	< 20	13.9	24	78	48	14	62	Load Break Switch closed and opened
			14	635		13.9	24	78	48	9	57	
			14	638		13.9	24	78	48	14	62	
90/1	79999/2011	CO-3min	14	640	< 20	13.9	24	78	48	13	61	Load Break Switch closed and opened
			14	635		13.9	24	78	48	8	56	
			14	638		13.9	24	78	48	13	61	
91/1	80000/2011	CO-3min	14	640	< 20	13.9	24	78	48	13	61	Load Break Switch closed and opened
			14	635		13.9	24	78	48	8	56	
			14	638		13.9	24	78	48	13	51	
92/1	80001/2011	CO-3min	14	640	< 20	13.9	24	78	48	4	52	Load Break Switch closed and opened
			14	635		13.9	24	78	48	9	57	
			14	638		13.9	24	78	48	9	57	
93/1	80002/2011	CO-3min	14	640	< 20	13.9	24	78	48	4	52	Load Break Switch closed and opened
			14	635		13.9	24	78	48	9	57	
			14	638		13.9	24	78	48	9	57	
94/1	80003/2011	CO-3min	14	640	< 20	13.9	24	78	48	13	61	Load Break Switch closed and opened
			14	635		13.9	24	78	48	8	56	
			14	638		13.9	24	78	48	13	61	

Figure 82: The results of test on the "Test Duty 1" , taken from the test report 11049

0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
95/1	80004/2011	CO-3min	14	640	< 20	13.9	24	78	48	14	62	Load Break Switch closed and opened
			14	635		13.9	24	78	48	9	57	
			14	638		13.9	24	78	48	14	62	
96/1	80005/2011	CO-3min	14	640	< 20	13.9	24	78	48	5	53	Load Break Switch closed and opened
			14	635		13.9	24	78	48	10	58	
			14	638		13.9	24	78	48	10	58	
97/1	80006/2011	CO-3min	14	640	< 20	13.9	24	78	48	11	59	Load Break Switch closed and opened
			14	635		13.9	24	78	48	11	59	
			14	638		13.9	24	78	48	6	54	
98/1	80007/2011	CO-3min	14	640	< 20	13.9	24	78	48	12	60	Load Break Switch closed and opened
			14	635		13.9	24	78	48	12	60	
			14	638		13.9	24	78	48	7	55	
99/1	80008/2011	CO-3min	14	640	< 20	13.9	24	78	48	12	60	Load Break Switch closed and opened
			14	635		13.9	24	78	48	12	60	
			14	638		13.9	24	78	48	7	55	
100/1	80008-1/2010	CO	14	640	< 20	13.9	24	78	48	13	61	Load Break Switch closed and opened
			14	635		13.9	24	78	48	8	56	
			14	638		13.9	24	78	48	13	61	

Figure 83: The results of test on the "Test Duty **1"** , taken from the test report 11049

TEST DUTY 1:

%5 of the I_1 while, I=31,5A

9.2. Test duty 1 (5% I_1) I = 31.5 A Table 5

Apparatus condition before the test: After test duty -1(100%I1)

Test no. /test duty	Oscillogram no.	Operation and time interval	U1R U1S U1T [kV]	IR IS IT [A]	DC [%]	U2R U2S U2T [kV]	URS UST UTR [kV]	TCR TCS TCT [ms]	TOR TOS TOT [ms]	TaR TaS TaT [ms]	TbR TbS TbT [ms]	REMARKS
0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
1/1	80009/2011	CO-3min	14	31.2	< 20	13.9	24	78	48	4	52	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	9	57	
			14	31.7		13.9	24	78	48	9	57	
2/1	80010/2011	CO-3min	14	31.2	< 20	13.9	24	78	48	4	52	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	9	57	
			14	31.7		13.9	24	78	48	9	57	
3/1	80011/2011	CO-3min	14	31.2	< 20	13.9	24	78	48	4	52	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	9	57	
			14	31.7		13.9	24	78	48	9	57	
4/1	80012/2011	CO-3min	14	31.2	< 20	13.9	24	78	48	11	59	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	11	59	
			14	31.7		13.9	24	78	48	6	54	
5/1	80013/2011	CO-3min	14	31.2	< 20	13.9	24	78	48	11	59	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	11	59	
			14	31.7		13.9	24	78	48	6	54	
6/1	80014/2011	CO-3min	14	31.2	< 20	13.9	24	78	48	10	58	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	10	58	
			14	31.7		13.9	24	78	48	5	53	
7/1	80015/2011	CO-3min	14	31.2	< 20	13.9	24	78	48	4	52	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	9	57	
			14	31.7		13.9	24	78	48	9	57	
8/1	80016/2011	CO-3min	14	31.2	< 20	13.9	24	78	48	4	52	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	9	57	
			14	31.7		13.9	24	78	48	9	57	
9/1	80017/2011	CO-3min	14	31.2	< 20	13.9	24	78	48	4	52	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	9	57	
			14	31.7		13.9	24	78	48	9	57	
10/1	80018/2011	CO-3min	14	31.2	< 20	13.9	24	78	48	10	52	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	10	57	
			14	31.7		13.9	24	78	48	5	57	

