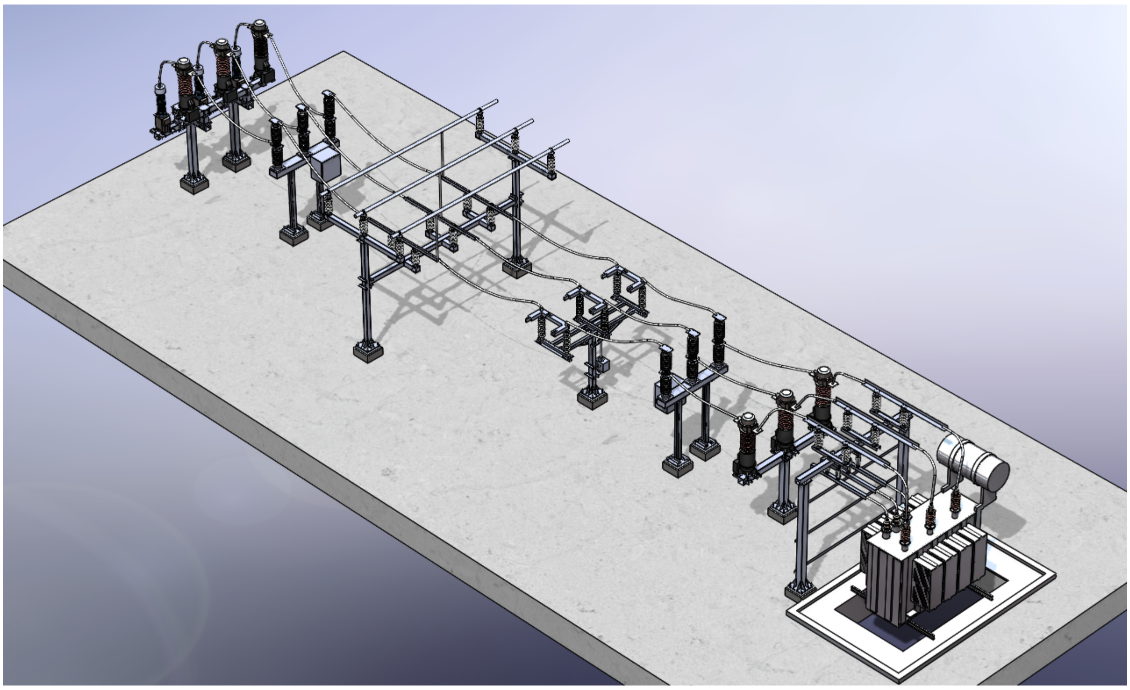


Evaluating Future Challenges and Possibilities of Electrical Substations

A review of future power system conditions and environmental aspects of substations

Master's Thesis in Sustainable electric power engineering and electromobility

Viktor Strandberg

Department of Electrical Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
www.chalmers.se

Master's thesis 2024

Evaluating future challenges and possibilities of electrical substations

A review of future power system conditions and environmental aspects of substations

Viktor Strandberg

CHALMERS
UNIVERSITY OF TECHNOLOGY

Department of Electrical engineering
Division of Electric power engineering
Chalmers University of Technology
Gothenburg, Sweden 2024

Evaluating future challenges and possibilities of electrical substations
A review of future power system conditions and environmental aspects of substations
Viktor Strandberg

Supervisors: Assoc. Prof. Thomas Hammarström, Department of Electrical Engineering
Tomas Nilsson, Business Unit Manager - Omexom

Examiner: Assoc. Prof. Thomas Hammarström, Department of Electrical Engineering

Master's Thesis 2024
Department Electrical engineering Division of Electric power engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Isometric view of the substation modeled in the thesis.

Typeset in LaTeX
Gothenburg, Sweden 2024

Evaluating future challenges and possibilities of electrical substations
A review of future power system conditions and environmental aspects of substations
Viktor Strandberg
Department of Electrical engineering
Chalmers University of Technology

Abstract

The future entails a significant expansion of the electrical power system in every aspect from production to distribution. The electrification is a necessity for addressing the future environmental challenges. With the electrification and expansion of the electrical power production comes the integration of high amounts of renewable energy sources. This thesis aims to evaluate what challenges arise from such an integration. Furthermore, the thesis aims to review the alternatives to the insulating gas SF_6 and the consequences of the alternatives on a substation design level.

It was found that renewable energy sources impact the frequency stability, voltage stability, rotor-angle stability, system protection while also injecting harmonic content to the system. These challenges may be mitigated using Flexible AC Transmission System (FACTS) -devices, battery energy storage and digitization of substations.

The fluorinated gas SF_6, one of the strongest green house gases known, is heavily used as insulating medium in high voltage switchgear. Due to its superior insulating and electronegative characteristics, the quest for an alternative insulating material in high voltage applications is, and will continue to be, a major challenge.

Several alternatives to SF_6 circuit breakers are highlighted in the thesis. Gas mixtures containing the compound C4-FN is found to be the most promising alternative. Electrostatic simulation on gas mixtures containing C4-FN and CO_2 found that the gas mixtures containing C4-FN was able to perform at the same level as SF_6 while maintaining the demanded size constraints.

Keywords: SF_6 alternatives, Future power system, RES integration

Acknowledgements

There are several people that I would like to thank that have been involved in the shaping and execution of this thesis. Firstly, I would like to thank my supervisor Thomas Hammarström. Thomas's profound understanding of the complex subject of high voltage technology helped to accelerate this thesis.

Secondly, I would like to extent my gratitude towards the company Omexom and their talented employees who gave me a spot in their office. They made this project possible and have provided me with insights to the field of electrical infrastructure. A special thanks to my supervisor at the company, Tomas Nilsson, who's expertise and knowledge was much appreciated.

Finally, a special thanks to my partner Linnea who exchanged ideas with me which was of great use to this project. Her support and encouragement helped me throughout this time.

Viktor Strandberg, Gothenburg, May 2024

List of Abbreviations

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

AIS	Air Insulated Switchgear
BESS	Battery Energy Storage Solution
DG	Distributed Generator
C4-FN	C4-fluoronitrile $(CF_3)_2CFC{\equiv}N$
CT	Current Transformer
DTB	Dead Tank Breaker
DVR	Dynamic Voltage Restorer
FACTS	Flexible AC Transmission System
GIL	Gas Insulated Line
GIS	Gas Insulated Switchgear
GWP	Global Warming Potential
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
LTB	Live Tank Breaker
MV	Medium Voltage
ODP	Ozone Depletion Potential
PD	Partial Discharge
RES	Renewable Energy Sources
RoCoF	Rate of Change of Frequency
SG	Synchronous Generator
STATCOM	Static Synchronous Compensator
SVK	Svenska kraftnät
TCR	Thyristor Controlled Rectifier
THD	Total Harmonic Distortion
TSO	Transmission System Operator
VT	Voltage Transformer

Contents

List of Figures

List of Tables

1 Introduction

1.1 Background

As the demand for green electrical power continues to rise, our electrical power system is undergoing a significant expansion. The transition into a decarbonized society poses new opportunities for the society, as well as various challenges, particularly challenges reflected in the electrical infrastructure[1].

At the core of the electrical infrastructure lie the substations, serving a pivotal role for a efficient transmission and distribution of electricity. The ambition to reduce greenhouse gas emissions extends beyond the electrical power production, encompassing every aspect of the electrical system.

One key element of this adaptation is the reduction of sulphur hexafluoride (SF_6), a gas commonly utilized in high-voltage switchgear due to its exceptional insulating properties and electronegative characteristics. While providing excellent dielectric properties, the gas at the same time possesses one major drawback. The gas is one of the strongest greenhouse gases known, with a global warming potential (GWP) of 23500, in relation to CO_2[2]. The impending ban on the gas will drastically reduce the environmental footprint of the electrical infrastructure[3].

While the ban will significantly reduce the carbon footprint of substations and associated equipment, it also presents a series of challenges. The transition away from SF_6 necessitates the development and implementation of alternative insulation technologies that can match or surpass its performance while also achieving a lowered environmental footprint.

1.2 Scope and aim

The aim of the thesis is to evaluate the future challenges posed on substations in the Swedish electrical grid as a result of the transition into an electrified society. In order to evaluate said challenges the thesis is separated into two segments. Firstly, the conditions of the future Swedish power system will be addressed with its corresponding challenges and plausible solutions. Secondly, as the ambition for a carbon free society not only relates to the power production, but also directly affects the infrastructure within the electrical grid, environmental aspects of substation will be addressed. The main overarching questions of the thesis are summarized in bullet points below.

- Power system
    - How will the future Swedish energy mix likely be compromised?
    - How will higher penetration of renewable energy solutions (RES) affect the power system?
    - What possible solutions exist to accommodate the challenges stemming from higher contribution of RES?
- Environmental
    - What SF_6-free alternatives are highlighted by research and what exists on the market?
    - What are the alternatives for mineral oil as insulation in power transformers?
    - How will the SF_6-free alternatives affect substation on a design level?

2

Theoretical background

The theoretical background have been divided into three sections. Power system theory, high voltage physics theory and a section on substations.

2.1 Power system theory

This section introduces concepts of power system theory with emphasis on power system stability.

2.1.1 Swing equation

The Swing equation in an electrical power engineering context describes the electromechanical dynamics of a synchronous generator (SG). The equation can be used in order to determine the dynamics of disturbances. In this section a short derivation of the swing equation is presented from [4] and [5].

The kinetic energy of a SG can be expressed as

$$E_n = \frac{1}{2} J \Omega_r^2 \tag{2.1}$$

where, J, is the inertia and Ω_r angular velocity of the rotor. The inertia constant, H, can be expressed as

$$H = \frac{E_n}{S_n} = \frac{\frac{1}{2} J \Omega_n^2}{\delta_n} \tag{2.2}$$

where, S_n, is the rated apparent power of the SG.

Applying Newton's second law of motion the behaviour for small deviations results in

$$T_a = T_m - T_e = \frac{dE}{dt} = J \Omega_r \frac{d\Omega_r}{dt} = Tm - Te \tag{2.3}$$

, where , T_a, is the net torque acceleration during an imbalance, T_m, the mechanical torque and T_e the electrical torque.

During a disturbance the difference between the speed deviation, $\Delta\delta_r$ and the synchronous speed,$\Delta\omega_s$ is small. The generator speed is almost equal to the synchronous speed which implies that torque is equal to the power expressed in per unit base, which gives, combined with 2.2 and 2.3, the following equation.

$$2H\frac{d\omega_r'}{dt} = P_m' - P_e' \tag{2.4}$$

From the Swing equation it may be observed that during a power imbalance, $P_m' - P_e' \neq 0$, the system frequency will either increase or decrease depending on the mechanical and electrical power difference. As such, the inertia constant, H, has a dampening effect on the frequency acceleration following a disturbance.

2.1.2 Power system stability

Power system stability may be defined as[6]:

> "Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact"

Power system stability can divided into three different sections with corresponding subsections. The classification is based on the size of the disturbance, time duration and the devices which are all important factors when addressing and evaluating issues related to power system stability[6]. The classifications are given in figure 2.1.

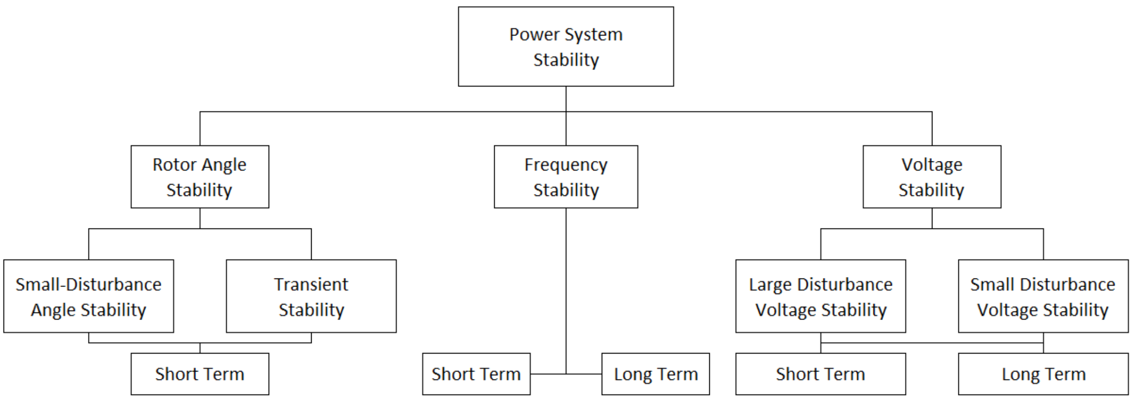


Figure 2.1: Stability classification

The three main categories are, rotor angle stability, frequency stability and voltage stability. All three concepts will be further discussed below.

Rotor angle stability

When multiple synchronous machines are interconnected, the machines must have the same frequency for the stator voltages and currents and the mechanical speed of the rotors must be synchronized to the same speed. This state is refereed to as synchronism and rotor angle stability refers to the ability to maintain its synchronism in the event of a disturbance of the system. In order to maintain synchronism the machines needs to be able to restore equilibrium between mechanical and electrical torque. Losing synchronism causes large fluctuations in the machine's output current, voltage and power and the protection system may need to isolate the unstable machine from the system[7][6]. Rotor angle stability can be further divided into two subcategories, namely, small-disturbance/small-signal stability and transient stability, which will be discussed below.

Small-disturbance stability

Small-disturbance stability refers to the ability to remain in synchronism with the power system during *smaller* disturbances ranging from 10-20 seconds. Small-disturbance stability issues can be local, i.e, when a local power system is being subjected to rotor oscillations from a larger power power plant. Damping is an important factor during these types of disturbances which depends on both generator characteristics and the characteristics of the local transmission system[6][5].

Transient stability

Transient stability is the ability to remain in synchronism during the event of a *severe* disturbance, i.e. short-circuit of a transmission line. The disturbance time ranges from 3-5 seconds. Transient stability are dependent on the initial state of operation and the disturbance size and can be analysed with the aid of the power-angle curve[6]. Such a curve is given in figure 2.2, where the red curve, P_e, is the electrical power output of a generator, P_m, is the mechanical power, δ, the rotor angle and $\delta_{unstable}$ the unstable point of operation. In equilibrium, the electrical power and mechanical power are equal and the rotor angle, δ, settles at the point of intersection. If the angles increases beyond $\delta_{unstable}$, synchronism is lost.

Consider a disturbance, i.e, short circuit on a line. High short circuit current causes voltage to drop and as a result, the electrical power immediately decreases. Figure 2.3 depicts the power angle curve following a disturbance. The blue curve is the electrical power during fault conditions. The mechanical power is larger than electrical power and, as a consequence from 2.4, the rotor starts to accelerate. The rotor angle will continue to accelerate to an angle $\delta_{critical}$ before starting to decelerate. If the unstable point is point is reached before the speed reaches its synchronous speed, the generator will continue to accelerate and lose synchronism with the grid.

The critical angle and critical fault clearing time can be evaluated using the equal area criterion. The equal area criterion is a graphical method of evaluating transient stability, see figure 2.4. The criterion of maintaining transient stability is that the acceleration area, A, is smaller or equal to the deceleration area, B[8].

Frequency stability

The term frequency stability refers to the capability of upholding a steady frequency following a disturbance that results in a significant imbalance between the power consumption and production. Frequency instability results in frequency fluctuations which may result in disconnection of generating devices for protection purposes[6],

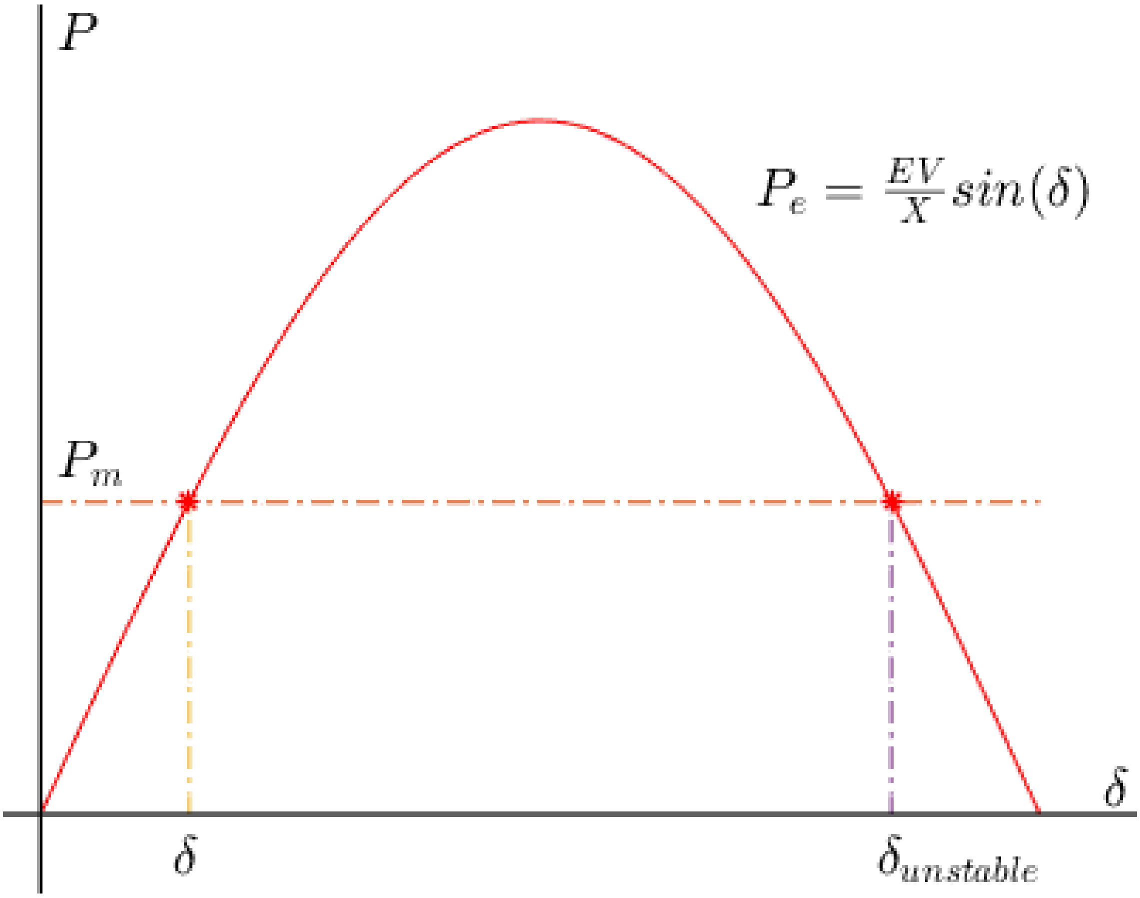


Figure 2.2: Arbitrary Power/Voltage curve for evaluation of transient stability

load shedding, accelerated aging of equipment and complete blackout[4]. Furthermore, there is a risk of voltage magnitude swings during frequency excursions which could result in undesirable operation of the concerned protection systems.

Frequency stability of a power system is determined by the disturbance size and time, availability of power reserves, system inertia and properties of the power system such as load frequency dependence. The rate of change of frequency(RoCoF) describes the initial change of frequency with respect to time. In order to limit the RoCoF and as a result, limit the transient frequency dip inertia is an important factor. Inertia refers to the amount of rotational energy stored in the system. During a disturbance, the heavy rotating masses of the various generating units will continue to rotate, mitigating the RoCoF magnitude.