0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
11/1	80019/2011	CO-3min	14	31.2	< 20	13.9	24	78	48	10	58	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	10	58	
			14	31.7		13.9	24	78	48	5	53	
12/1	80020/2011	CO-3min	14	31.2	< 20	13.9	24	78	48	10	58	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	10	58	
			14	31.7		13.9	24	78	48	5	53	
13/1	80021/2011	CO-3min	14	31.2	< 20	13.9	24	78	48	3	51	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	8	56	
			14	31.7		13.9	24	78	48	8	56	
14/1	80022/2011	CO-3min	14	31.2	< 20	13.9	24	78	48	3	51	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	8	56	
			14	31.7		13.9	24	78	48	8	56	
15/1	80023/2011	CO-3min	14	31.2	< 20	13.9	24	78	48	9	57	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	4	52	
			14	31.7		13.9	24	78	48	9	57	
16/1	80024/2011	CO-3min	14	31.2	< 20	13.9	24	78	48	9	57	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	4	52	
			14	31.7		13.9	24	78	48	9	57	
17/1	80025/2011	CO-3min	14	31.2	< 20	13.9	24	78	48	9	57	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	4	52	
			14	31.7		13.9	24	78	48	9	57	
18/1	80026/2011	CO-3min	14	31.2	< 20	13.9	24	78	48	10	58	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	10	58	
			14	31.7		13.9	24	78	48	5	53	
19/1	80027/2011	CO-3min	14	31.2	< 20	13.9	24	78	48	5	53	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	10	58	
			14	31.7		13.9	24	78	48	10	58	
20/1	80028/2011	CO	14	31.2	< 20	13.9	24	78	48	13	61	Load Break Switch closed and opened
			14	31.2		13.9	24	78	48	13	61	
			14	31.7		13.9	24	78	48	8	56	

Figure 84: The results of test on the "Test Duty 1" %5 of the I1, taken from the test report 11049

TEST DUTY 2:

I_{2a} =630 A

:

Test no. /test duty	Oscillogram no.	Operation and time interval	U1R U1S U1T [kV]	IR IS IT [A]	DC [%]	U2R U2S U2T [kV]	URS UST UTR [kV]	TCR TCS TCT [ms]	TOR TOS TOT [ms]	TaR TaS TaT [ms]	TbR TbS TbT [ms]	REMARKS
0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
1/2a	80029/2011	CO-3min	2.78	645	< 20	2.77	4.8	78	48	17	65	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	17	65	
			2.78	648		2.77	4.8	78	48	12	60	
2/2a	80030/2011	CO-3min	2.78	645	< 20	2.77	4.8	78	48	23	71	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	28	76	
			2.78	648		2.77	4.8	78	48	28	76	
3/2a	80031/2011	CO-3min	2.78	645	< 20	2.77	4.8	78	48	23	71	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	28	76	
			2.78	648		2.77	4.8	78	48	28	76	
4/2a	80032/2011	CO-3min	2.78	645	< 20	2.77	4.8	78	48	7	55	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	12	60	
			2.78	648		2.77	4.8	78	48	12	60	
5/2a	80033/2011	CO-3min	2.78	645	< 20	2.77	4.8	78	48	28	76	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	28	76	
			2.78	648		2.77	4.8	78	48	23	71	
6/2a	80034/2011	CO-3min	2.78	645	< 20	2.77	4.8	78	48	13	61	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	8	56	
			2.78	648		2.77	4.8	78	48	13	61	
7/2a	80035/2011	CO-3min	2.78	645	< 20	2.77	4.8	78	48	27	75	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	27	75	
			2.78	648		2.77	4.8	78	48	22	70	
8/2a	80036/2011	CO-3min	2.78	645	< 20	2.77	4.8	78	48	15	63	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	20	68	
			2.78	648		2.77	4.8	78	48	20	68	
9/2a	80037/2011	CO-3min	2.78	645	< 20	2.77	4.8	78	48	16	64	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	16	64	
			2.78	648		2.77	4.8	78	48	11	59	
10/2a	80038/2011	CO-3min	2.78	645	< 20	2.77	4.8	78	48	15	63	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	10	58	
			2.78	648		2.77	4.8	78	48	15	63	