Voltage stability

The term voltage stability refers to the capability of upholding steady voltages for each bus in the system following a disturbance. Maintaining equilibrium between supply and demand is an important ability related to voltage stability. Voltage instability in the form of over/under-voltages may result in, area outages, increased ageing, flashovers, dielectric breakdown and line tripping from protection systems

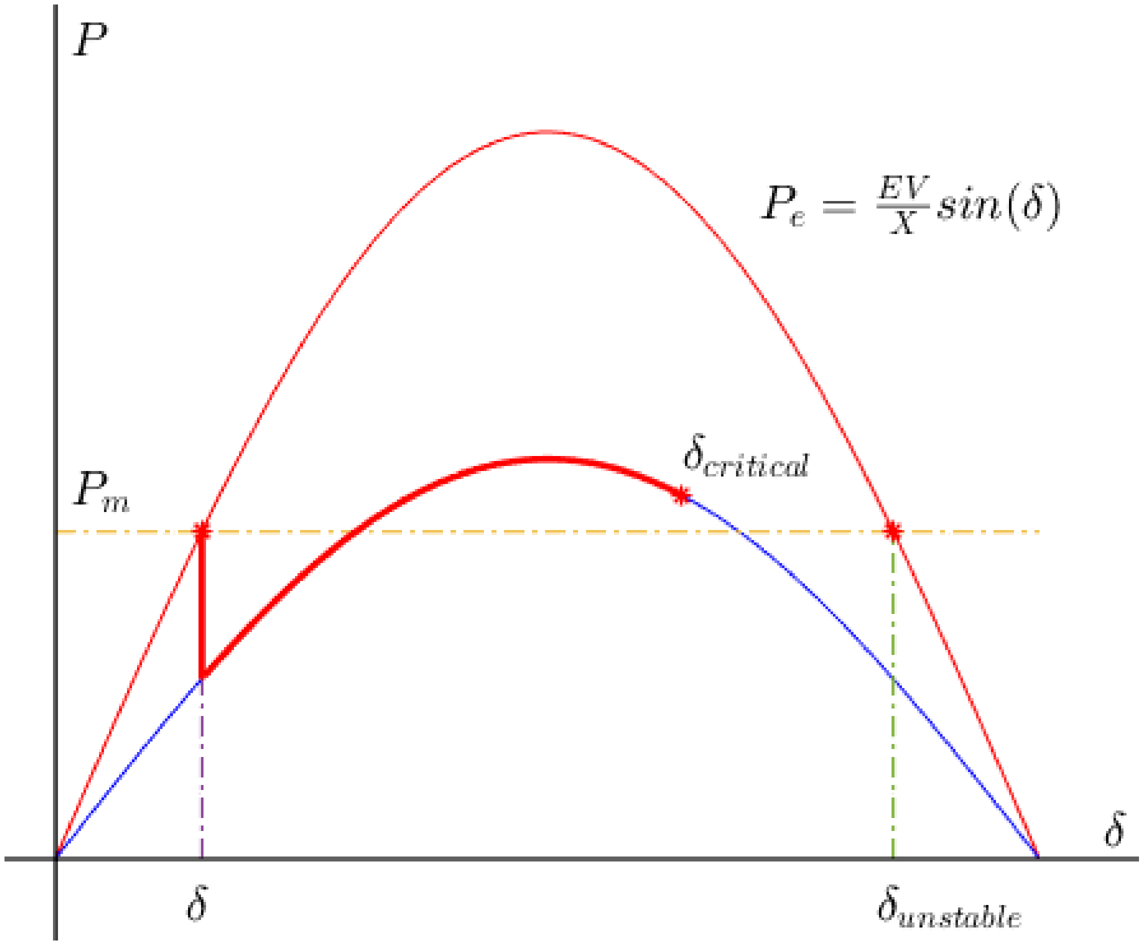


Figure 2.3: PV-curve during fault

which could result in cascading disconnections of loads. Undervoltages are the most common due to the mostly inductive loads of the Nordic synchronous system, but overvoltages may still occur[6][9].

Voltage stability may be divided into two sub-categories, namely small- and large-disturbance voltage stability. Large-disturbance voltage stability concerns the ability to maintaining adequate bus voltage magnitudes following a large disturbance, such as faults or loss of generating units, whereas small-disturbance voltage stability refers to smaller perturbations, such as incremental increases in the power demand. Furthermore, voltage stability can be separated into long- and short-term. Short term voltage stability is related to the dynamics of loads and HVDC-converters in a time-scope of seconds. Long-term voltage stability, on the other hand, is related to equipment such as tap-changers and current limiters of generating units. The time-scope of long-term voltage stability may exceed into minutes.

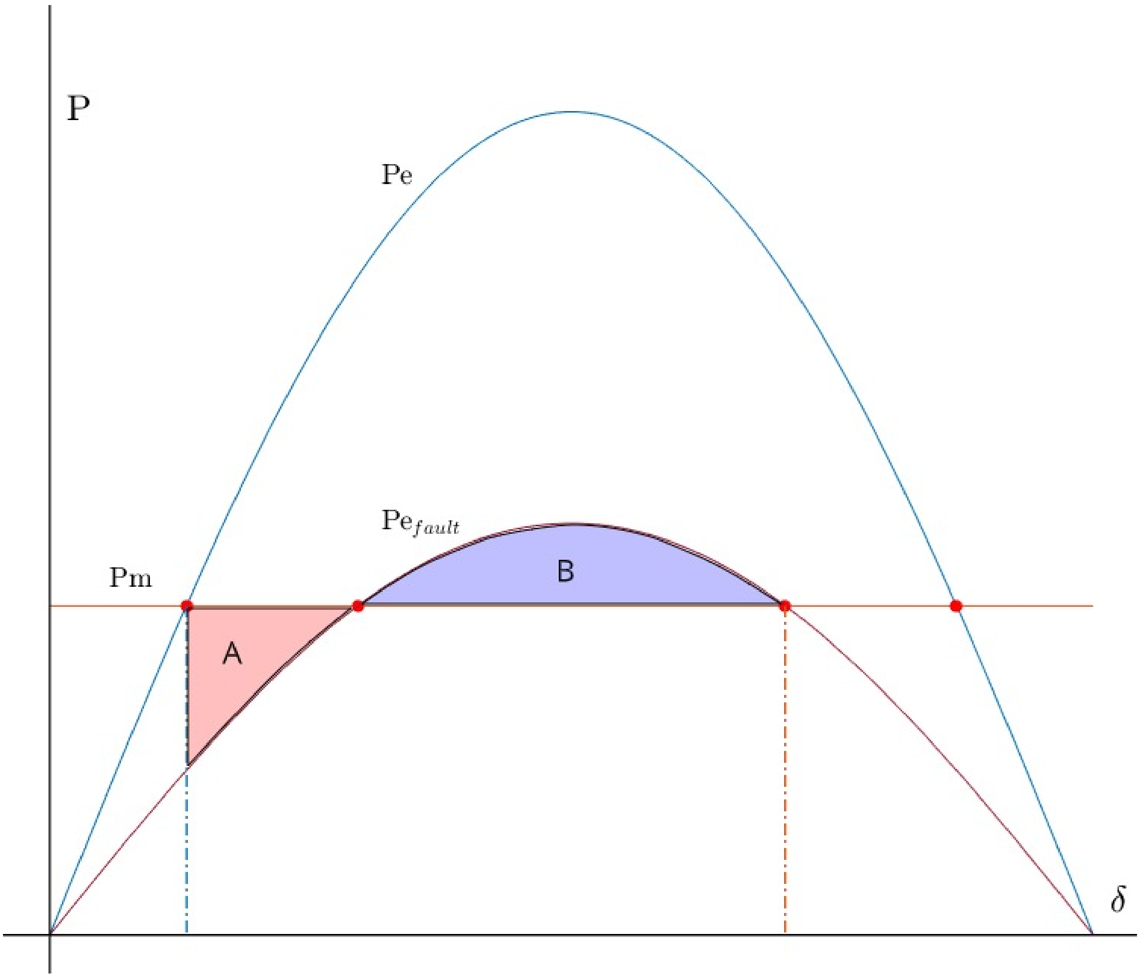


Figure 2.4: Equal area criterion

2.2 High voltage physics

High voltage physics refers to the physical phenomenons occurring during conditions of high electric potentials and strong electric fields. The power system, for transmission and distribution purposes, operates on high voltages which facilitates the need of understanding subject. This section introduces basic concepts in the field of high voltage technology.

2.2.1 Basic electrical field theory

The electric field (E-field), denoted as E, represents a fundamental concept in electromagnetism, characterizing the influence exerted by electric charges on the surrounding space. At its core, the electric field is defined as the force experienced by a unit charge placed within it.

Several equations govern the behaviour of electric fields, but the most fundamental in describing the dynamics of electric fields are Faraday's law and Gauss' law.
Faraday's law, expressed mathematically as:

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{2.5}$$

, which describes the relationship between changes in the electric field, E, and the time rate of change of the magnetic flux density $\frac{\partial B}{\partial t}$. One direct product of Faraday's law is electromagnetic induction, which is a fundamental principle behind operation of transformers and generators.

The electric field, E, may also be expressed as the divergence of the electric potential, or

$$E = -\nabla V \tag{2.6}$$

Gauss's law, another fundamental equation governing electric fields, states:

$$\nabla \cdot E = \frac{\rho}{\epsilon_0 \epsilon_r} \tag{2.7}$$

Here, ρ represents the charge density, ϵ_r is the relative permittivity, a non linear material property and ϵ_0 is the permittivity of free space.

2.2.2 Breakdown

Electrical discharge and breakdown are important phenomenons occurring within electrically stressed systems. As it is an inevitable consequence of high voltage systems it is important to have a grasp on the underlying physical mechanisms that interplay.

Electrical breakdown is the phenomenon that occurs when an electric field stronger than the dielectric strength is applied to a dielectric material. When the conditions of a dielectric breakdown are achieved, the previously insulating dielectric is able to transport charge and have consequently become conductive. The corresponding discharge manifests as an electrical arc, a result from the created plasma channel that is formed during the discharge[10]. There are several types of discharges occurring under widely different circumstances and manifesting different behaviours. In this report, electrical breakdown in gaseous medium is of particular interest. The physical mechanisms behind breakdown in gas is presented in the following section.

2.2.2.1 Breakdown in gas

Consider a parallel plate geometry in figure 2.5 surrounded by air with the applied voltage, U, over the anode, seperated by a distance, d, to the cathode. Due to cosmic radiation, air molecules are ionized and ion/electron pairs are generated. Being in the presence of a uniform electric field, E, the free electrons are accelerated towards the cathode. The accelerated electrons collide with ambient air molecules and, if achieved a certain kinetic energy (ionization energy), will ionize the molecule. The second free electron undergo the same process and, as a result, an avalanche is generated connecting the anode and cathode by a plasma channel[11]. This hypothesis is commonly referred to as the Townsend's breakdown phenomena and will be approached mathematically below.

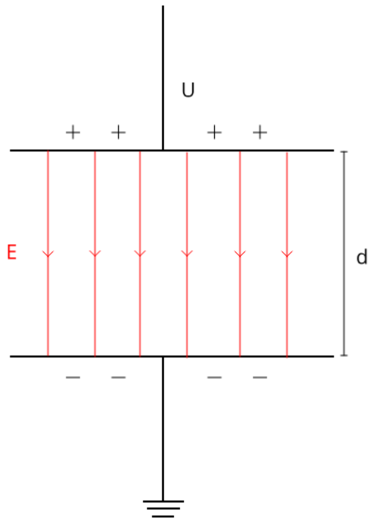


Figure 2.5: Basic electric field

Townsend's breakdown

The ionization energy, W$_i$, is a characteristic property of each gas. The first ionization potential may be defined as,

$$u_i = \frac{W_i}{e} \tag{2.8}$$

, where, e, is the elementary charge. If the collision is ionizing the electron must travel a distance $x \geq x_i$, where, w_i, is the ionization distance. 2.8 may be rewritten as,

$$Ex_i = u_i \tag{2.9}$$

Assuming the electron travels in a straight line and the probability of a collision during the traveled distance, Δx, is $\frac{\Delta x}{\lambda}$, where, λ, is the mean free path. The probability for no collisions during traveled distance, Δx, may be defined as

$$S(x + \Delta x) = S(x)(1 - \frac{\Delta x}{\lambda}).$$

Letting $\Delta x \rightarrow 0$ yields,

$$\frac{dS(x)}{dx} = -\frac{S(x)}{\lambda} \Rightarrow \frac{dS(x)}{S(x)} = -\frac{dx}{\lambda}.$$

Integration yields,

$$[ln(S(x))]_{S(0)}^{S(x)} = -[\frac{x}{\lambda}]_0^x$$

As such, the probability for no collisions may be expressed as

$$S(x) = e^{-\frac{x}{\lambda}} \tag{2.10}$$

The number of ionizing collision per unit length may be expressed as

$$\alpha = \frac{1}{\lambda} e^{-\frac{U_i}{\lambda E}} \tag{2.11}$$

, where, α, is Townsend's first ionization coefficient.

The average current may be expressed as

$$I = I_0 e^{\frac{\alpha}{d}}$$

Secondary process at the cathode may be defined as

$$I_0 = i_0 + \gamma I_+(0) = i_0 + \gamma I_0(e^{\frac{\alpha}{d}} - 1) \tag{2.12}$$

, where, γ, is Townsend's second ionization coefficient. It refers to the number of generated electrons at the cathode when hit by an ion. Combining 2.11 and 2.12 yields

$$I = \frac{i_0 e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \tag{2.13}$$

From 2.13 it can be observed that if

$$1 - \gamma(e^{\alpha d} - 1) = 0 \Rightarrow I \rightarrow \infty$$

This is reffered to as, Townsend's breakdown criterion which occurs at

$$e^{\alpha d} = 1 + \frac{1}{\gamma} \tag{2.14}$$

or at

$$\alpha d = ln(1 + \frac{1}{\gamma}) \tag{2.15}$$

Paschen's law

The mean free path, λ, may expressed as inversely proportional to the product of pressure, p, and a constant, A.

$$\lambda = \frac{1}{Ap} \Rightarrow \frac{\alpha}{p} = Ae^{-\frac{Bp}{E}}$$

, where B is another constant. Combing with 2.15 results in the following expression,

$$ln(1 + \frac{1}{\gamma}) = Apde^{-\frac{Bpd}{U_{bd}}}$$

Solving for, U_{bd}, resulting the following equation

$$U_{bd} = \frac{Bpd}{ln[\frac{Apd}{ln(1+\frac{1}{\lambda})}]} \tag{2.16}$$

2.16 is known as Paschen's law and it can be observed that breakdown voltage for a given gaseous medium, is a function of the gas pressure and the separation distance between the anode and cathode.

2.2.3 Electronegativity and electron affinity

As suggested in the section on Townsend's breakdown phenomena, the dynamics of *free electrons* is a vital parameter in regards to formation of electron avalanches and, ultimately, electric breakdown. Hence, it may be established that the attachment of electrons for a given gas plays an integral role to the dielectric strength. The concept of electron affinity and electronegativity is directly related to the attachment of electrons.

Consider an electron with low kinetic energy which collides with a neutral gas where the electron becomes attached. If the electron can find a position of lower potential energy in the gas molecule, the negative ion is stable. Electron affinity refers to the energy difference between the final and initial state, in other words, the released energy from the attachment process. Regarding high dielectric strength, it is required to have a high electron affinity[12].

Historically, the term *electronegative* gases have been applied to gases demonstrating high electron affinity. Such description is, from a physical point of view, false. Electronegativity relates to an atom's ability to attract electrons to itself.[13]. Although *electron affinity* is the relevant parameter when describing dielectric strength for gases, electronegativity and electron affinity demonstrates correlation. Electronegative gases create new energy levels where free electrons may be attached. Thus, electronegativity contributes to a higher electron affinity. This is the reason why fluorinated gases, which are highly electronegative, often display high dielectric strength[12].

2.2.4 SF_6

Sulfur hexaflouride, SF_6, is a highly electronegative gas with high electron affinity used widely in high voltage engineering applications. The molecular composition of SF_6 is given in figure 2.6. The dielectric strength of SF_6 is roughly 3 times higher than air[14], making SF_6 an unparalleled insulator. Thus, SF_6 finds a distinguished usage in GIS applications where the volume of the apparatus may be significantly reduced owning to the superior dielectric strength of SF_6.

Additionally, SF_6 displays favourable characteristics such as high thermal conductivity and arc quenching ability. As a result, SF_6 is highly used as insulating medium in high voltage circuit breaker[15]. Being able to quench arcs is not a direct result from high electron affinity, but rather rate of recovery of dielectric strength[16].

As stated in the introduction of the report, SF_6 is extremely effective at trapping infrared radiation, making SF_6 on of the strongest greenhouse gases ever known. Therefor there have been extensive research in finding alternatives with comparable electrical characteristics and lower climate footprint.

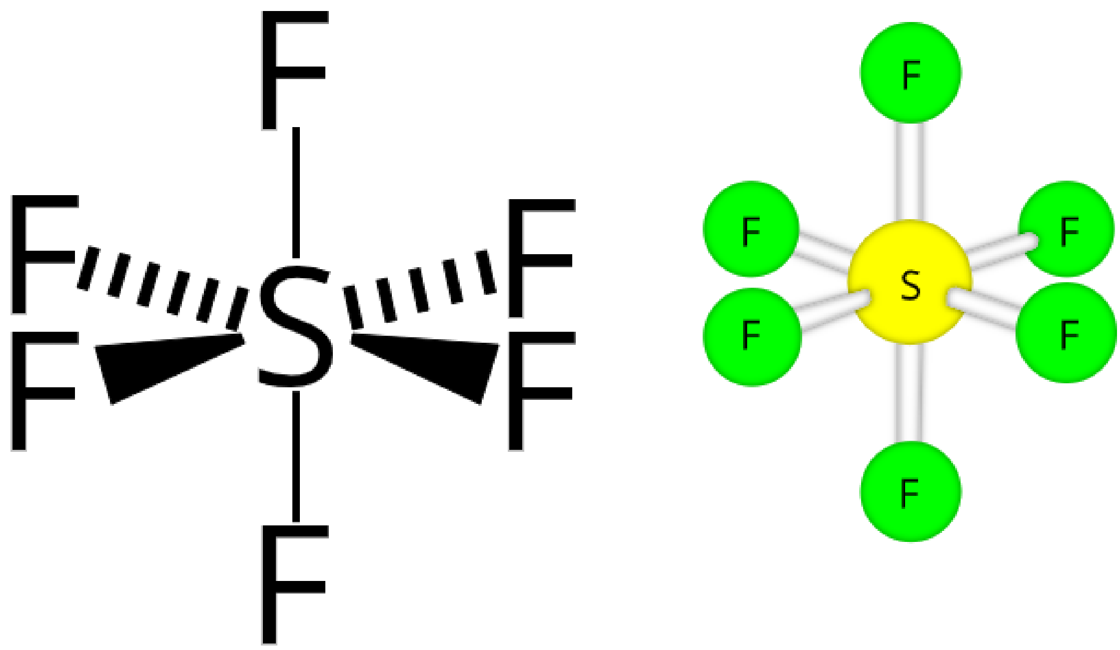


Figure 2.6: SF_6 molecule

2.3 Substation

A substation is a facility that plays a pivotal role in transmission and distribution of electricity. The primary role of the substation is to transform the voltage to either a higher or lower level, depending on the role of the particular station. Furthermore, the substation also serves as a hub for monitoring and control of the power grid. Substations varies in size and function. A typical substation consists of transformers, switchgear, protection systems, monitoring systems, and control systems. This section will provide a description high voltage circuit breakers, which are further discussed in this report.

2.3.1 Circuit breaker

A circuit breaker is a device found within electrical systems with the objective to carry and, when necessary, break the passing current. The circuit breaker mechanically separates the energized contacts and in applications with high voltage ratings, a resulting electrical arc is formed between the contacts. Hence, the objective is to additionally extinguish the arc, making medium with high electron affinity a requirement. The device come in several types, air blast circuit breaker, oil circuit breaker, vacuum circuit breaker and SF_6 circuit breaker[17]. The latter will be focused upon in this section.

2.3.1.1 SF_6 circuit breaker

Due to the excellent dielectric and arc-extinguishing characteristics of SF_6, SF_6 circuit breakers are widely used as switchgear in the distribution of electricity. There are two main categories of the breaker, dead-tank breaker and live tank breaker. Both offering advantages and disadvantages over the other[18]. A figure highlighting the components of a live tank circuit breaker is given in figure 2.7

The most crucial component of the circuit breaker is the interrupter. The objective of the interrupter is to separate the circuit breaker contacts, extinguish the arc between the contacts and as a result, interrupt the passing current. An axisymmetric drawing of an interrupter in open position is provided in figure 2.8. Additionally, a figure of a circuit breaker in closed position is provided in figure 2.9

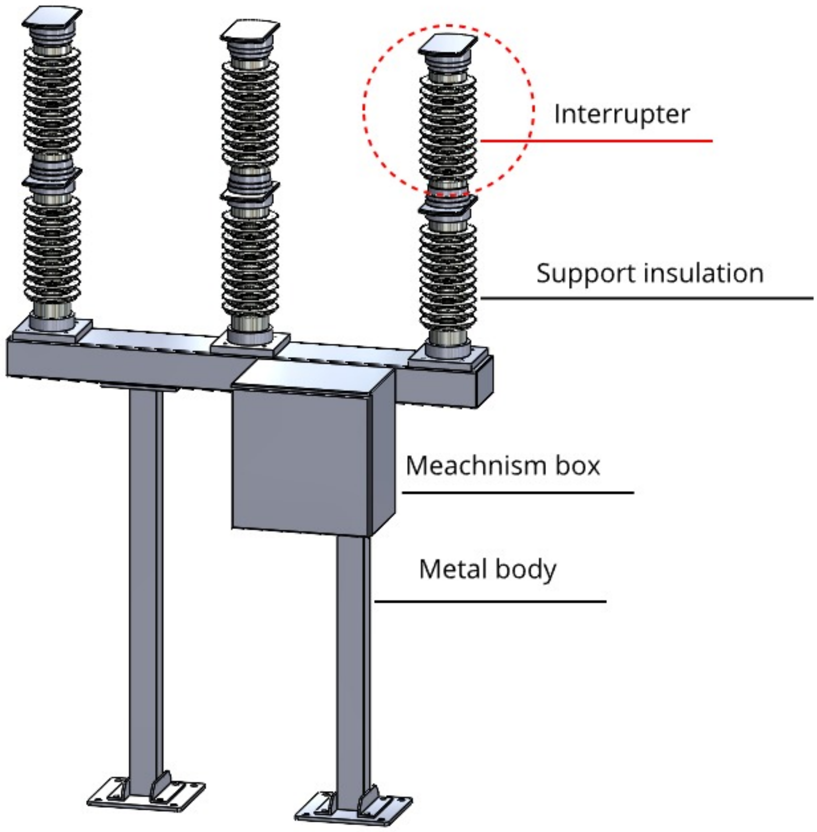


Figure 2.7: Parts of SF_6 circuit breaker, interrupter highlighted in red

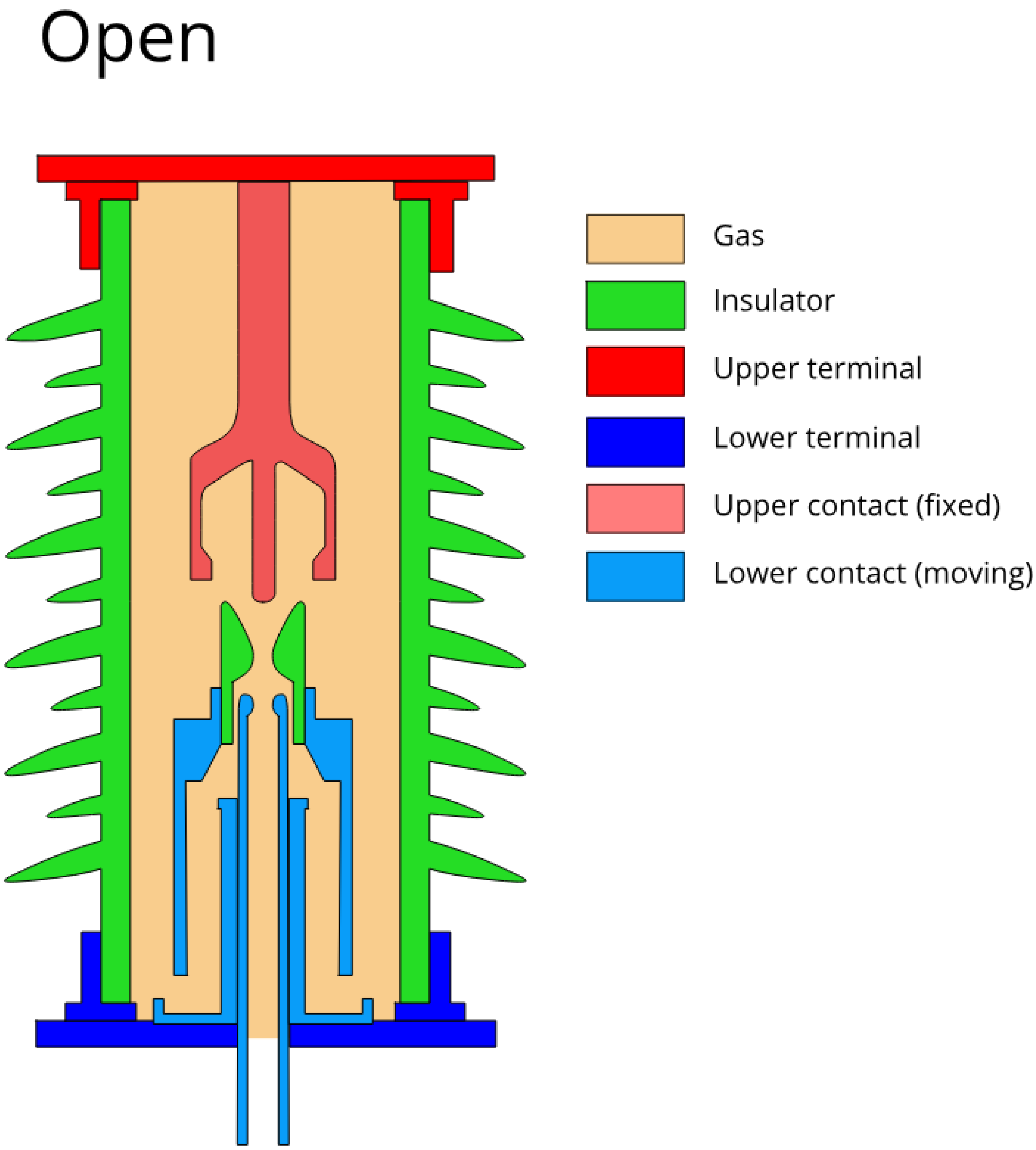


Figure 2.8: Sketch of interrupter in open position

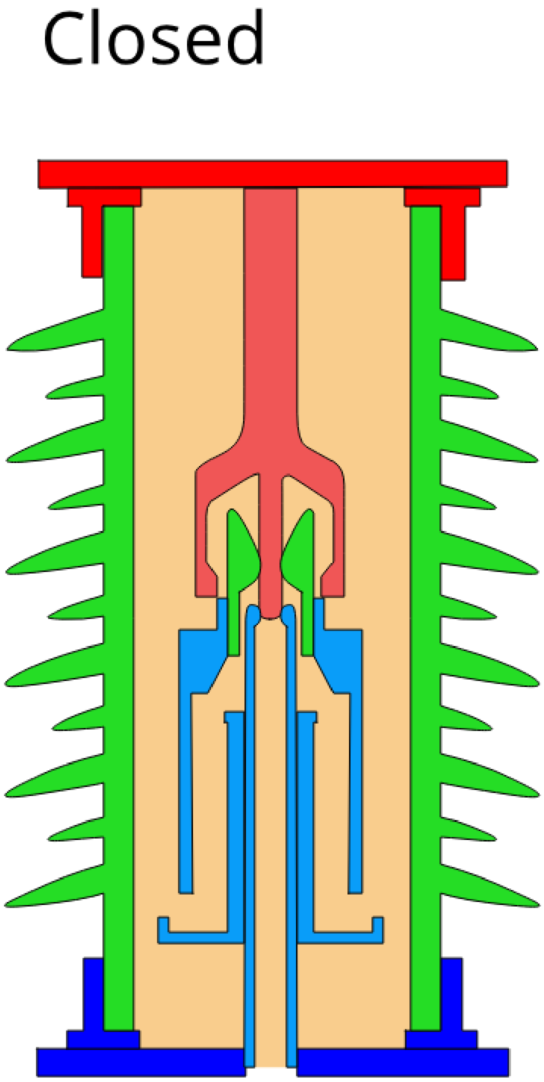


Figure 2.9: Sketch of interrupter in closed position

3
Methods

3.1 Mechanical drawing

To be able to evaluate the results of replacing an SF_6 breaker with an alternative a mechanical model of a substation needs to be made. The substation will be a 50 / 10 kV, air insulated substation with a design voltage of 72.5 kV. Furthermore, the model will focus the primary side of the substation. The model will contain: power transformer, disconnector, voltage transformer, current transformer, busbar, cable tray and circuit breakers. A two dimensional sketch of the substation is provided in figure 3.1. The station model will be created with the CAD software SolidWorks.

The SF_6 circuit breaker dimensions will be, to a certain extent, based on the live tank circuit breaker from Hitachi, refer to figure A.1 in Appendix 1.

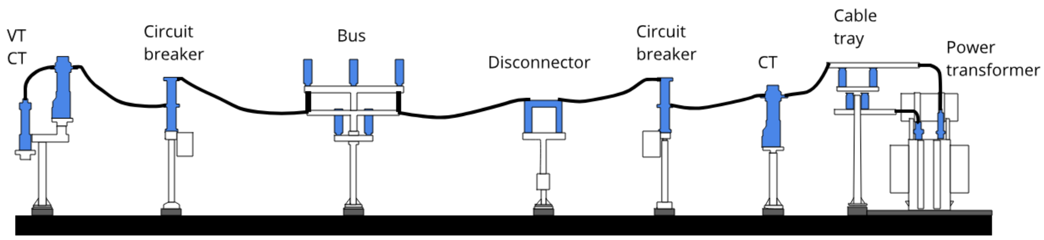


Figure 3.1: 2D sketch of substation model

3.2 Simulation

To be able to evaluate how the SF_6-free alternatives will affect the circuit breaker size electrostatic simulation will be conducted in COMSOL Multiphysics. The simulated geometry will be an interrupter from a SF_6-circuit breaker, see figure 3.2.

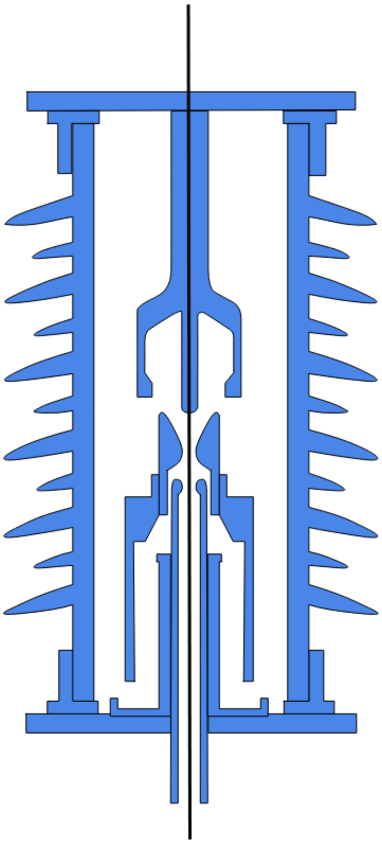


Figure 3.2: Simulated interrupter geometry

The steps of the simulation are summarized below.

1. Simulate electric field, E_n
2. Calculate critical field for the gas E_{crit}
3. Find ratio $\frac{E_n}{E_{crit}}$
4. Compare ratio with alternatives
5. Find scale factor that yields the same result as SF_6

3.2.1 Limitations

Since the simulated geometry is based on an SF_6-circuit breaker the alternative gases needs to be able to operate based on the same technology. Due to this, alternatives such as vacuum will not be able to assessed in the simulation. Furthermore, the geometry will be provided from the CAD-model of the substation. Hence, the breaker will be of Live-tank breaker type and should, theoretically, be able to operate in a minimum ambient temperature of - 40 ° C[19].

3.2.2 Critical field

Breakdown voltage may be derived by bond energy calculation. The bond energy refers to the required energy needed to break the chemical bonds in the molecule. Bond energy for certain chemical bonds are provided in table 3.1. Furthermore, the

Table 3.1: Bond energy in eV for various certain bonds

Bond	Bond energy [eV]
C = O	8.3
S - F	3.4
C - F	4.6
C ≡ N	9.23
C - C	3.6
O = O	5.18

Data from [20]

breakdown voltage may be expressed as

$$V_b = \frac{U_b}{Q_b} \tag{3.1}$$

, where, Q_b, is the amount of charge that is required for breaking the electric field ($226.6 * 10^{-6} C$ at atmospheric pressure and 1 cm[20]).

3.2.3 Comparing to alternative gases

From the simulation the normal electric field along the symmetrical axis may be extracted, see figure 3.2, black curve. Now the ratio between the normal electric field and critical electric field may be calculated. This process is iterated for every gas alternative.

To be able to find at what size the alternative gases corresponds to the same field ratio as SF_6 the *scale* function will be used in combination with a parametric sweep solution.

4

Literature study - Power system aspects

4.1 Swedish power production today

The Swedish power production 2022 is given by SVK[21]. The power production is distributed among hydroelectric power ($\simeq$ 43 %), nuclear power ($\simeq$ 31 %), wind power ($\simeq$ 20 %), thermal, such as, combined heat and power (CHP) ($\simeq$ 5 %) and $\leq$ 1 % of solar and unspecified power. The hourly and annual production reported by SVK is presented in figures 4.1 4.2 and 4.3 respectively[22]. Nuclear plant are continuously operated throughout the year, with power dips during the summer from maintenance. Hydroelectric power production is used in a regulatory manner in order to regulate the remaining required power demand. Swedish power production is characterized by large export and high power quality.

4.2 Future power system

In order to assess the future challenges for substations the future conditions of the Swedish power system needs to be evaluated. The consequences of integration of renewable based power production following the electrification of the transport and industry will be reviewed.

4.2.1 Electrification

The Paris agreement's long term goal is to keep the increased global temperature below 2° C. In order to accomplish the necessary goals to maintain the global warming within the desired limit, drastic reductions of greenhouse gases needs to be realized. One key element of addressing decarbonization is electrification of several sectors.

4.2.1.1 Industry

The transition from previously fossil fueled Swedish industry into an electrified sector is the most energy demanding part of the green transition. Today the required energy demand of the entire industry is 45 TWh[23]. The Swedish steel industry is introducing a new technology that allows for production of manufacturing of iron where the oxygen is removed by hydrogen gas. The removal of oxygen from the iron