0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
11/2a	80039/2011	CO-3min	2.78	645	< 20	2.77	4.8	78	48	15	63	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	20	68	
			2.78	648		2.77	4.8	78	48	20	68	
12/2a	80040/2011	CO-3min	2.78	645	< 20	2.77	4.8	78	48	16	64	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	16	64	
			2.78	648		2.77	4.8	78	48	11	59	
13/2a	80041/2011	CO-3min	2.78	645	< 20	2.77	4.8	78	48	14	62	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	9	57	
			2.78	648		2.77	4.8	78	48	14	62	
14/2a	80042/2011	CO-3min	2.78	645	< 20	2.77	4.8	78	48	15	63	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	15	63	
			2.78	648		2.77	4.8	78	48	10	58	
15/2a	80043/2011	CO-3min	2.78	645	< 20	2.77	4.8	78	48	14	62	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	9	57	
			2.78	648		2.77	4.8	78	48	14	62	
16/2a	80044/2011	CO-3min	2.78	645	< 20	2.77	4.8	78	48	16	64	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	21	69	
			2.78	648		2.77	4.8	78	48	21	69	
17/2a	80045/2011	CO-3min	2.78	645	< 20	2.77	4.8	78	48	17	65	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	17	65	
			2.78	648		2.77	4.8	78	48	12	60	
18/2a	80046/2011	CO-3min	2.78	645	< 20	2.77	4.8	78	48	13	61	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	8	56	
			2.78	648		2.77	4.8	78	48	13	61	
19/2a	80047/2011	CO-3min	2.78	645	< 20	2.77	4.8	78	48	13	61	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	8	56	
			2.78	648		2.77	4.8	78	48	13	61	
20/2a	80048/2011	CO	2.78	645	< 20	2.77	4.8	78	48	15	63	Load Break Switch closed and opened
			2.78	647		2.77	4.8	78	48	20	68	
			2.78	648		2.77	4.8	78	48	20	68	

Figure 85: The results of test on I_{2a} =630 A, taken from the test report 11049

TEST DUTY 4a:

I_{4a} =16 A

Test no. /test duty	Oscillogram no.	Operation and time interval	U1R U1S U1T [kV]	IR IS IT [A]	DC [%]	U2R U2S U2T [kV]	URS UST UTR [kV]	TCR TCS TCT [ms]	TOR TOS TOT [ms]	TaR TaS TaT [ms]	TbR TbS TbT [ms]	REMARKS
0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
1/4a	80049/2011	CO-3min	14	16.1	< 20	13.9	24	78	48	8	56	Load Break Switch closed and opened
			14	16.5		13.9	24	78	48	3	51	
			14	16.2		13.9	24	78	48	8	56	
2/4a	80050/2011	CO-3min	14	16.1	< 20	13.9	24	78	48	8	56	Load Break Switch closed and opened
			14	16.5		13.9	24	78	48	3	51	
			14	16.2		13.9	24	78	48	8	56	
3/4a	80051/2011	CO-3min	14	16.1	< 20	13.9	24	78	48	8	56	Load Break Switch closed and opened
			14	16.5		13.9	24	78	48	3	51	
			14	16.2		13.9	24	78	48	8	56	
4/4a	80052/2011	CO-3min	14	16.1	< 20	13.9	24	78	48	8	56	Load Break Switch closed and opened
			14	16.5		13.9	24	78	48	3	51	
			14	16.2		13.9	24	78	48	8	56	
5/4a	80053/2011	CO-3min	14	16.1	< 20	13.9	24	78	48	8	56	Load Break Switch closed and opened
			14	16.5		13.9	24	78	48	3	51	
			14	16.2		13.9	24	78	48	8	56	
64a	80054/2011	CO-3min	14	16.1	< 20	13.9	24	78	48	8	56	Load Break Switch closed and opened
			14	16.5		13.9	24	78	48	3	51	
			14	16.2		13.9	24	78	48	8	56	
7/4a	80055/2011	CO-3min	14	16.1	< 20	13.9	24	78	48	8	56	Load Break Switch closed and opened
			14	16.5		13.9	24	78	48	3	51	
			14	16.2		13.9	24	78	48	8	56	
8/4a	80056/2011	CO-3min	14	16.1	< 20	13.9	24	78	48	8	56	Load Break Switch closed and opened
			14	16.5		13.9	24	78	48	3	51	
			14	16.2		13.9	24	78	48	8	56	
9/4a	80057/2011	CO-3min	14	16.1	< 20	13.9	24	78	48	8	56	Load Break Switch closed and opened
			14	16.5		13.9	24	78	48	3	51	
			14	16.2		13.9	24	78	48	8	56	
10/4a	80058/2011	CO	14	16.1	< 20	13.9	24	78	48	8	56	Load Break Switch closed and opened
			14	16.5		13.9	24	78	48	3	51	
			14	16.2		13.9	24	78	48	8	56	