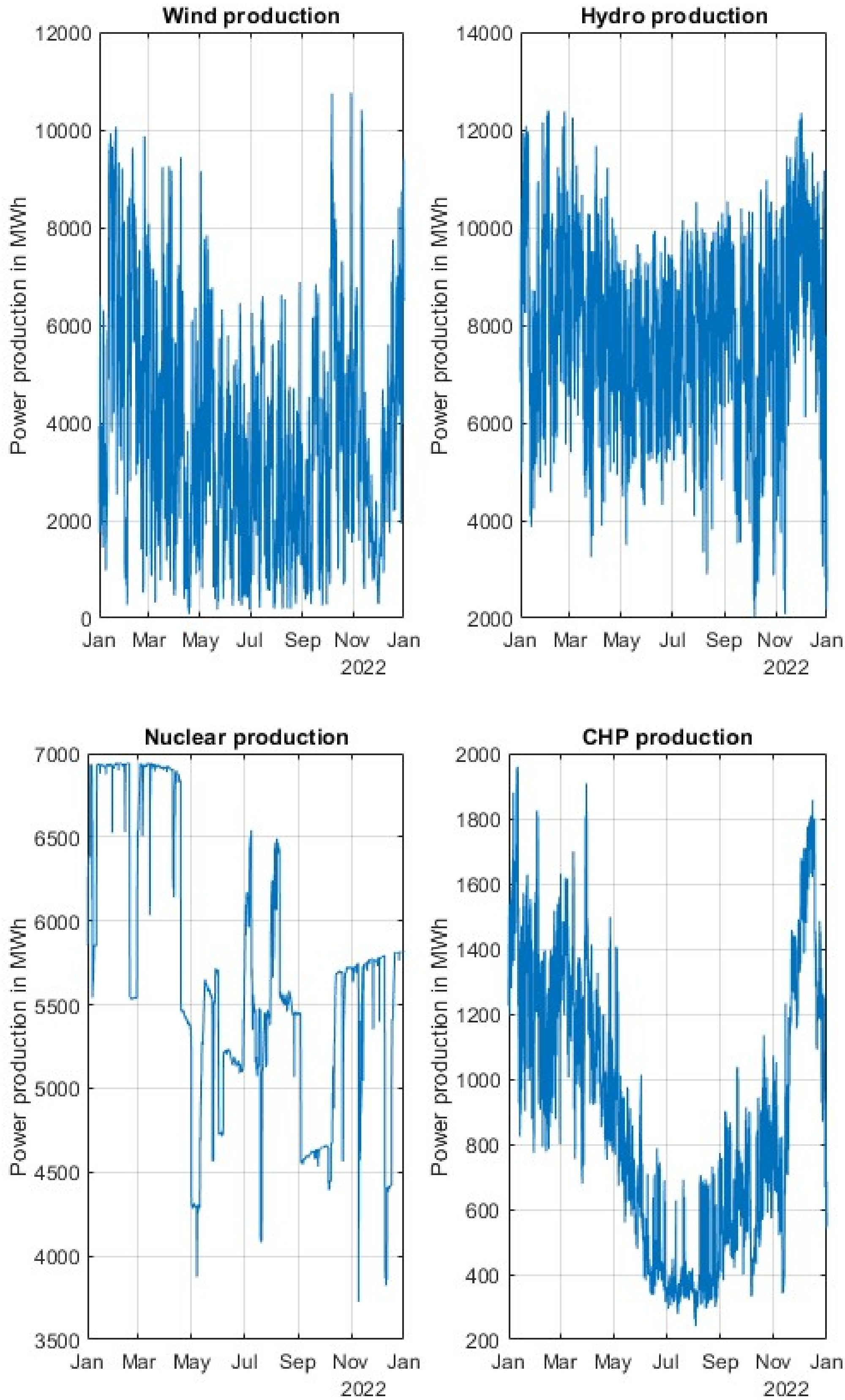


Figure 4.1: Hourly Swedish power production 2022 - wind, hyrdo, nuclear, CHP

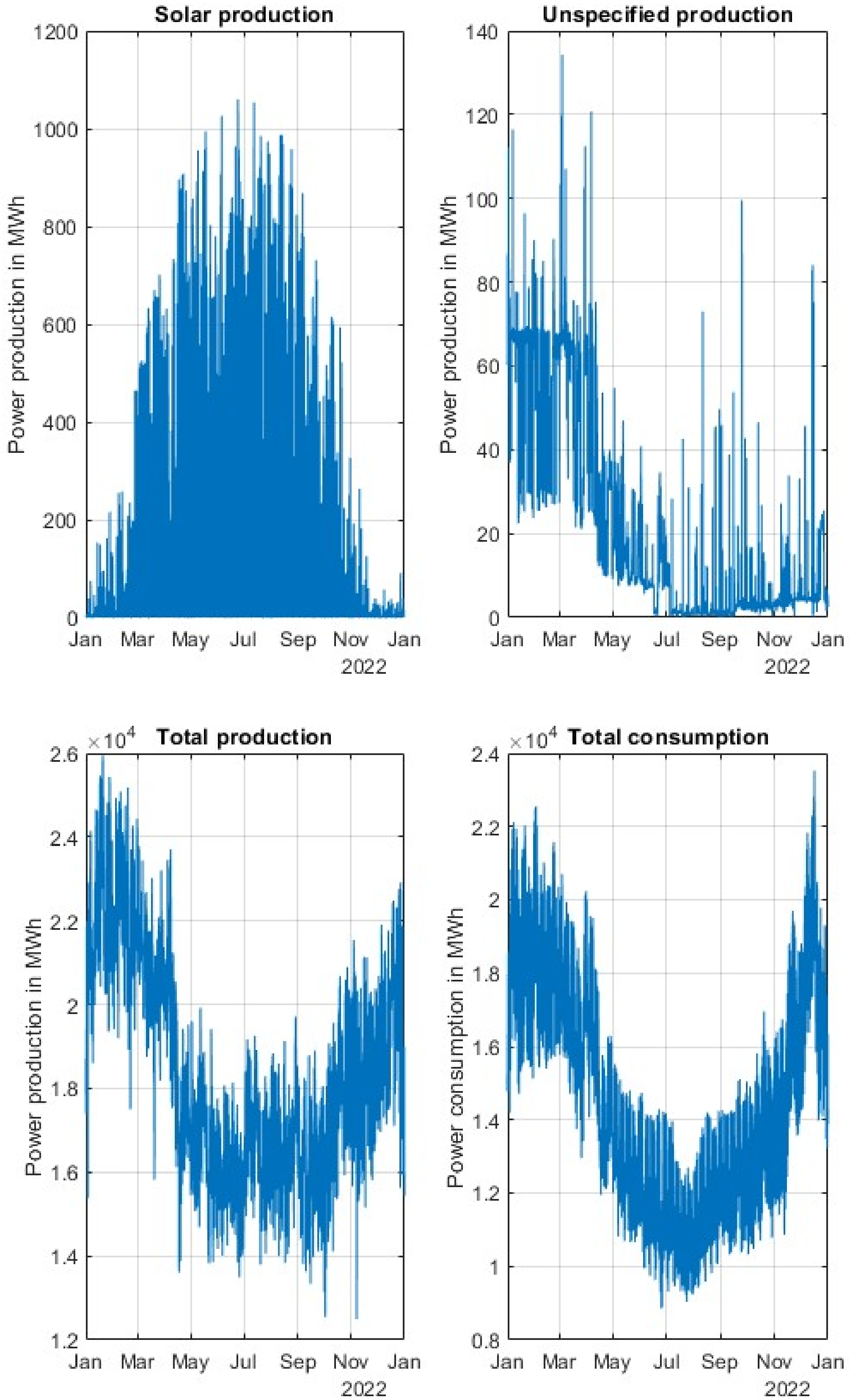


Figure 4.2: Hourly Swedish power production 2022 - solar, unspecified, total production, total consumption

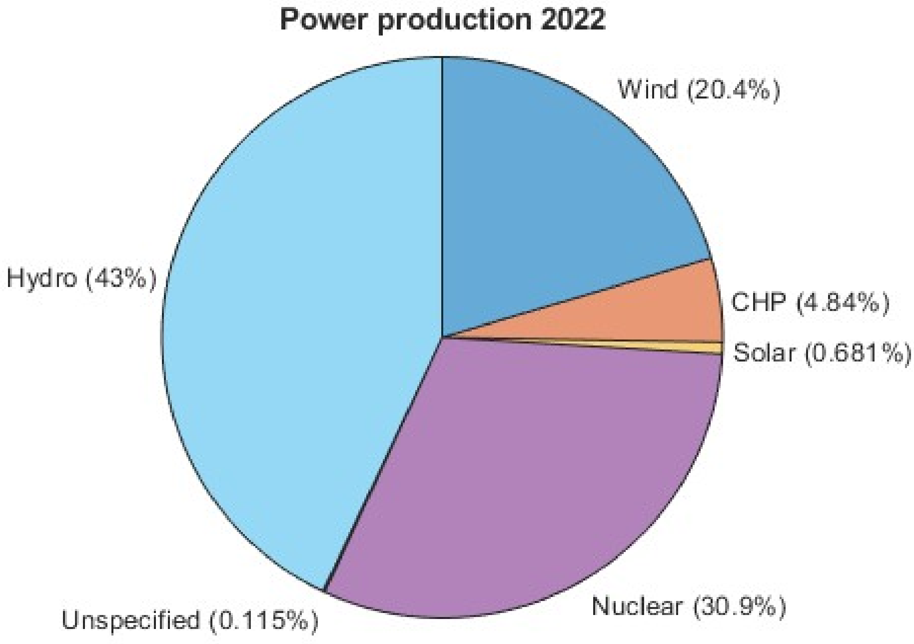


Figure 4.3: Swedish energy mix 2022

is essential for steel production and by using hydrogen gas, the byproduct is water instead of CO_2 which is the byproduct from traditional steel production[24]. Additionally, as new mineral reserves are being found, the steel production increases[25]. The required annual energy from the steel production is expected to be 55 TWh[26] electrical energy.

4.2.1.2 Transport

The electrification of the transport sector is essential to achieve the necessary climate goals. As of 2023, 80 percent of the vehicle energy consumption is supplied by fossil fuels[26]. Companies such as Volvo and Scania are completely replacing their fossil fueled car sand trucks with electrified vehicles[27].

4.2.1.3 Hydrogen gas

Production of hydrogen gas is expected to be a huge consumer of future power production as it is coupled with the electrification of the industry, see 4.2.1.1. The expected energy demand is predicted to be in the range of 22 - 100 TWh annually by 2050[28]. Due to the huge energy demands, hydrogen technology will have a considerable impact of shaping the future electrical system. The technology could also be applied to the transport and vehicle industry in order to reduce emissions, but is currently not economically possible in an industrial scale[29]. Furthermore, the technology also has potential in energy storage applications[30].

4.2.2 TSO's future analysis

The Swedish power system will expand in the future in order to fulfill the Paris agreement, where electrification is one of the most fundamental parts. In 2021 and 2024 the Swedish TSO(Transmission System Operator) Svenska Kraftnät(SVK) have made a long term market analysis with 4 different scenarios regarding the future power production and its corresponding challenges and required actions on the transmission system[31][32]. The four different scenarios are:

- SF - Small scale renewable (Småkaligt Förnybart)
- FM - Flight plans mixed (Färdplaner Mixat)
- EP - Electrification planable (Elektrifiering Planerbart)
- EF - Electrification renewable (Eletrifiering Förnybart)

Each scenario will be discussed below. The analyses both use the same four scenarios, but in the 2024 analysis, the consumption in each scenario is drastically increased. The differences in production predictions by the year 2045 from the analyses are presented in table 4.1.

Table 4.1: Prediction differences 2021 and 2024 analysis

	2021	2024	2021	2024	2021	2024	2021	2024
	SF		**FM**		**EP**		**EF**	
Consumption	174	200	188	250	266	343	286	342
Nuclear	0	0	14	58	55	110	0	0
Wind on-shore	76	133	88	96	85	96	98	168
Wind off-shore	6	3	29	7	39	24	113	66
Solar	28	13	8	15	11	16	18	22

Data from [32][31]

Scenario - SF

In the SF scenario from 2024 the electricity consumption will rise to around 200 TWh in 2045, where the power demand primarily is a result of the electrification of the industry, albeit less extensive than the other scenarios, and transport sectors. The SF scenario predicts a high focus on energy efficiency and governing of resources. Small scaled, decentralized production due to economical incitements with high integration of both wind and solar. Nuclear reactors are expected to gradually close and fully decommissioned by 2045.

As a result of the decommissioning of the southern nuclear power plants large power flow will occur between the north and south, making reinforcement of the transmission grid necessary. The increase of renewable based power production, which causes fluctuations in frequency and voltage, as well as lowered utility of planable power results in challenges related to operation and stability.

Scenario - FM

The FM scenario predicts an annual power demand of 250 TWh in 2045. Increased power production from renewable based production and 2 remaining nuclear reactors. Great expansion of solar energy due to lowered prices, but in a smaller extent in comparison of SF.

Scenario - EP

In the EP scenario a drastic power demand is predicted in Sweden as well as the whole of Europe. The renewable based production is expanded as well as the planble. The Swedish demand is predicted to be around 343 TWh, with a slightly higher production.

Investments in nuclear power results in a prolonged lifetime. In this scenario support of new nuclear power is found politically and new reactors built in area SE3. Furthermore, hydrogen gas is an important feature to the system.

Scenario - EF

The EF scenario predicts the highest power demand with almost doubled consumption around 342 TWh, annually and a slightly higher production. EF also predicts a huge expansion of power delivered to H_2-gas applications, with a consumption of 86 TWh by 2045. Furthermore, in the scenario off-shore wind power is predicted to be the main contributor of the annual power production.

4.2.3 Swedish Energy Agency's future analysis

The Swedish Energy Agency published a long term analysis of the Swedish electrical power system in 2023[28]. The Swedish government has launched a plan for integration of new nuclear power plants, see 4.2.4, but as the reforms have only been announced and not yet decided, the publication have not been able to consider the reforms in the proposed future scenarios.

The publication suggests three different future scenarios: Higher electrification, Lower electrification, Sensitivity case industry.

Higher electrification

The scenario *Higher electrification* predicts a considerable electrification of society. The scenario predicts a higher electrification grade in the Nordic countries compared to the EU average. Establishment of highly energy demanding industries are assumed, a result of the demand of sustainable products from the consumers, such as: carbon free steel and batteries. The transport sector is electrified to a large extent. Increased energy demand from servers and electrified machinery is predicted.

In the scenario an annual expansion of power production in order to meet the demand needs to be in the range of 3.5 TWh/year between the years 2021 to 2030.

Afterwards, between the years 2030-2035 the expansion rate is further increased to 12 TWh/year. In terms of power production, each power type needs to be expanded. The greatest potential is found in new nuclear power and off/on-shore wind. The energy balance presented in table 4.2.

Table 4.2: Predicted energy usage/supply - Higher electrification case

Higher electrification - energy balance [TWh]						
Data from [28], A.2: table 11		2020	2025	2035	2045	2050
Usage	Industry	47	54	128	172	187
	Transport	2.9	7.3	23	37	41
Supply	Nuclear	47	52	52	66	66
	Wind	28	51	123	156	179
	Solar	1.0	3.1	7.4	18	32
	Import-export	-25	-41	-18	-4,2	-13

Lower electrification

The *Lower electrification* scenario, as *Higher electrification*, predicts an expansion of the power production. But several complications are expected, such as, too slow expansion of the electrical power production and electrical grid compared to the increasing demand. The electrification of industry is predicted to be lowered than in *Higher electrification* due to no increase in the extraction of iron to the steel industry, disabling the high energy demands. Lower electrification is also predicted for the transport sector as compared to *Higher electrification*.

Three existing nuclear power plants see a prolonged lifetime, with new plants being established in the future. The greatest increase in energy production can be found in wind power. *Lower electrification* predicts a lower expansion of off shore wind, 21 TWh by 2050, in comparison to *Higher electrification*, 57 TWh 2050. Energy export is assumed to be lower than import. The energy balance presented in table 4.3.

Table 4.3: Predicted energy usage/supply - Lower electrification case

Lower electrification - energy balance [TWh]						
Data from [28], A.1: table 3		2020	2025	2035	2045	2050
Usage	Industry	47	50	104	130	132
	Transport	2.9	6.6	18	27	30
Supply	Nuclear	47	52	52	28	31
	Wind	28	51	86	130	130
	Solar	1.0	3.1	7.1	9.4	13
	Import-export	-25	-47	-18	2.8	6.0

Sensitivity case industry

Sensitivity case industry has the same foundation as *Lower electrification* but the industry's and transport sector transition into being electrified is delayed.

The sensitivity case predicts a prolonged lifetime of existing nuclear power plants, but with investments into new nuclear power is non-profitable. Sweden remains a large exporter of power throughout the sensitivity case. The energy balance presented in table 4.4.

Table 4.4: Predicted energy usage/supply - Sensitive case industry

Sensitivity case industry - energy balance [TWh]						
Data from [28], A.3: table 19		2020	2025	2035	2045	2050
Usage	Industry	47	50	67	91	97
	Transport	2.9	6.7	18	29	32
Supply	Nuclear	47	52	52	28	28
	Wind	28	51	70	116	127
	Solar	1.0	3.1	7.4	9.4	9.4
	Import-export	-25	-48	-39	-25	-21

4.2.4 Political aspects

The Kristersson Cabinet launched November 2023 a plan for an expansion of new nuclear power with a massive long term expansion. The ambition of the proposition is that around ten new reactors should be operating by 2045. A coordinator has been elected with the purpose of simplifying the process[33].

Continuous operation of old nuclear power plants and, if necessary, the establishment of new nuclear power have found support from a majority of the Swedish citizens in opinion polls, with only 1/10 of the participants possessing the opinion that Swedish nuclear power should be decommissioned. The support of new nuclear power have increased significantly over the past decade[34][35][36].

The Kristersson Cabinet has given permission for three different applications of offshore wind power parks as of November 2023 with an additional 14 applications under review. These permitted parks include, Kriegers flak, Galene and Kattegatt syd, which are expected to produce 2.7, 1.7 and 5 TWh respectively. Offshore wind power is believed to play an important role in the future European energy generation[37][38][39][40].

4.3 Integration of renewables - Consequences

Regardless of a future expansion of the Swedish nuclear power generation the Swedish energy mix will posses RES with high penetration. This sections reviews the consequences of having a high share of renewable based power production in the power system. It should be emphasized that this section only reviews the *downsides* of RES integration. There are several beneficial aspects of RES integration, but they are not reflected upon in this section.

4.3.1 Power quality

Traditionally, the power generation is found in large power plants that are centrally controlled. Renewables, on the other hand, are usually smaller scaled and distributed within both the transmission and distribution system and independently controlled. Due to wind and solar being, to some extent, unpredictable in their power production as a result of the weather dependency, power quality issues related to frequency and voltage are found[41].

From 2.4, frequency will increase when the produced power is larger than the consumed and decrease when the power production is smaller than the power consumption. As a result from the variations in power production from renewables, as well as negligible inertia, the risk of frequency instability increases. The Swedish TSO has reported a negative trend in frequency stability. Maintaining nominal frequency is crucial for maintaining stability in the system. Over/under frequencies leads to increased aging of equipment, higher losses, temperatures rises, insulation damage and more [4]. Frequency instability could result in load shedding, generator tripping and activation of other protection equipment, resulting in a cascading effect.

Additionally, voltage fluctuations are correlated to power fluctuations. Maintaining voltage stability is crucial for maintaining continuous operation. Overvoltages have potential consequences such as, potentially harming people, damaged insulation, flashovers, overheating. Undervoltages increases power losses since current is increased, higher heating losses and risk of equipment damage and failure. Voltage instability have serious consequences on the operation of the power system. Power losses, damaging/aging equipment, overheating, line tripping and flashovers are all consequences related to both transient and continous voltage instability.

Harmonics are distorted waveforms of the fundamental voltage and current waveform. Since only the fundamental components deliver active power, high harmonic content leads to increased reactive power and power losses, malfunctions of generators, unwanted trippings of circuit breakers or fuses, disturbances in electronics and more[42][43].

Solar power generates DC, which must be converted to AC in order to be interconnected with the synchronous AC power system. For solar as well as wind power plants, the DC to AC conversion is carried out by utilization of power electronic converters. Power electronic converters offers several beneficial advantages, such as, reliability, cost effective, simple. However, the converter additionally generates low order harmonics. In the case of wind power, power converters are used to be able to utilize variable speed and power control. Harmonic components are injected to the system from wind power[44].

Harmonics generated by the switching of the power electronics devices is not the only source of harmonics from RES. Harmonics generated as multiples of the grid frequency may be found at the point of common coupling[45].

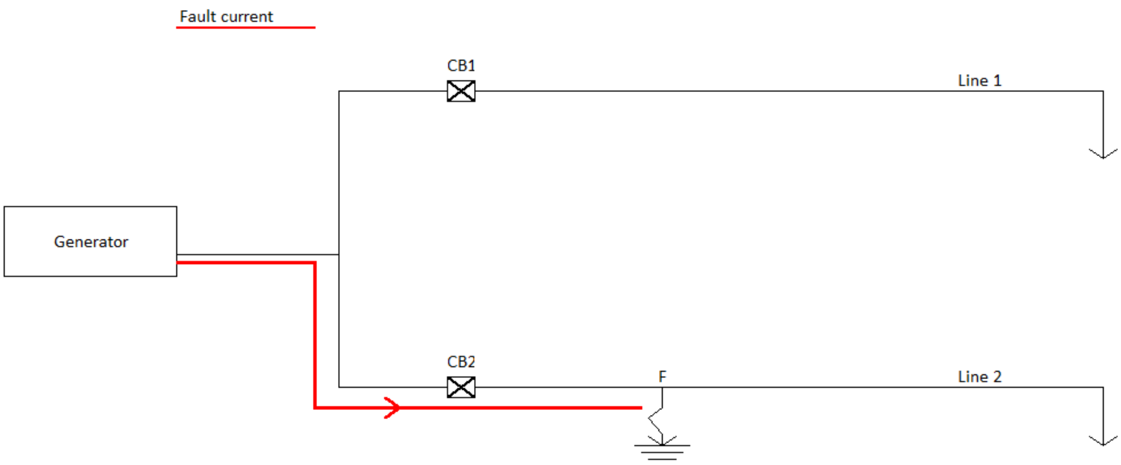


Figure 4.4: Generic network topology without DG

4.3.2 Distributed generation

The term distributed generator (DG) finds no fully accepted definition within the available literature regarding the technology. The US department of energy provides a definition of DG as a application of a small either standalone or integrated energy production installed in the vicinity of load centers. Technologies such as, PV, wind turbines, fuel cells, combustion turbines, micro-hydro turbines and are all examples of DG units. IEEE provides a definition as a power generator smaller than 10 MW that may be interconnected at any point in the grid[46].

DG-units also come with their disadvantages. When a DG is added to a power network, the flow of power will become more complicated. Different current magnitudes will be found in different locations of the network under normal operating conditions as well as during fault conditions. Integrating multiple smaller power sources alters the system topology from a traditionally radial network into a meshed bidirectional system. Such a transformation inflicts challenges for the protection system of the network[47].

Consider a simple power network with a source and two feeders protected with a overcurrent relay, see figure 4.4. Downstream short circuit on line 1 leads to fault current flowing from the source, through the breaker. The overcurrent relay measures the current amplitude and sends a signal to the circuit breaker which trips the line. The fault is successfully cleared.

Now consider the same network with two DG's connected to each feeder, see figure 4.5. Same fault is applied as before, now fault current from the power source as well as the two DG's flow to the fault. If the fault current magnitude from DG 2 is large enough, an unwanted tripping of breaker 2 will occur. A new protection scheme needs to be utilized after connecting the DG's.

[48] specifies *five* power system protection related issues emerging from interconnec-

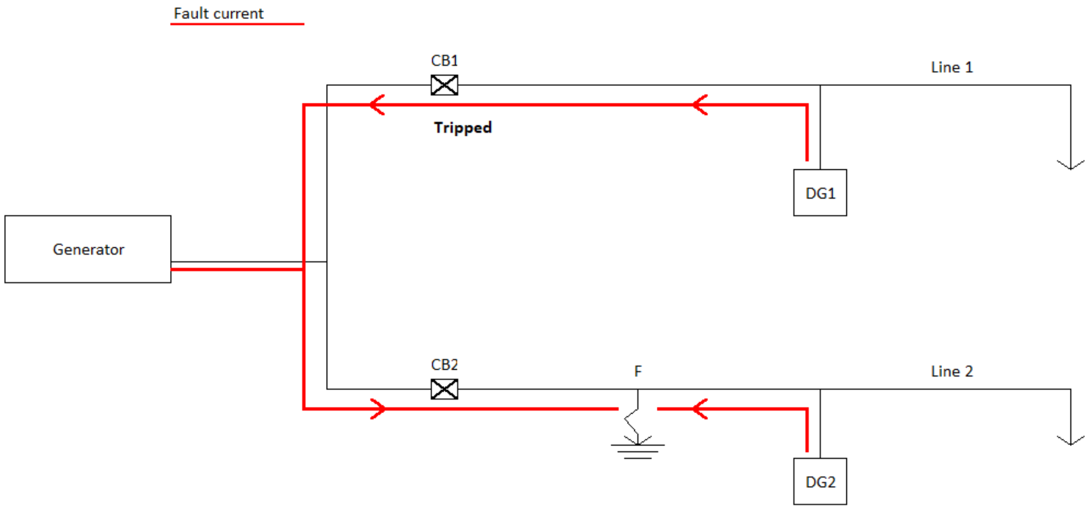


Figure 4.5: Generic network topology including DG

tion of DG units. The identified issues include:

1. Relay desensitization
2. Unintentional islanding
3. Nuisance trippping
4. Automatic reclosers out of synchronism
5. Ferroresonance

1. Relay desensitization

Fault current contribution from a DG results in a voltage increase along the feeder. The voltage difference between the feeder and generator terminal decreases, resulting in a smaller magnitude fault current seen by the relay. The relay has become *desensitized*, and may not operate as intended during fault conditions.

2. Unintentional islanding

Unintentional islanding refers to the state when a fraction of the distribution system is isolated from the rest, and still being energized by the connected DG. Island operation for DGs are undesirable as it may negatively affect the power quality of the system.

3. Nuisance tripping

Nuisance tripping refers to the event of unwanted tripping during normal operation, without fault. For instance, transient current from starting an induction motor. As DGs alters the impedance characteristics of the system, conventional relay coordination may not be able to distinguish transients from fault.

4. Automatic reclosers out of synchronism

DG may continue operating during the open interval of the automatic recloser, resulting in a continued feed of the fault which could lead to failed arc extinction of the automatic recloser, leading to an unsucessful reclosing. The reliability of the system is weakened as failing to reclose will result in a complete trip of the breaker.

5. Ferroresonance

During island operation with the DG as the primary source, ferroresonance may occur. During ferroresnonance, voltage magnitdues reaching 3-4 p.u. is a possibility for both SG and induction generators. According to [48], there are 4 conditions that needs be satisfied in order for ferroresonance to occur. The DG must be operating in islanding condition, the DG must be abple to supply the nessecary load, a transformer must be wihtin the island of operation as a non-linear reactance and a capactive coupling to ground in the range of 30-400 % must be present.

4.4 Integration of renewables - Solutions

In summary, integration of renewables causes challenges for configuration of protection schemes, owning to the fact that renewable energy sources are intermittent and distributed within the system. Issues related to power quality can be summarized as:

- Frequency oscillations
- Voltage oscillations
- Harmonics

Strategies to deal with discussed issues will be addressed below.

4.4.1 Maintaining stability

Power quality is closely related to the *stability* of the system. Strategies how to increase stability will be discussed in this section.

4.4.1.1 Frequency ancillary services

SVK utilizes several services in the context of frequency stability. These services are market based and are composed of power reserves purchased from actors on the balance market. The power reserves are categorized into three categories. These include, Fast Frequency Reserve(FRR), Frequency Containment Reserve(FCR) and Frequency Restoration Response(FFR), which exhibits different characteristics and purposes[49][50]. An overview of the Nordic ancillary services are provided in table 4.5.

Table 4.5: Frequency ancillary services in the Nordic synchronous system

	FFR	**FCR-D up**	**FCR-D down**	**FCR-N**	**aFRR**	**mFRR**
Regulating purpose	Up	Up	Down	Up/down	Up/down	Up/down
Activation	Automatic at frequency deviations at low rotational energy	Automatic within 49.9-50.1 Hz	Automatic within 50.1-50.5 Hz	Automatic within 49.9-50.1 Hz	Automatic at 50 Hz deviation	Manual by request
Endurance	30 s alt. 5 s	20 min	20 min	1 h	1 h	1 h

The purpose of FFR is to achieve the necessary utility in order to manage the transient frequency deviations that occurs when operating with low rotational energy in the system[51].

The purpose of FCR is to stabilize the frequency following a deviation. FCR in the Nordic system is compromised of Frequency Containment Reserve Normal(FCR-N) and Frequency Containment Reserve - Disturbance(FCR-D) which are further composed of FCR-D up and FCR-D down. FCR-N is activated following a frequency deviation under normal operation wheras FCR-D is activated following a disturbance providing appropriate upwards or downwards regulation[52][53].

In order to restore the frequency back to nominal following a disturbance Frequency Restoration Response(FRR) is used. The service can either be activated automatically (aFRR) or manually (mFRR)[50].

Battery energy storage have the potential of becoming an important tool in the future, following the expansion of renewable based production[54]. The technology can be used for, among other applications, FCR-D and FRR. The increasing demand of stabilizing back up power in the system have resulted in investments from several actors in the energy market[55].

4.4.1.2 Energy storage

With the ongoing trend of decommissioning of nuclear power in addition to a significant increase in power electronic converter based generation from RES system is inertia is steadily reduced. From 2.4, reduced inertia results in a higher rate of change of frequency and, subsequently, a weakened frequency stability[56]. Power system inertia reflects the system's rotational energy which is, for a transient time period, maintained following a disturbance in the system power balance. Inertia may be provided by other means, such as discharge of an energy storage. Energy storage exists in widely different forms such as hydroelectric dams, rotating flywheels, supercapacitors and batteries.

Battery energy storage solutions (BESS) offers heightened reliability and power quality to the power system by providing frequency support and mitigation of peak load. The technology is expected to play a major role in the future decarbonization of human civilization[57].

4.4.1.3 FACTS

Reactive power is an important factor related to voltage magnitudes. Voltage drops occurs due to flow of apparent power through the inductive reactances exhibited by the transmission system. Power transfer and voltage support becomes limited due when high reactive power is being transferred. When reactive power demand is increased following a disturbance with limited reactive power generating resources, voltage stability is threatened[6].

FACTS are devices found in both transmission and distribution systems that enable control of reactive power flow in a given location and as a result, provides controllability of voltage and active power flow. Several devices exists in the FACTS-family and may be categorized into series and shunt compensators.

One example of a shunt compensating device is the Thyristor controlled rectifier (TCR). The TCR is a device that consists of two anti-parallel connected thyristor in series with an inductor, see figure 4.6. By changing the firing angle of the thyristors and as result, the current through the device, the reactance of the device is changed from a system point of view. As a result, voltage may be controlled[58].
Series compensation can be realized by both active and passive devices. Since the reactance of a series device is

$$Q_{compensator} = I^2 X_{compensator} \tag{4.1}$$

, the device provides reactive power compensation passively and as a result, only a capacitor or inductor is needed to perform series compensation.

Series compensators are able to increase active power flow to a greater extent than shunt compensators[59]. As a result, transient stability is increased due to the increased active power flow[60], which results in a larger deacceleartion area considering the equal area criterion, refer to figure 2.4.

In comparison to shunt compensators, series compensators require more extensive protection. In the event a fault, since the device is connected in series, the full fault current will run through the device. A typical protection system of a series compensator may consist of a bypass breaker, spark gap, damping inductor, varistor and more.

FACTS-devices mainly concerns the transmission system. FACTS in the distribution system are sometimes refereed to as D-FACTS. One example of a device in the D-FACTS category is the dynamic voltage restorer (DVR). The DVR is a series connected voltage source converter that injects voltage to a line in order to mitigate

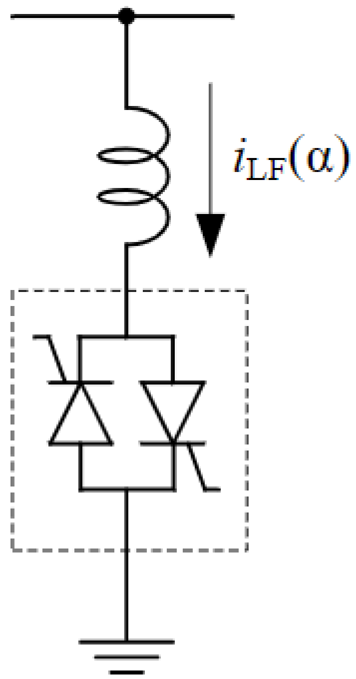


Figure 4.6: TCR: Circuit diagram

voltage dips by injecting reactive power, see figure 4.7. It is also capable of acting as an active filter. The disadvantages of the device is that it is unable to mitigate voltage interruptions and similar to that of the series compensator, require extensive protection[61].

A device found both in distribution as well as transmission system application is the static VAR compensator (STATCOM). STATCOM is a shunt connected VSC that injects current into the line. The device is used as for voltage dip mitigation, reactive power compensation and active current filtering. It can also be used to suppress flicker and voltage fluctuations[61] and mitigate harmonics. Circuit diagram of a STATCOM is presented in figure 4.8.

D-FACTS are mainly deployed and paid directly by customers with high power quality demands. FACTS are deployed, as the name suggests, in the transmission system by the TSO. Although FACTS devices have several positive qualities, they have disadvantages that disable them from widespread usage. FACTS-devices are expensive, both investment cost and maintenance[62].

4.4.2 Reducing harmonic content

As previously discussed, integration of renewable based power results in higher harmonic content. Harmonic mitigation strategies are presented below.

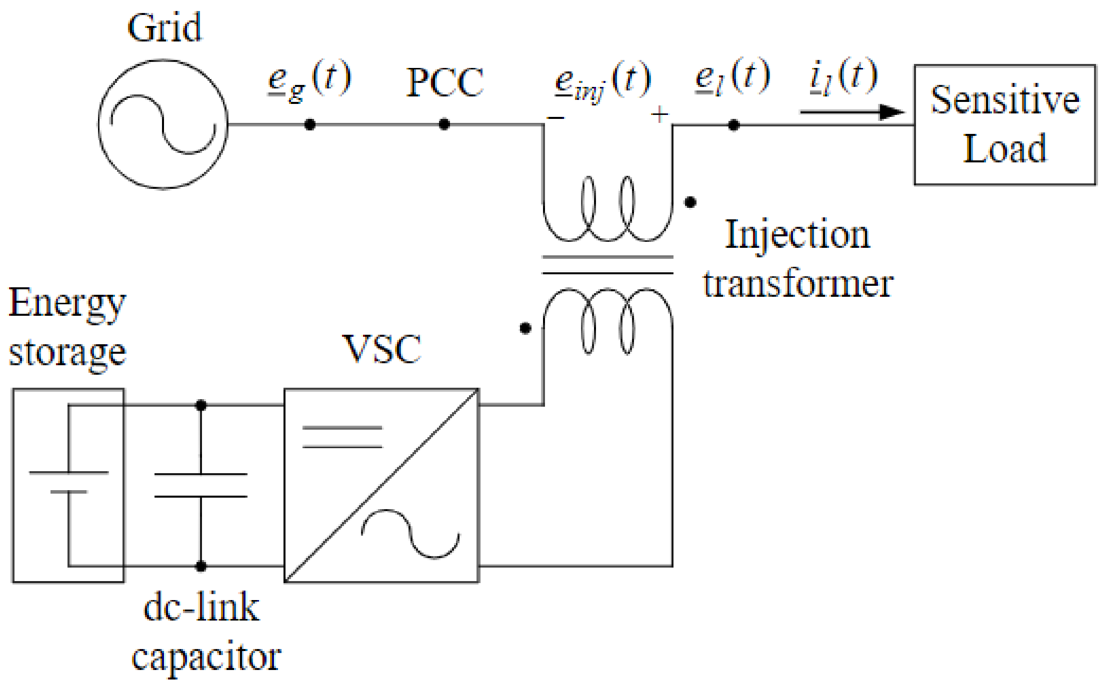


Figure 4.7: DVR: Circuit diagram

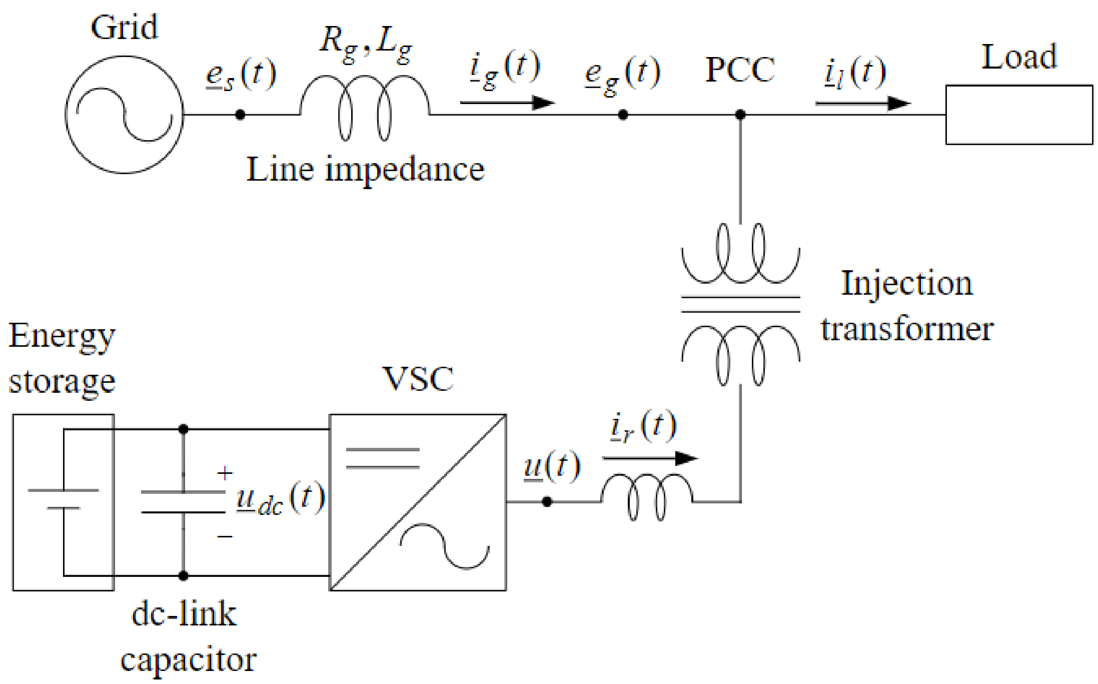


Figure 4.8: STATCOM: Circuit diagram

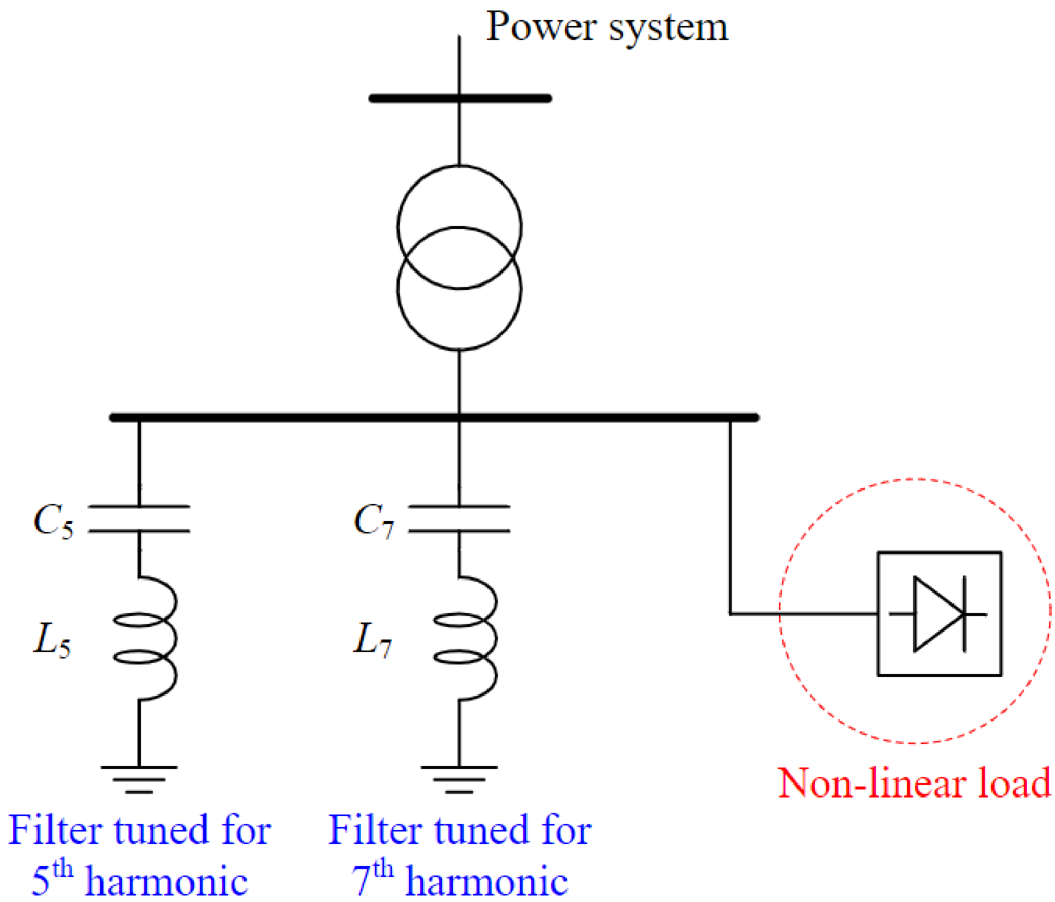


Figure 4.9: Passive filter - principle

4.4.2.1 Passive filtering

Passive filtering can be realized by adding LC filters which can be tuned to a specific frequency, see figure 4.9, which results in a zero impedance path for the specific frequency. As a result, the harmonic content is trapped in the LC-circuit, removing it from the system[63].

Passive filtering is cheap and easily implemented. The disadvantages are that the filter may cause resonance with the rest of the system and each specific harmonic needs its own filter.

4.4.2.2 Active filtering

The principle of active filtering is to inject the same harmonic in the opposite direction, see figure 4.10, causing the waveforms to cancel out[63].

Active filters are expensive and require complex control strategy, which is the main disadvantages of the technology. In comparison of passive filters, active filters have the ability to compensate different frequencies with the same device, less sensitive

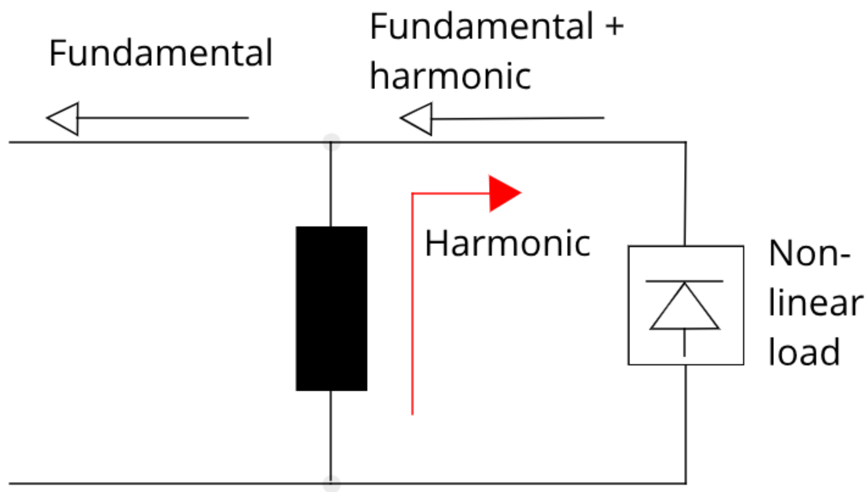


Figure 4.10: Active filter - principle

to aging and a lowered risk of overloading.