Figure 86: The results of test on I_{4a} =16 A, taken from the test report 11049

I_{4a} =3,2 A

Test no. /test duty	Oscillogram no.	Operation and time interval	U1R U1S U1T [kV]	IR IS IT [A]	DC [%]	U2R U2S U2T [kV]	URS UST UTR [kV]	TCR TCS TCT [ms]	TOR TOS TOT [ms]	TaR TaS TaT [ms]	TbR TbS TbT [ms]	REMARKS
0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
1/4a	80059/2011	CO-3min	14	4	< 20	13.9	24	78	48	7	55	Load Break Switch closed and opened
			14	3.9		13.9	24	78	48	2	50	
			14	4		13.9	24	78	48	7	55	
2/4a	80060/2011	CO-3min	14	4	< 20	13.9	24	78	48	7	55	Load Break Switch closed and opened
			14	3.9		13.9	24	78	48	2	50	
			14	4		13.9	24	78	48	7	55	
3/4a	80061/2011	CO-3min	14	4	< 20	13.9	24	78	48	7	55	Load Break Switch closed and opened
			14	3.9		13.9	24	78	48	2	50	
			14	4		13.9	24	78	48	7	55	
4/4a	80062/2011	CO-3min	14	4	< 20	13.9	24	78	48	7	55	Load Break Switch closed and opened
			14	3.9		13.9	24	78	48	2	50	
			14	4		13.9	24	78	48	7	55	
5/4a	80063/2011	CO-3min	14	4	< 20	13.9	24	78	48	7	55	Load Break Switch closed and opened
			14	3.9		13.9	24	78	48	2	50	
			14	4		13.9	24	78	48	7	55	
6/4a	80064/2011	CO-3min	14	4	< 20	13.9	24	78	48	7	55	Load Break Switch closed and opened
			14	3.9		13.9	24	78	48	2	50	
			14	4		13.9	24	78	48	7	55	
7/4a	80065/2011	CO-3min	14	4	< 20	13.9	24	78	48	7	55	Load Break Switch closed and opened
			14	3.9		13.9	24	78	48	2	50	
			14	4		13.9	24	78	48	7	55	
8/4a	80066/2011	CO-3min	14	4	< 20	13.9	24	78	48	7	55	Load Break Switch closed and opened
			14	3.9		13.9	24	78	48	2	50	
			14	4		13.9	24	78	48	7	55	
9/4a	80067/2011	CO-3min	14	4	< 20	13.9	24	78	48	11	59	Load Break Switch closed and opened
			14	3.9		13.9	24	78	48	11	59	
			14	4		13.9	24	78	48	6	54	
10/4a	80068/2011	CO	14	4	< 20	13.9	24	78	48	8	56	Load Break Switch closed and opened
			14	3.9		13.9	24	78	48	3	51	
			14	4		13.9	24	78	48	8	51	

Figure 87: The results of test on I_{4a} =3,2 A, taken from the test report 11049