4.4.2.3 STATCOM

In [64], harmonic mitigation by introducing a static synchronous compensator, STATCOM, is investigated. The study investigates THD of a Australian distribution system with various penetrations of RES. A case scenario with 100 % penetration of RES found resulted in 2.5 - 3 % THD of voltage and 3.5 % THD in current across the distribution network. The paper integrated a STATCOM model which was able to significantly reduce the voltage THD to 0.5 - 1 %. The STATCOM was also able to reduce the current THD to 2-2.5 %.

4.4.3 Protection of DG networks

As discussed in section 4.3.2, the system topology is altered when interconnected with DG and conventional relay schemes risk becoming ineffective. [48] identified 5 different protection related challenges concerning interconnection of DG's. Additionally, the paper proposes solution for mitigating the emerging errors.

The first example in 4.3.2 dealt with unwanted tripping due to altered fault current contributions as a result of integrating DG units, see figure 4.4 and 4.5. Such a problem can be resolved by adding a designated feeder. Another solution is to force a generator tripping - this means coordination between generator and feeder relay must be realized[65].

Relay desensitization can be resolved by ensuring that the DG and feeder relay can, independently and non sequentially, detect faults. Sequential fault detection refers to the event when one relay is unable to distinguish a fault until another relay has operated and the fault conditions is altered, enabling the first relay to detect the fault. Sequential fault detection is undesirable, and if the issue cannot be resolved by changing the relay settings, a Direct Transfer Trip Scheme can be deployed. The scheme relies on communication between the breakers in order to simultaneously open during fault.

Nuisance tripping can be avoided by adequate coordination between the DG and utility grid. In the case where this is invalid, waveform analysis can be used. Information on voltage, current and power flow can be used to determine fault location and if the trip was correct. If the trip is determined as a nuisance trip, pick up and time delay of the relay may be adjusted.

The proposed method for avoiding the issue of out of phase automatic reclosers is to use over- and under-frequency and voltage relays. This allows for delay of reclosing until the machines are disconnected from the system.

It is difficult to accomplish a satisfactory anti-island protection. The paper points out *two* methods of avoiding island operation. Transfer trip scheme may be used. By monitoring the affected circuit breakers that could island the DG. By the use of an algorithm, one is able to distinguish island operation. If the condition is fulfilled, the affected DG's are tripped.

Over/undervoltage relays can be used in order to detect the voltage swells/dips. If ferroresonance is detected the immediate action will be to trip the line. The negative consequences that follow ferroresonance can be mitigated by adjusting the reactance at the affected location.

4.4.3.1 Digital substations

It can be concluded that the integration of RES in the power system has, among other things, consequences on the system protection. One common thread throughout the proposed actions in order to handle the resulting protection related issues is *information*. By having access to necessary real-time system data system protection becomes enhanced. This can be achieved by the usage of a digital substation.

Substations today use analog and binary data for monitoring and operation of protection systems. Processing analog data is power demanding and requires a large amount of labor. Digital substations with the help of fibre-optical cables and software, digitizes the data and, as a result, have the ability to enhance reliability and flexibility of the station[66].

There several beneficial aspects following a digitization of a substation. Design, construction and maintenance cost are lowered. With the transition to an electrified society, substations will become the naval point of information in the electrical infrastructure. Digital substations are necessary in order to quickly integrate Wide Area Monitoring, AI-tools and more[67].

4.5 Summary

In order to achieve satisfactory decarbonization several instances of the society requires electrification. As a result, a substantial expansion of RES may be expected. Integration of RES with high penetration yields several challenges for the future power system. Power quality challenges, voltage/frequency stability, harmonic content and increased complexity of power system protection. Several methods of maintaining high quality power and reducing harmonic content exists, such as FACTS devices, filtering, energy storage and digital substation.

This chapter has evaluated future challenges from a power system point of view. Decarbonization in the field of electric power engineering encompasses additional topics. The following chapter focuses on environmental challenges from the electrical infrastructure itself, where primarily alternatives to the insulating gas SF_6 will be assessed.

5

Literature study - environmental aspects

The environmental section evaluates the future environmental coupled challenges related to substations. Firstly, replacement for the insulating gas SF_6 is considered. Alternatives pointed out by recent research are assessed and alternatives offered by manufacturers are presented. Lastly, alternatives for transformer insulation are reviewed, both liquid and solid insulation.

5.1 Environmental impacts of substations

In order to assess the environmental impacts contributed by the usage of electrical switchgear and substations several LCA-studies are reviewed. The results found from the studies are presented below.

Paper [68] provides a life cycle assessment (LCA) concerning a 132 kV hybrid substation insulated with SF_6. The LCA found that SF_6 losses contributed the greatest impact related to global warming. The second largest contributor in the global warming category was found to be the operating phase of the substation. The LCA is utilizing the 2018 Italian energy production mix.

In [69], an LCA on the Danish distribution network from 2013 is conducted. The study concluded that the impact is more significant in the distribution network compared to the transmission network because the power losses are greater in the distribution network. SF_6 emissions in electricity transmission were found to be a significant factor in the climate change category, while emissions in the distribution network were negligible in comparison. Metal depletion can be linked to the electrical infrastructure, with emphasis on cables and transformers.

The paper [70] reviews 16 studies that deals with LCA's of electrical grids. The paper found that power losses was a major contributor in the climate change category (62 %). Results show that the applied energy mix is of major significance. High penetration of renewables results in significantly lower impact of power losses when compared to fossil-based mix.

The LCA in [71] aims to characterize the environmental impacts from substation equipment, adopting an average European energy mix. The LCA on transformers found that power losses had the greatest environmental impacts, followed by infrastructure related processes: transport, manufacturing, maintenance and end of life.

The paper theorizes that higher equipment efficiency could result in higher energy and material input. The trade-off between increased equipment efficiency and material usage is an aspect that should be considered during grid planning.

Transformer transport is highlighted to have impact on climate change, fossil depletion, terrestrial ecotoxicity and ozone depletion. Disposal of transformer oil generates high transformer end of life impact.

In regards of substation equipment, SF_6 leakages are found to be of major significance as it contributes with 78 % of the total GWP 100 score in the LCA.

Summarizing [68], [69], [70] and [71] it may be concluded that the most significant factors concerning environmental impacts are: power losses, which is heavily influenced by the applied energy mix, SF_6 emissions, material extraction, infrastructure and transformer oil.

5.2 Replacing SF_6

SF_6 is an exceptional gas insulator, which is a result of its electronegative properties. The attachment of electrons plays a vital part in the formation of an electron avalanche, which ultimately results in a breakdown. Therefore, electronegativity and electron affinity are important characteristics in the context of dielectric strength. SF_6 with its excellent electron affinity properties manifests superior insulation qualities, enabling drastically reduced equipment sizes, see figure 5.1. Additionally, the electronegative qualities of the gas provides excellent arc-extinguishing properties. As a result, SF_6 plays a dominant role as insulation/extinguishing medium in high voltage circuit breakers, where arcs are an inevitable consequence of separating the energized contacts while operating. The gas also exhibits favorable properties such as, non-toxicity and as a result of its molecular composition, the atoms immediately recombine following an arc where the molecule is broken down to its core components[12][72].

The major disadvantage of SF_6 is the environmental impact of the gas. The global warming potential (GWP) is estimated to be in the range of 25000, relative to CO_2 with an estimated life time of 800-3200 years. There is no evidence that SF_6 contributes the ozone depletion[73].

In terms of global warming, radiative forcing from fluorinated gases (F-gases) make up 12.5 % of man made green house gases and, as of 2015, SF_6 contributes to 0.15 % to the global radiative forcing. Furthermore, 58 % of the global emissions of SF_6 originates from electrical equipment where the main contributors to SF_6 related emissions is linked to production and operation[74].

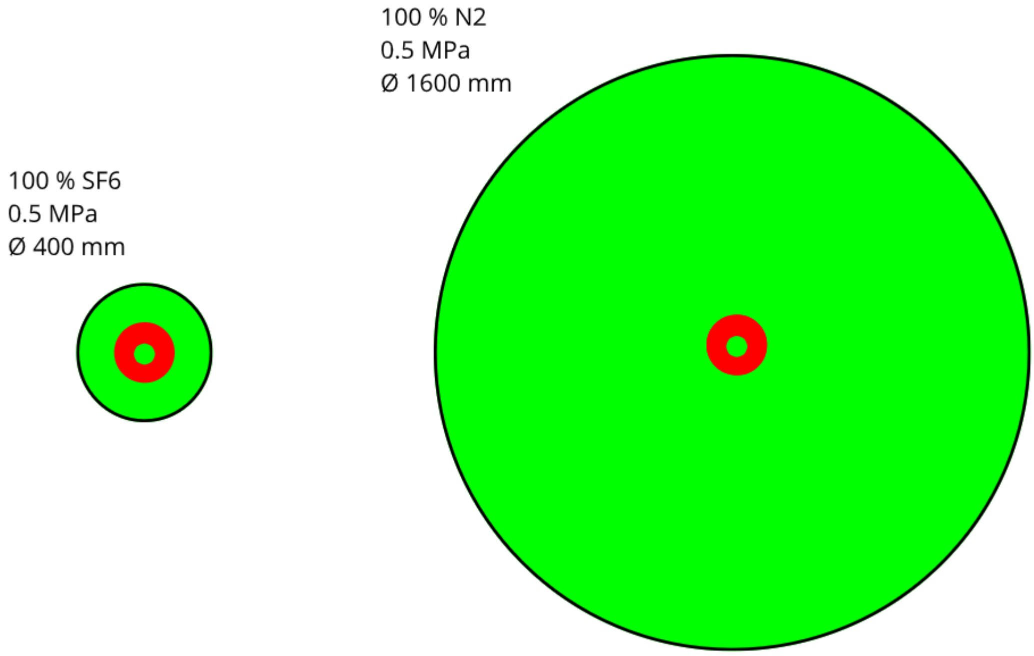


Figure 5.1: GIL dimensions under same pressure based on breakdown voltage - SF_6 (left) in comparison of N_2 (right)

SF_6 is expected to be banned by 2026 in the EU. The number of substations that utilizes SF_6 is expected to be around 10 million and the amount of substations is expected to increase by 40 % by 2050, as a result of the electrification. The ban is expected to mandate SF6-free substations up to 24 kV by 2026 and in 2030 also includes substations up to 52 kV. Substations that already utilizes the gas will be allowed to continue its usage during its lifetime since replacing the gas would require a redesign of the switchgear.

5.2.1 Alternatives - research

The search of alternative gases is divided into two sections. The first, aims to evaluate what alternatives are *pointed out* by research. The second section aims to introduce alternatives offered by manufacturers of high voltage equipment.

5.2.1.1 C4-FN & C5-FK

Paper [75] points out several important factors related to safety and environment when substituting SF_6 to an alternative gas. These are, non-flammable, non-toxic, low global warming potential and no ozone depletion potential. Additionally, the paper points out important properties for high voltage insulation applications. These include, dielectric strength, heat dissipation, thermal and chemical stability, boiling point, arc-quenching and dielectric recovery.

The paper concludes that usage of natural gases as mixture component have several beneficial aspects. Reduction of the boiling point, enhanced arc-quenching abilities and lowered GWP. Furthermore, the paper points out C_4F_7N (C4-FN) as reasonable alternative. By adding CO_2 a lower GWP is attained and arc-quenching ability is enhanced. The paper also highlights that C_4F_7N (C5-FK) is at an early stage of development and that further research is necessary.

In [76] SF_6 emissions are studied under large uncertainties. Emissions from SF_6 are compared to the gas mixtures using C5-FK and C4-FN, which have been demonstrated to posses satisfactory arc-quenching and insulation properties. The emissions from SF_6 are estimated to 1.6-3.3 Mt CO_2-eq annually from operational leakage. Switching to C5-FK or C4-FN for 145 kV GIS estimates saving in the range of 50-360 t CO_2-eq over the equipment's lifespan. Furthermore, the paper estimates reduction of carbon footprint by 14 Mt CO_2-eq over a period of 50 years, considering a phase out scenario starting from 2020.

Important requirements for alternative gases in circuit breaker applications are highlighted in [77]. These include, high dielectric strength, no ozone depletion potential (ODP), non-flammability, low GWP, arc quenching, stability, material compatibility, heat dissipation capability and availability on the market. The paper lists properties of SF_6, given in table 5.1.

Table 5.1: Properties of SF_6 and alternatives

Data from [77]	GWP	Boiling point [°C]	Flammabilitiy	Toxicity TWA [ppmv]	Dielectric Strength
SF_6	23500	-64	No	1000	1
CO_2	1	-78.5	No	5000	0.3
C5-PFK	26.5	<1	No	225	2
C4-PFN	2100	-4.7	No	65	2

The paper points out several promising alternative gases given the requirements. The most likely candidates are C5 perfluoroketone (C5-PFK) and C4 perfluoronitrile (C4-PFN), although, the paper concludes that the market will likely converge into a single alternative in the future. In pure form, the gases demonstrates superior dielectric strength in comparison of SF_6, but it can also be observed that high dielectric strength is correlated with a high boiling point, see table 5.1. A high boiling point is an undesirable quality in electrical switchgear applications where low temperature requirements are found. Therefore, a buffer gas needs to be implemented. In HV applications CO_2 is used and air in MV applications. The properties of the gas mixtures are given in table 5.2.

Table 5.2: Properties of gas mixtures in MV/HV switchgear

Data from [77]	GWP	DS	T_{min} [° C]	VA
SF_6	23500	1	-41...-31	-
CO_2	1	0.4-0.7	$\leq$ -48	-
CO_2/C5-PFK/O_2	1	0.86	-5...5	HV
CO_2/C4-PFN	327-690	0.87-0.96	-25...-10	HV
Air/C5-PFK	0.6	0.85	-25...-15	MV
N_2/C4-PFN	1300-1800	0.9-1.2	-25...-20	MV
DS	Dielectric strength at 0.55 MPa			
T_{min}	Minimum operating temperature			
VA	Voltage application			

Chapter 18 in [78] provides an historical overview of alternative gases as well as an overview of the market as of 2023. The most important quality of an alternative gas is dielectric strength, which can be related to how strongly electronegative the gas is, or specifically, the gas molecule's ability to attach free electrons.

The two most promising gas insulator candidates as SF_6 alternatives from more recent research are fluoronitrile (C_4F_7N) and fluoroketone ($C_5F_{10}O$) which both exhibits low toxicity levels and adequate GWP values. These compounds exists on the market from 3M™, namely, 3M™Novec™4710 and 3M™Novec™5110, which have begun seeing applications within electrical equipment. For instance, a mixture of CO_2, O_2 and 3M™Novec™4710 labeled green gas for grid (g^3) from GE has been developed and seen usage for GIS and gas insulated lines (GIL). Another solution for GIS and GIL applications is AirPlus™ from ABB which combines 3M™Novec ™ 5110 with dry air.

5.2.1.2 Vacuum

Paper [79] compares the electromechanical properties of SF_6 and vacuum circuit breakers in the medium voltage range. The paper states that in oil and air were the dominant insulating materials for circuit breakers until the 1980's, when SF_6 entered the market and became dominant for medium and high voltage applications. The paper predicts that vacuum based circuit breakers will see technological advancement in the coming future. Vacuum breakers have higher dielectric strength at small distances, requires less periodic maintenance and have a higher rate of rise recovery voltage.

The paper investigates opening and closing time of the breaker in aid of the motion curve, which is an important parameter that provides desired information about the device. The parameters from [79] are given in table 5.3.

Table 5.3: Results from the vacuum breaker test

Parameter	SF_6	Vacuum
Opening time [ms]	54.40	22.30
Closing time [ms]	71.90	44.20
Contact wipe [mm]	25.20	4.34
Contact stroke [mm]	56.90	18.37
Total distance [mm]	82.70	22.70
Data from [79]		

The opening time is an important parameter in terms of protection of transmission and distribution facilities. Closing time is important due to the fact that during closing, unwanted arcs between the electrodes may occur that could result in explosion. The contact wipe refers to the required distance for the contacts to not separate following a vibration as a result of the motion during operation. In order to dampen the arc during a malfunction of the system, the fixed and moving contact must reach a certain distance between each other, which is refereed to as the contact stroke. The final parameter, total distance, is the sum of the contact wipe and contact stroke.

From the results, the paper concludes that vacuum breakers operates faster, has to move a shorter distance and is less complicated than the SF_6 breaker and demonstrates more favourable properties than its counterpart.

Additionally, [78] also highlights vacuum breaker technology as an attractive solution. Using vacuum between the contacts and as a result, quenching the resulting arc from operating the device, combined with either solid dielectric or dry air as insulation around the vacuum interrupter and in the bushings eliminates the need of SF_6 completely. Such technologies are, as of 2023, being developed by Siemens and Mitsubishi. The devices exists for applications within the MV range ($\leq$ 72.5 kV), higher voltage applications are expected to become available in the future, albeit being a challenge technically.

When summarizing the results from [76], [75], [80], [79], [77] and [78] it can be concluded that the compounds fluoronitrile and fluoroketone as well as vacuum are promising alternatives.

5.2.2 Alternatives - market

The following section reviews the present SF_6-free alternatives offered by manufacturers on the market.

5.2.2.1 C4-FN

3M™ Novec™ 4710 & 5110

The previously discussed compounds C4-FN and C5-FK is currently being marketed as 3M™ Novec™ 4710 and 3M™ Novec™ 5110, respectively. According to the company, the gases are intended to be used as insulation within applications for GIS, GIL and circuit breakers[81][82]. Parameters provided by the technical data are provided in table 5.4.

In pure form, both gases demonstrates higher dielectric strength in comparison of SF_6 at absolute pressures ranging from 20 - 100 kPa. The test conditions are uniform field distribution with a parallel plate geometry with a separation distance of 2.5 mm. 5110 mixed with air demonstrates a slightly lower breakdown voltage than that of SF_6 which is also the case for 4710 mixed with CO_2.

Table 5.4: Properties of Novec 5110 and Novec 4710 (C5-FK) & (C4-FN)

Data from [81][82]	5110 (C5-FK)	4710 (C4-FN)
Flammability	No	No
Boiling point [°C]	26.9	-4.7
DBV [kV]	18.4	27.5
GWP	<1	2100
ODP	0	0

DBV: Dielectric breakdown voltage

In pure form, both gases demonstrates higher dielectric strength in comparison of SF_6 at absolute pressures ranging from 20 - 100 kPa. The test conditions are uniform field distribution with a parallel plate geometry with a separation distance of 2.5 mm. 5110 mixed with air demonstrates a slightly lower breakdown voltage than that of SF_6 which is also the case for 4710 mixed with CO_2.

One advantage of using a small dosage of C4-FN in mixture with either N_2, O_2 or CO_2 is that the arc-quenching capability is greatly enhanced, as well as the dielectric strength. Using pure N_2, O_2 or CO_2, alternative gas breaker technology, such as vacuum, needs to be deployed due to its reduced arc-quenching properties. However, vacuum breaker technology have lackluster scalability since the dielectric strength exhibits a saturation effect in relation to the electrode distance. Hence, vacuum breaker technology does not see applications in the voltages above 145 kV[83]. By using C4-FN and bypassing the need for vacuum interrupters C4-FN may be directly adapted into already existing SF_6-breaker technology and as a result, skipping the need for complete re-innovation of breaker technology.

The mixture ratios varies, depending on the application. As pressure increases, the dielectric strength of the gas mixture increases, but also the minimum operating temperature. Table 5.5 lists multiple common mixture ratios that sees applications. It should be mentioned that the minimum operating temperature may be decreased

Table 5.5: Common C4-FN mixture ratios with corresponding minimum temperature

C4-FN [%]	O_2 [%]	CO_2 [%]	Min. temp [°C
5	13	82	-25
3.5	10	86.5	-30
3.5	13	83.5	-30
5	0	95	-25
Data from [83]			

by lowering the gas pressure.

Hitachi has recently launched an Eco-friendly brand which consist of an SF_6-free portfolio which is marketed under the name EconiQ™. The alternative gas is a mixture of C4-FN, CO_2 and 0_2[84]. As of 2021, over 150 breakers from the series have been installed worldwide. The Econiq™ brand provides solutions for, live tank breakers (LTB), dead tank breakers (DTB), current transformers, GIL, GIS and plug and switch system hybrid switch gear (PASS)[85]. A roadmap over the portfolio is provided in table 5.6.

Table 5.6: Roadmap of the Ecnoiq™ series

Data from [85]	2022	2023	2024	2025
Live Tank Breaker LTB	72.5 kV 145 kV		420 kV	245 kV
Dead Tank Breaker DTB	420 kV	72.5 kV 145 kV	550 kV	245 kV
Plug and Switch System hybrid Switchgear PASS			72.5 kV 145 kV	
Gas-Insulated Switchgear GIS	72.5 kV 145 kV 420 kV		550 kV	245 kV
Gas-Insulated Line GIL	420 kV		245 kV 550 kV	

General electric promotes its alternative gas as green gas for grid (g^3), which is a mixture of C4-FN with either CO_2 or N_2[86]. The existing applications are GIS (145 & 420 kV), GIL (420 kV) and live tank circuit breakers (145 kV)[87].

5.2.2.2 Vacuum

Siemens utilizes vacuum technology and clean air as insulation medium. Clean air is a composition of 80 % N_2 and 20 % O_2 and offers solutions for 145 kV GIS, voltage transformers (VT) up to 420 kV, LTB and DTB up to 145 kV[88].

5.3 Transformer insulation

Transformer insulation require high breakdown strength, partial discharge(PD)-resistance, thermal and chemical stability, high electric resistance, low losses and cooling properties. The dominant type of insulation are combination of liquids and solids, specifically, oil and cellulose. Layers of paper are, under heat and pressure, compressed into a solid mass which is called a pressboard. Oil is impregnated into the paper mass, filling up pores and voids which enhances dielectric strength and reduces dielectric losses in addition to providing excellent heat dissipation as the oil is able to transport the heat[89][90].

5.3.1 Oilimpregnated paper insulation

The most common oil used for insulation purposes in transformers are mineral oils, due to its relatively low cost and other relevant characteristics. Some important oil qualities are

- Dielectric strength
- Viscosity
- Pour point
- Flash and fire point

Viscosity is a measurement of a fluid's resistance of deformation or resistance of flow at a given rate. Viscosity determines the circulation, thus heat transfer is greatly affected by the viscosity of a fluid. The pour point is determined as the temperature when oil stops flowing. The flash and fire point are related to the temperature at which the oil will starts burning. The flash points is at which temperature the oil vapour in combination with the ambient air becomes flammable and the fire point is defined as the temperature where the fire will be sustained for 5 seconds[89]. Dielectric breakdown in liquids can either be initiated by a formation of an electron avalanche or initiated by liquid impurities. Containment's such as gas bubbles or moisture with lower dielectric strength in combination with high electric stress results in breakdown of the liquid.

Mineral oils also have a high ageing resistance. However, mineral oil possesses several negative qualities. These are, low flash and fire point as well as a relatively weak dielectric strength. The most negative aspect of usage of mineral oil are the environmental related issues[91]. Mineral oils are non-degradable, a hazardous property in the event of leakage. The relatively low flash and fire point is another concern as mineral oil are highly combustible.

Mineral-based oil originates from fossilized materials such as algae and zooplankton. Due to the extremely long-time process of fossilization the oil deposits will not be replenished within the scope of the human timescale, requiring continuous discoveries of such deposits. Therefor it cannot be guaranteed that mineral oil will be available in the future[92].

Esters

Esters or vegetable oils consists of triglycerides and have several appealing qualities. Their sources are renewable with non-fossil origin and biodegradable. These characteristics results in more environmentally friendly and safer alternative than mineral oils for both off and on-shore applications[91][93].

Synthetic esters are obtained from alcohols. Synthetic esters are characterized by high viscosity, high flash and fire points in comparison to mineral oils. Compared to natural esters, the synthetic esters exhibits higher performance when operating in lower temperatures. A comparison for certain relevant parameter are provided in table 5.7.

Table 5.7: Properties of vegetable oil compared to mineral oil

Property	Mineral oil	Vegetable Oil Saturated	Vegetable Oil Unsaturated
Viscosity at 40 ° C [cSt]	13	29	37.6
Flash point [°C]	154	225	260
Pour point[°C]	-40	20	-22
Breakdown voltage [kV]]	45	60	56

Data from [94]

Although the alternatives to mineral oil posses several positive qualities such as, high breakdown voltage, high flash and fire point and biodegradability, they also exhibit several drawbacks. Drawbacks associated with natural esters are pour point, ionization resistance, dielectric loss and oxidative stability.

One major drawback of natural esters as insulating medium in transformers is the pour point. At low temperatures the oil exhibits high rate of crystallization. The crystallization rate is heavily dependent on their saturation level. IEC 60296 requires a pour point of -40°, which is accomplished by mineral oil, but not by natural esters.

5.3.2 Dry-type transformers

Solid insulated transformers, commonly refereed to as dry-type transformers, are transformers where the transformer windings are either resin-encapsulated or resin-bonded. This technology finds applications in voltage transformers and power transformers in the medium voltage range. Due to air inclusions found within the layers between the insulation high field strengths are unacceptable. In comparison to oil-insulated type transformers, dry-type transformers exhibit worse heat dissipation characteristics as heat is removed by conduction from the resin encapsulation. The disadvantageous characteristics limits the dry-type transformers power ratings.

However, as the environmentally hazardous consequences of mineral oil are eliminated, the dry-type transformers finds applications in the medium voltage range, undeterred by the increased price[12].

The absolute most advantageous property of oil/paper-insulated insulation is the relatively cheap price in addition to its highly beneficial thermal properties. The units offer the lowest losses in relation to price as well as being able to operate in inauspicious conditions.

One possibility that is enabled from dry-type insulation is the ability to reduce core and winding volume – a property which originates from the possibility of using solid material with high temperature ratings. Although higher operation temperature leads to increased power losses the severe consequences of potential oil leakage and ignition from oil units are bypassed. This property is the reason that dry-type transformers have become available to an affordable price, albeit a higher price than conventional oil-paper insulated transformers.

A drawback of the dry-type units is the fact that the ambient air has influence on insulation characteristics. This is apparent in environments characterized by high influence of contaminations such as moisture. The resulting weakened dielectric strength have severe consequences on the transformers, particularly in higher voltage ratings[95].

5.4 Summary

This chapter has highlighted several negative environmental aspects of the electrical switchgear. One of the strongest environmental loads is related to SF_6 emissions. The next chapter aims to determine how the alternative gases found in this chapter will affect a studied substation on a design level.

6

Technical study

6.1 Mechanical model of a substation

For visual aid a mechanical model of a substation is developed. The substation is a 50 / 10 kV substation and the model contains the primary side of the substation. It should be mentioned that the devices in the model are rated 72.5 kV, but in a real application the devices would be subjected to a voltage of 50 kV. The modeled components are inspired by real components and a real model of a similar substation. The real mechanical substation model is provided in figure A.2 and A.3 in appendix 1. Figure 6.1 and 6.2 depicts the modeled station in a two-dimensional view as well as an isometric view. The model components are summarized in table 6.1. It should be noted that the substation model is of H-type configuration, meaning that there are two equal series of apparatuses interconnected between the bus bars. For convenience, only one series of the substation is henceforth depicted.

Table 6.1: Description of CAD model

Order	Component	Figure	Function
1	VT	6.3	Voltage measurement
2	CT 1	6.3	Current measurement
3	Circuit breaker 1	6.5	Break running current
4	Bus	6.4	Central point for distribution
5	Disconnector	6.6	Isolate substation during maintenance
6	Circuit breaker 2	6.5	Break running current
7	CT 2	6.7	Current measurement
8	Cable tray	6.8	Mechanical support for secondary side
9	Power transformer	6.9	Transform voltage

The circuit breaker is based on Hitachi's SF_6 circuit breaker, rated 72.5 kV[96]. The circuit breaker interrupter is based on figure 2.8, and normalized to the size of Hitachi's circuit breaker.

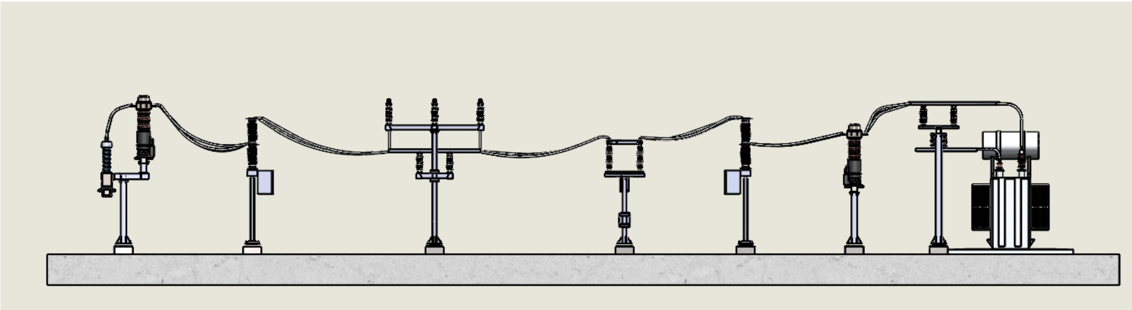


Figure 6.1: Substation - 2D sketch

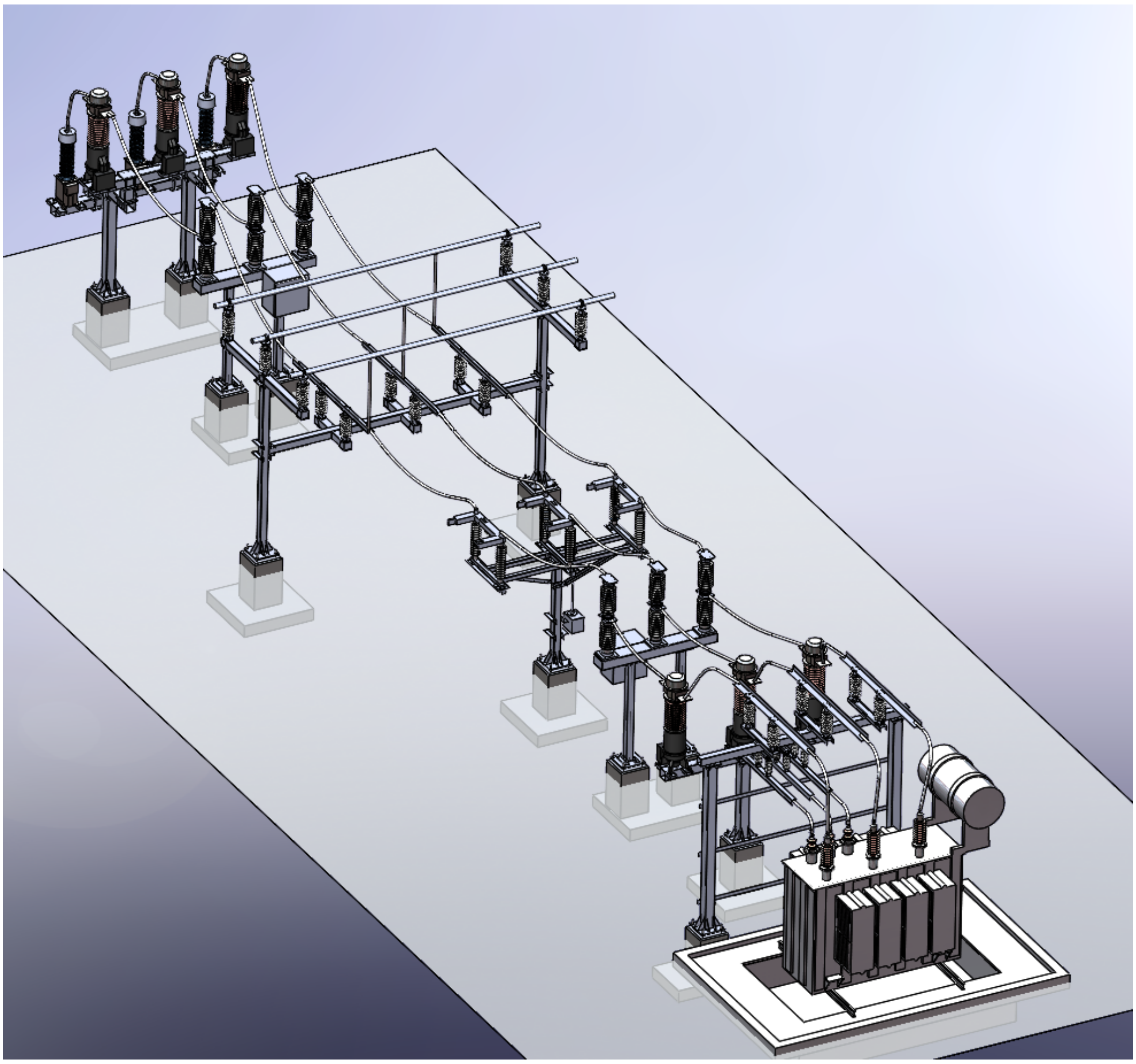


Figure 6.2: Substation - Isometric

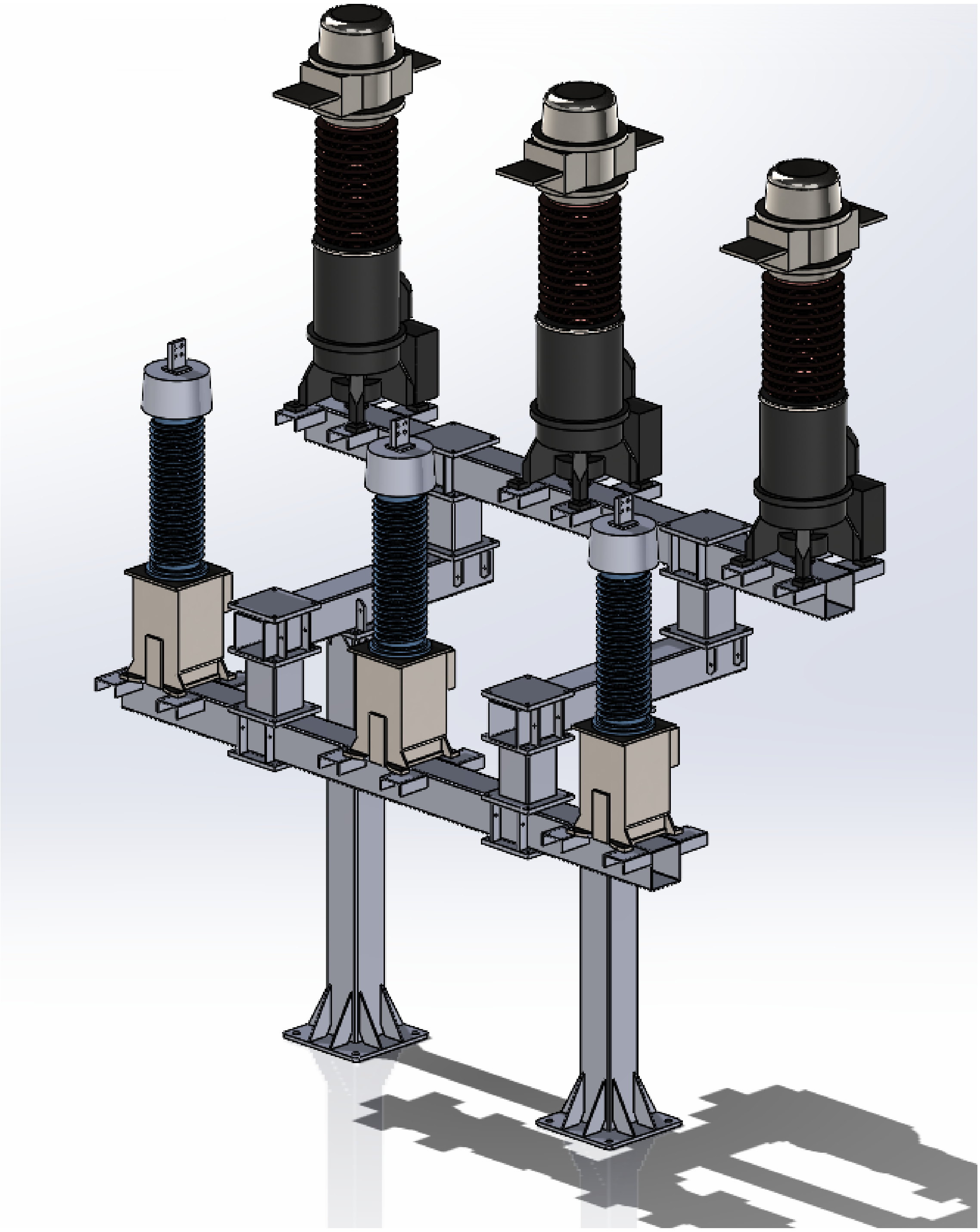


Figure 6.3: Voltage and current transformer

The voltage transformer is mounted on the same frame as the second current transformer.