I_{4b} =1,5 A

Test no. /test duty	Oscillogram no.	Operation and time interval	U1R U1S U1T [kV]	IR IS IT [A]	DC [%]	U2R U2S U2T [kV]	URS UST UTR [kV]	TCR TCS TCT [ms]	TOR TOS TOT [ms]	TaR TaS TaT [ms]	TbR TbS TbT [ms]	REMARKS
0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
1/4b	80069/2011	CO-3min	14	1.50	< 20	13.9	24	78	48	4	52	Load Break Switch closed and opened
			14	1.55		13.9	24	78	48	3	51	
			14	1.60		13.9	24	78	48	4	52	
2/4b	80070/2011	CO-3min	14	1.50	< 20	13.9	24	78	48	4	52	Load Break Switch closed and opened
			14	1.55		13.9	24	78	48	3	51	
			14	1.60		13.9	24	78	48	4	52	
3/4b	80071/2011	CO-3min	14	1.50	< 20	13.9	24	78	48	4	52	Load Break Switch closed and opened
			14	1.55		13.9	24	78	48	3	51	
			14	1.60		13.9	24	78	48	4	52	
4/4b	80072/2011	CO-3min	14	1.50	< 20	13.9	24	78	48	4	52	Load Break Switch closed and opened
			14	1.55		13.9	24	78	48	3	51	
			14	1.60		13.9	24	78	48	4	52	
5/4b	80073/2011	CO-3min	14	1.50	< 20	13.9	24	78	48	4	52	Load Break Switch closed and opened
			14	1.55		13.9	24	78	48	3	51	
			14	1.60		13.9	24	78	48	4	52	
6/4b	80074/2011	CO-3min	14	1.50	< 20	13.9	24	78	48	4	52	Load Break Switch closed and opened
			14	1.55		13.9	24	78	48	3	51	
			14	1.60		13.9	24	78	48	4	52	
7/4b	80075/2011	CO-3min	14	1.50	< 20	13.9	24	78	48	4	52	Load Break Switch closed and opened
			14	1.55		13.9	24	78	48	3	51	
			14	1.60		13.9	24	78	48	4	52	
8/4b	80076/2011	CO-3min	14	1.50	<20	13.9	24	78	48	4	52	Load Break Switch closed and opened
			14	1.55		13.9	24	78	48	3	51	
			14	1.60		13.9	24	78	48	4	52	
9/4b	80077/2011	CO-3min	14	1.50	< 20	13.9	24	78	48	4	52	Load Break Switch closed and opened
			14	1.55		13.9	24	78	48	3	51	
			14	1.60		13.9	24	78	48	4	52	
10/4b	80078/2011	CO	14	1.50	<20	13.9	24	78	48	4	52	Load Break Switch closed and opened
			14	1.55		13.9	24	78	48	3	51	
			14	1.60		13.9	24	78	48	4	52	

Figure 88: The results of test on I_{4b} =1,5 A, taken from the test report 11049

TEST DUTY 6b:

I_{6b} =28 A

Test no. /test duty	Oscillogram no.	Operation and time interval	U1R U1S U1T [kV]	IR IS IT [A]	DC [%]	U2R U2S U2T [kV]	URS UST UTR [kV]	TCR TCS TCT [ms]	TOR TOS TOT [ms]	TaR TaS TaT [ms]	TbR TbS TbT [ms]	REMARKS
0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
1/6b	80079/2011	CO-3min	14	27.9	< 20	24	24	78	48	9	57	Load Break Switch closed and opened
			14	28.0		24	24	78	48	6	54	
			-	-		-	24	78	48	-	-	
2/6b	80080/2011	CO-3min	14	27.9	< 20	24	24	78	48	9	57	Load Break Switch closed and opened
			14	28.0		24	24	78	48	6	54	
			-	-		-	24	78	48	-	-	
3/6b	80081/2011	CO-3min	14	27.9	< 20	24	24	78	48	9	57	Load Break Switch closed and opened
			14	28.0		24	24	78	48	6	54	
			-	-		-	24	78	48	-	-	
4/6b	80082/2011	CO-3min	14	27.9	< 20	24	24	78	48	9	57	Load Break Switch closed and opened
			14	28.0		24	24	78	48	6	54	
			-	-		-	24	78	48	-	-	
5/6b	80083/2011	CO-3min	14	27.9	< 20	24	24	78	48	9	57	Load Break Switch closed and opened
			14	28.0		24	24	78	48	6	54	
			-	-		-	24	78	48	-	-	
6/6b	80084/2011	CO-3min	14	27.9	< 20	24	24	78	48	9	57	Load Break Switch closed and opened
			14	28.0		24	24	78	48	6	54	
			-	-		-	24	78	48	-	-	
7/6b	80085/2011	CO-3min	14	27.9	< 20	24	24	78	48	9	57	Load Break Switch closed and opened
			14	28.0		24	24	78	48	6	54	
			-	-		-	24	78	48	-	-	
8/6b	80086/2011	CO-3min	14	27.9	< 20	24	24	78	48	9	57	Load Break Switch closed and opened
			14	28.0		24	24	78	48	6	54	
			-	-		-	24	78	48	-	-	
9/6b	80087/2011	CO-3min	14	27.9	< 20	24	24	78	48	9	57	Load Break Switch closed and opened
			14	28.0		24	24	78	48	6	54	
			-	-		-	24	78	48	-	-	
10/6b	80088/2011	CO	14	27.9	< 20	24	24	78	48	9	57	Load Break Switch closed and opened
			14	28.0		24	24	78	48	6	54	
			-	-		-	24	78	48	-	-	

Figure 89: The results of test on I_{6b} =28 A, taken from the test report 11049

TEST DUTY 6a:

I_{6a} =48 A

Test no. /test duty	Oscillogram no.	Operation and time interval	U1R U1S U1T [kV]	IR IS IT [A]	DC [%]	U2R U2S U2T [kV]	URS UST UTR [kV]	TCR TCS TCT [ms]	TOR TOS TOT [ms]	TaR TaS TaT [ms]	TbR TbS TbT [ms]	REMARKS
0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
1/6a	80089/2011	CO-3min	-	-	< 20	-	24	78	48	-	-	Load Break Switch closed and opened
			-	-		-	24	78	48	-	-	
			14	47.8		13.9	24	78	48	8	56	
2/6a	80090/2011	CO-3min	-	-	< 20	-	24	78	48	-	-	Load Break Switch closed and opened
			-	-		-	24	78	48	-	-	
			14	47.8		13.9	24	78	48	8	56	
3/6a	80091/2011	CO-3min	-	-	< 20	-	24	78	48	-	-	Load Break Switch closed and opened
			-	-		-	24	78	48	-	-	
			14	47.8		13.9	24	78	48	8	56	
4/6a	80092/2011	CO-3min	-	-	< 20	-	24	78	48	-	-	Load Break Switch closed and opened
			-	-		-	24	78	48	-	-	
			14	47.8		13.9	24	78	48	8	56	
5/6a	80093/2011	CO-3min	-	-	< 20	-	24	78	48	-	-	Load Break Switch closed and opened
			-	-		-	24	78	48	-	-	
			14	47.8		13.9	24	78	48	8	56	
6/6a	80094/2011	CO-3min	-	-	< 20	-	24	78	48	-	-	Load Break Switch closed and opened
			-	-		-	24	78	48	-	-	
			14	47.8		13.9	24	78	48	8	56	
7/6a	80095/2011	CO-3min	-	-	< 20	-	24	78	48	-	-	Load Break Switch closed and opened
			-	-		-	24	78	48	-	-	
			14	47.8		13.9	24	78	48	8	56	
8/6a	80096/2011	CO-3min	-	-	< 20	-	24	78	48	-	-	Load Break Switch closed and opened
			-	-		-	24	78	48	-	-	
			14	47.8		13.9	24	78	48	8	56	
9/6a	80097/2011	CO-3min	-	-	< 20	-	24	78	48	-	-	Load Break Switch closed and opened
			-	-		-	24	78	48	-	-	
			14	47.8		13.9	24	78	48	8	56	
10/6a	80098/2011	CO	-	-	< 20	-	24	78	48	-	-	Load Break Switch closed and opened
			-	-		-	24	78	48	-	-	
			14	4.7		13.9	24	78	48	8	56	

Figure 90: The results of test on I_{6a} =48 A, taken from the test report 11049

APPENDIX-B : THE TEST DATA OF POWER FREQUENCY VOLTAGE TEST

Position of switching devices			Voltage applied to			Earth connected to			Free terminals			Level of testing voltage [kV]	Test results
LSB – S1	LSB – S2	LSBF – S3	LSB – S1	LSB – S2	LSBF – S3	LSB – S1	LSB – S2	LSBF – S3	LSB – S1	LSB – S2	LSBF – S3		
closed	closed	closed	l1, L1	l1, L1	l1, L1	l2,l3,L2,L3,F	l2,l3,L2,L3,F	l2,l3,L2, L3,F	-	-	-	50	Withstood 60 sec
			l2, L2	l2, L2	l2, L2	l1,l3,L1,L3,F	l1,l3,L1,L3,F	l1,l3,L1, L3,F	-	-	-	50	Withstood 60 sec
			l3, L3	l3, L3	l3, L3	l1,l2,L1,L2,F	l1,l2,L1,L2,F	l1,l2,L1, L2,F	-	-	-	50	Withstood 60 sec
closed	open	open	l1, L1	L1	L1	l2,l3,L2,L3,F	L2,L3, l1,l2,l3,F	L2,L3, l1,l2,l3,F	-	-	-	50	Withstood 60 sec
			l2, L2	L2	L2	l1,l3,L1,L3,F	L1,L3, l1,l2,l3,F	L1,L3, l1,l2,l3,F	-	-	-	50	Withstood 60 sec
			l3, L3	L3	L3	l1,l2,L1,L2,F	L1,L2, l1,l2,l3,F	L1,L2, l1,l2,l3,F	-	-	-	50	Withstood 60 sec
open	open	closed	L1	L1	l1, L1	L2,L3, l1,l2,l3,F	L2,L3, l1,l2,l3,F	l2,l3,L2,L3,F	-	-	-	50	Withstood 60 sec
			L2	L2	l2, L2	L1,L3, l1,l2,l3,F	L1,L3, l1,l2,l3,F	l1,l3,L1,L3,F	-	-	-	50	Withstood 60 sec
			L3	L3	l3, L3	L1,L2, l1,l2,l3,F	L1,L2, l1,l2,l3,F	l1,l2,L1,L2,F	-	-	-	50	Withstood 60 sec
open	open	open	l1	l1	l1	L1,L2,L3, l2,l3,F	L1,L2,L3, l2,l3,F	l2,l3,L1,L2 L3,F	-	-	-	50	Withstood 60 sec
			l2	l2	l2	L1,L2,L3, l1,l3,F	L1,L2,L3, l1,l3,F	l1,l3,L1,L2 L3,F	-	-	-	50	Withstood 60 sec
			l3	l3	l3	L1,L2,L3, l1,l2,F	L1,L2,L3, l1,l2,F	l1,l2,L1,L2 L3,F	-	-	-	50	Withstood 60 sec
closed	open	open	l1, L1	L1	L1	-	l1	l1	l2,l3,L2, L3,F	L2,L3, l2,l3,F	L2,L3, l2,l3,F	60	Withstood 60 sec
			l2, L2	L2	L2	-	l2	l2	l1,l3,L1, L3,F	L1,L3, l1,l3,F	L1,L3, l1,l3,F	60	Withstood 60 sec
			l3, L3	L3	L3	-	l3	l3	l1,l2,L1, L2,F	L1,L2, l1,l2,F	L1,L2, l1,l2,F	60	Withstood 60 sec
open	open	closed	L1	L1	l1, L1	l1	l1	-	L2,L3, l2,l3,F	L2,L3, l2,l3,F	l2,l3,L2 L3,F	60	Withstood 60 sec
			L2	L2	l2, L2	l2	l2	-	L1,L3, l1,l3,F	L1,L3, l1,l3,F	l1,l3,L1 L3,F	60	Withstood 60 sec
			L3	L3	l3, L3	l3	l3	-	L1,L2, l1,l2,F	L1,L2, l1,l2,F	l1,l2,L1 L2,F	60	Withstood 60 sec
open	open	closed	l1	l1	l1, L1	L1	L1	-	l2,l3, L2,L3,F	l2,l3, L2,L3,F	l2,l3, L2,L3,F	60	Withstood 60 sec
			l2	l2	l2, L2	L2	L2	-	l1,l3, L1,L3,F	l1,l3, L1,L3,F	l1,l3, L1,L3,F	60	Withstood 60 sec
			l3	l3	l3, L3	L3	L3	-	l1,l2, L1,L3,F	l1,l2, L1,L2,F	l1,l2, L1,L2,F	60	Withstood 60 sec

REFERENCES

[1] Brown, R., *Electric power distribution reality*. Book- CRS Press: USA, 2005

[2] Fink, H., *Medium voltage Switchgear,* Patent Application: USA, 2011

[3] Bertolotto B., *Medium voltage air insulated switchgear*, Research paper for ABB Service SRL. Milan: Italy, 2010

[4] Byeon, J., *Solid insulated switchgear,* Research paper for Lsis CO LTD. Anyang-si: Korea, 2013

[5] Oishi, K., *Gas insulated switchgear apparatus*, Research paper for Hitachi LTD. Tokyo: Japan, 1980

[6] Vaghini, A., Perli G., Rossi A., *Switch and disconnector apparatus for electric substations,* Research paper for Vei Power Distribution Spa. Milan: Italy,2004

[7] Cortinovis, G., *Medium voltage circuit breaker I*. Research paper for ABB Technology AG. Zurich: Sweden, 2012

[8] Cortinovis, G., *Medium voltage circuit breaker I,* Research paper for ABB Technology AG. Zurich: Sweden, 2011

[9] Vaghini, A., Perli G., Rossi A., *Isolator/ Circuit breaker device for electric substations*, Research paper for Vei Power Distribution Spa. Milan: Italy, 2004

[10] Schneider Technical Document, SF_6 gas properties and use in MV and HV switchgear.

[11] Capiel C., *Switchgear and* SF_6 *gas,* Research paper for ABB Technology AG. Zurich: Sweden, 2010

[12] Füshlel D., Hogg P., Mantel L., *Gas insulated switchgear with grounding and disconnecting switches,* Research paper for ABB Technology AG. Zurich: Sweden, 1996

[13] IEEE Standard Requirements,Terminology, and Test Code for High Voltage Test Techniques, IEEE Std. 60060

[14] Amano, H., Takehiro K., Kayaba H., *Gas insulated switchgear,* Research paper for Hitachi LTD. Tokyo: Japan, 1987

[15] Cronin, J., Wilson M., *Rotary switch for gas insulated substations,* Research paper for Gould Inc. Rolling Meadows: USA, 1979

[16] Yamauchi, P., *Gas insulated switchgear,* Research paper for Mitsubishi Denki Kabushiki Kaisha: Japan, 1989

[17] Franchi, C. Piazza C., Montelaghi F., *Gas insulated switchgear device,* Research paper for ABB Service SRL. Milan: Italy, 2000

[18] http://www.electricalreview.co.uk/features/5010-11509

[19] Piazza, C., Guerra G., *Gas insulated switchgear device,* Research paper for ABB Service SRL. Milan: Italy, 2004

[20] Kuhl, D., Mann M, Saxl D., *Metal- encapsulated, gas- insulated combined switch disconnector and earthing switch*, Research paper for ABB Technology AG. Zurich: Sweeden, 2012

[21] Nickander A., *Utilizing the ring operation mode of medium voltage distribution feeder,* Research paper at Tampere University of Technology: Finland, 2003

[22] Technical Catalogue, Schneider SM6-36

[23] Ciaessence, M., *Dielectric insulation medium*, Research paper for ABB Technology AG. Zurich: Sweden, 2011

[24] Turkish Distribution Utility Technical Requirements, TEDAŞ MYD 95-002, 1995

[25] Technical Catalogue, Schneider Electric RM6, 2010

[26] Technical Catalogue, ABB Safering RMU, 2013

[27] IEEE Standard Requirements,Terminology, and Test Code for Insulation levels and dielectric tests, IEEE Std. 60076-03

[28] IEEE Standard Requirements,Terminology, and Test Code for High voltage switchgear and controlgear, IEEE Std. 61271-001

[29] IEEE Standard Requirements,Terminology, and Test Code for High voltage switchgear and controlgear, IEEE Std. 61271-101

[30] IEEE Standard Requirements,Terminology, and Test Code for High voltage switchgear and controlgear, IEEE Std. 61271-200

[31] IEEE Standard Requirements,Terminology, and Test Code for High voltage switchgear and controlgear, IEEE Std. 60694

[32] IEEE Standard Requirements,Terminology, and Test Code for High voltage switchgear and controlgear, IEEE Std. 60529

[33] IEEE Standard Requirements,Terminology, and Test Code for High voltage switchgear and controlgear, IEEE Std. 60625

[34] Jiles D., Mina M, Magnell S., *Introduction to magnetism and magnetic materials*, CRS Press University: USA, 1998

[35] Nitu S., *Comparison between model and experiment in studying the electric arc*, Research paper at University of Politehnica: Romania, 2008

[36] Yuan L., *Simulation of Fault Arc Using Conventional Arc Models*, Research paper at Nanjing Normal University: China, 2013

[37] Rutgers W., *The Comparison of test Circuits with Arc Models*, Research paper at IEEE and Lou van der Sluis, Delft University of Technology: Netherland, 1995

[38] Schavemaker P., *An improved Myr type Arc Model Based on Current Zero Measurements*, Research paper at IEEE and Lou van der Sluis: Netherland, 2000

[39] Gustavsson N., E*valuation and Simulation of Black-box Arc Models for High Voltage Circuit-breakers*, Research paper at Berlin, 2004

[40] Lisovsky V.A., *Electron drift velocity determination in CF4 and* SF_6 *in a strong electric field from breakdown curves of Black-box Arc Models for High Voltage Circuit-breakers.* Research paper at UK, 1999