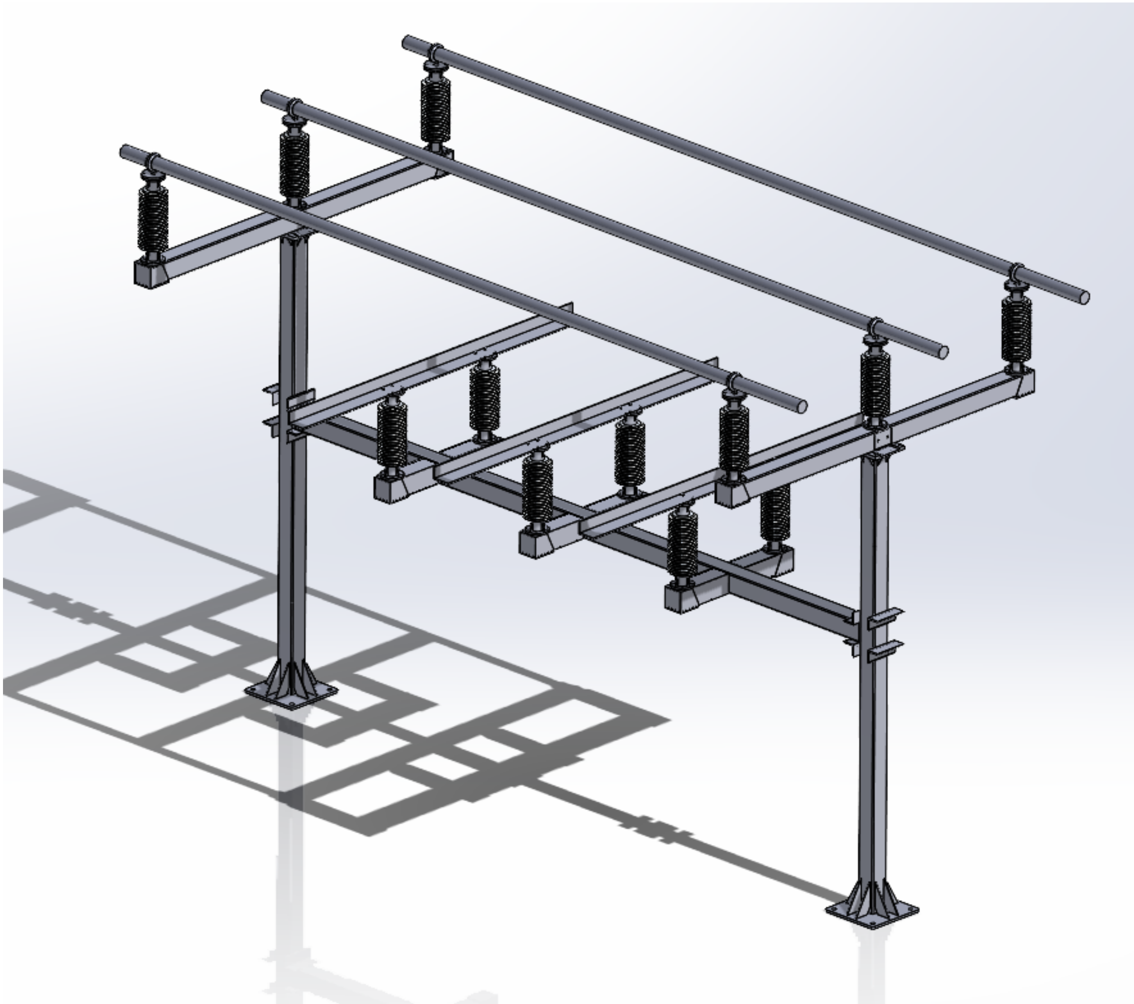


Figure 6.4: Bus bar

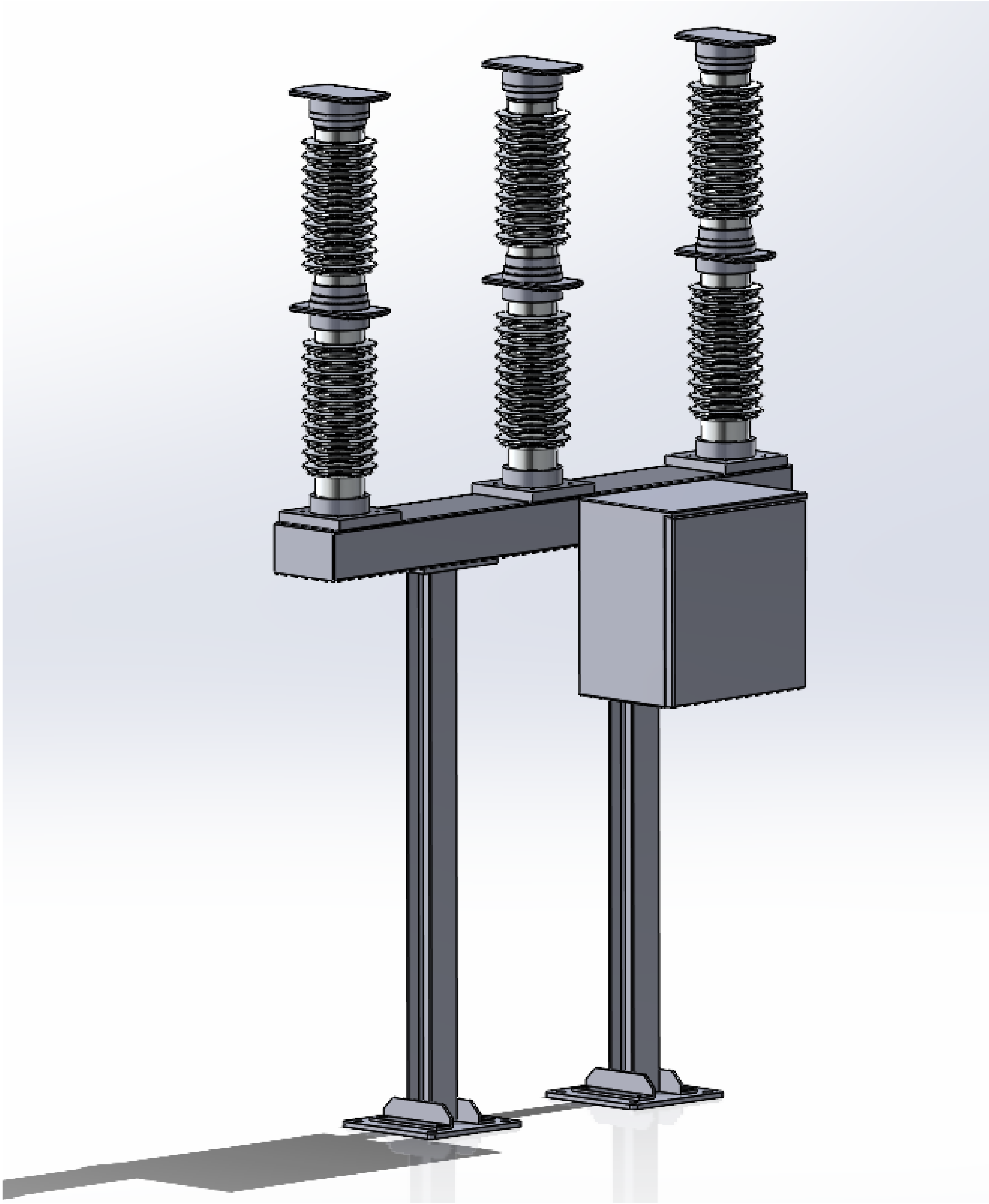


Figure 6.5: Circuit breaker

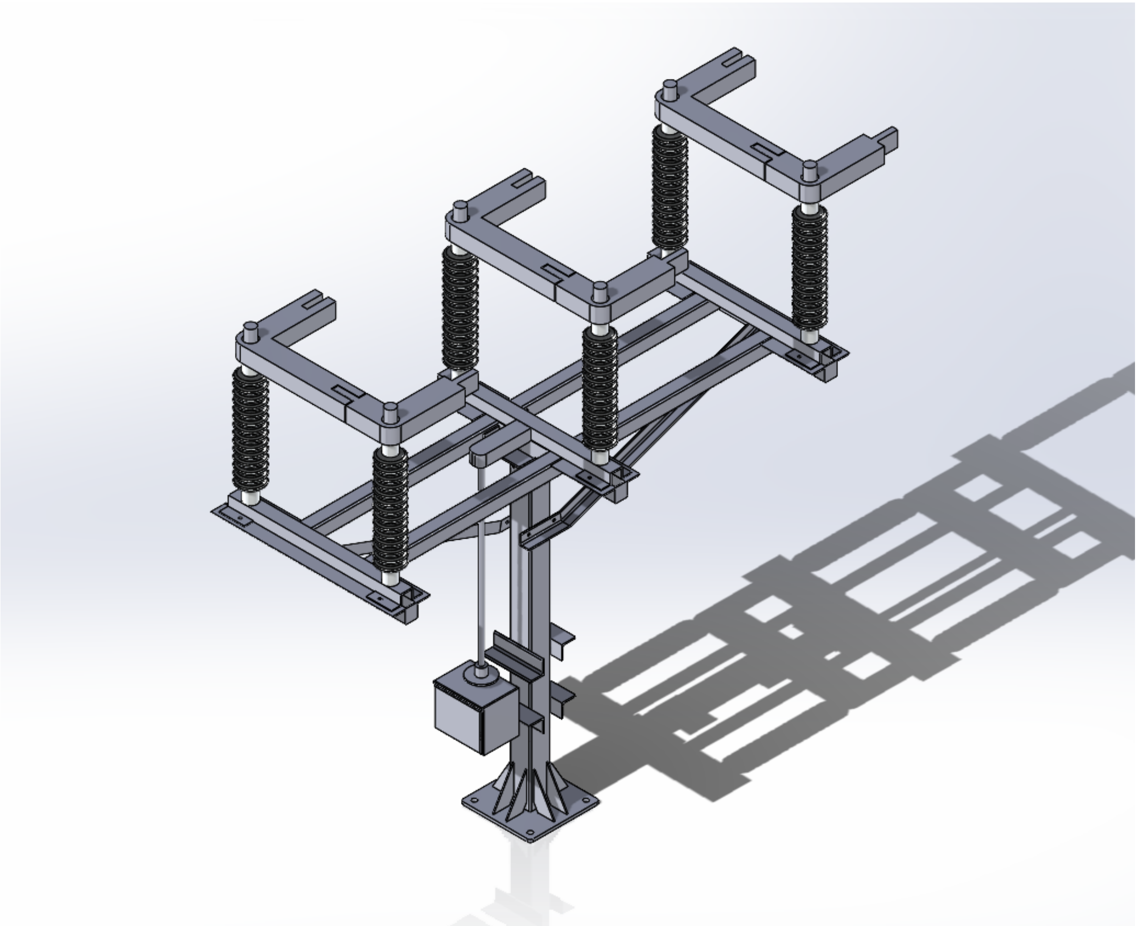


Figure 6.6: Disconnector

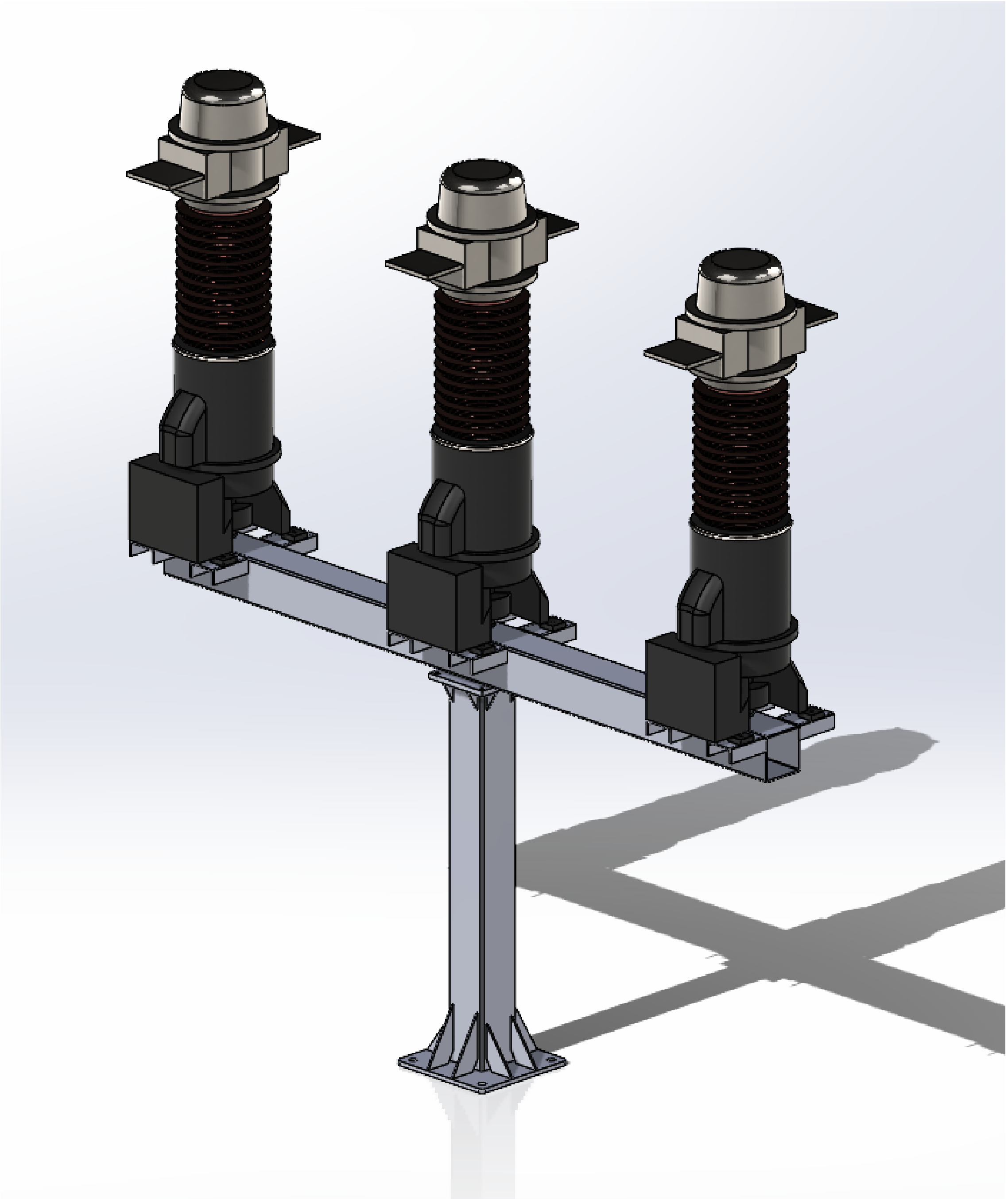


Figure 6.7: Current transformer

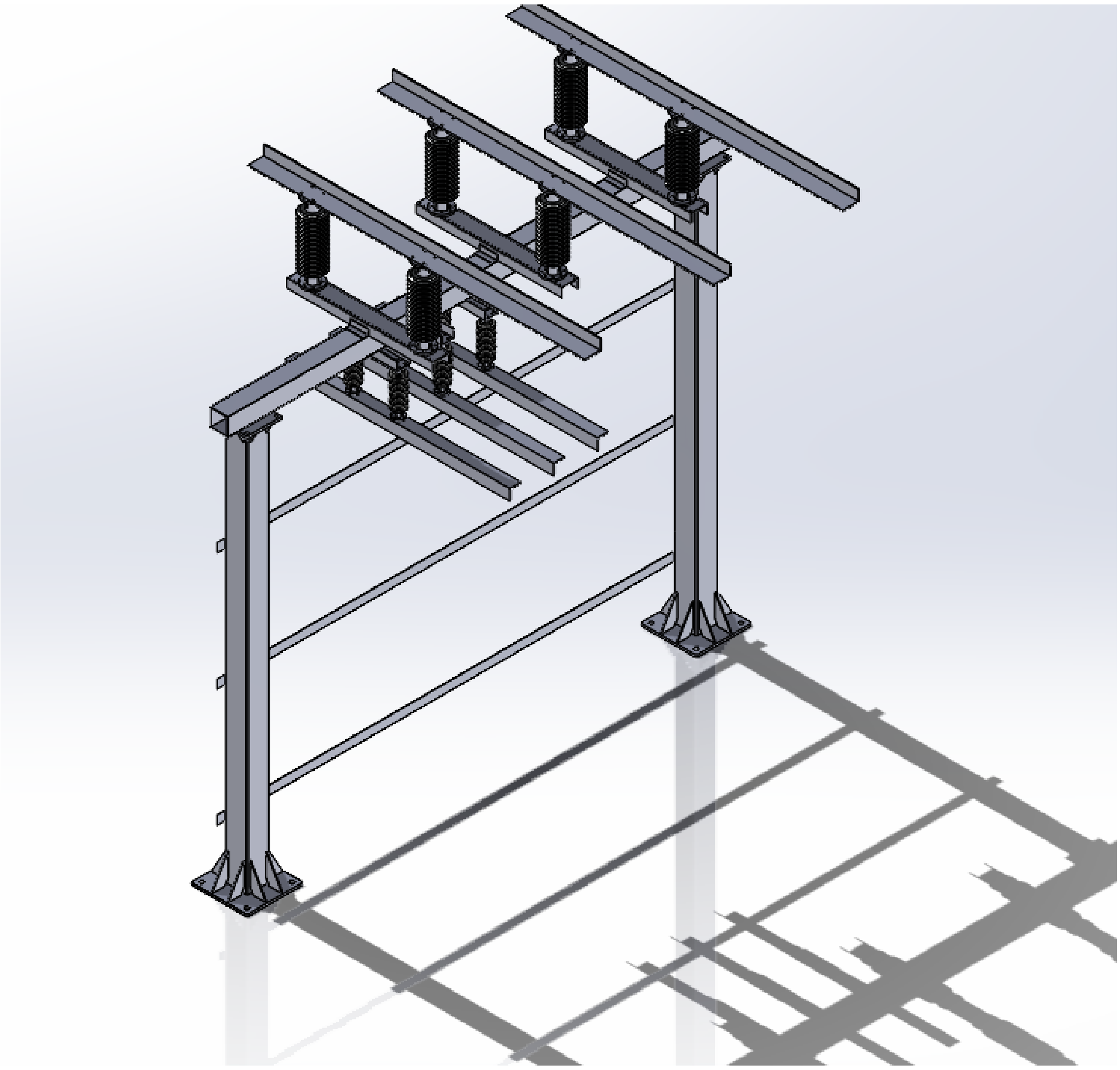


Figure 6.8: Cable tray

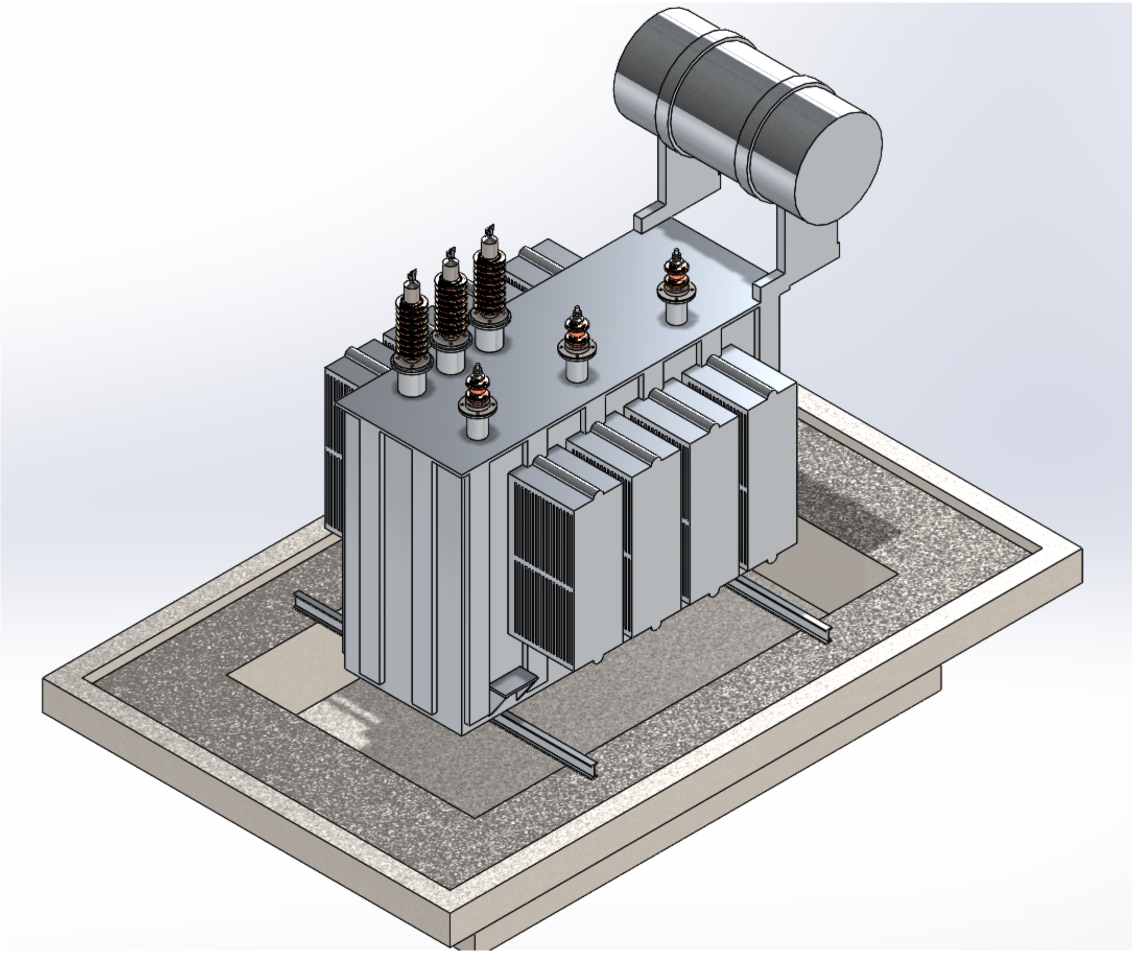
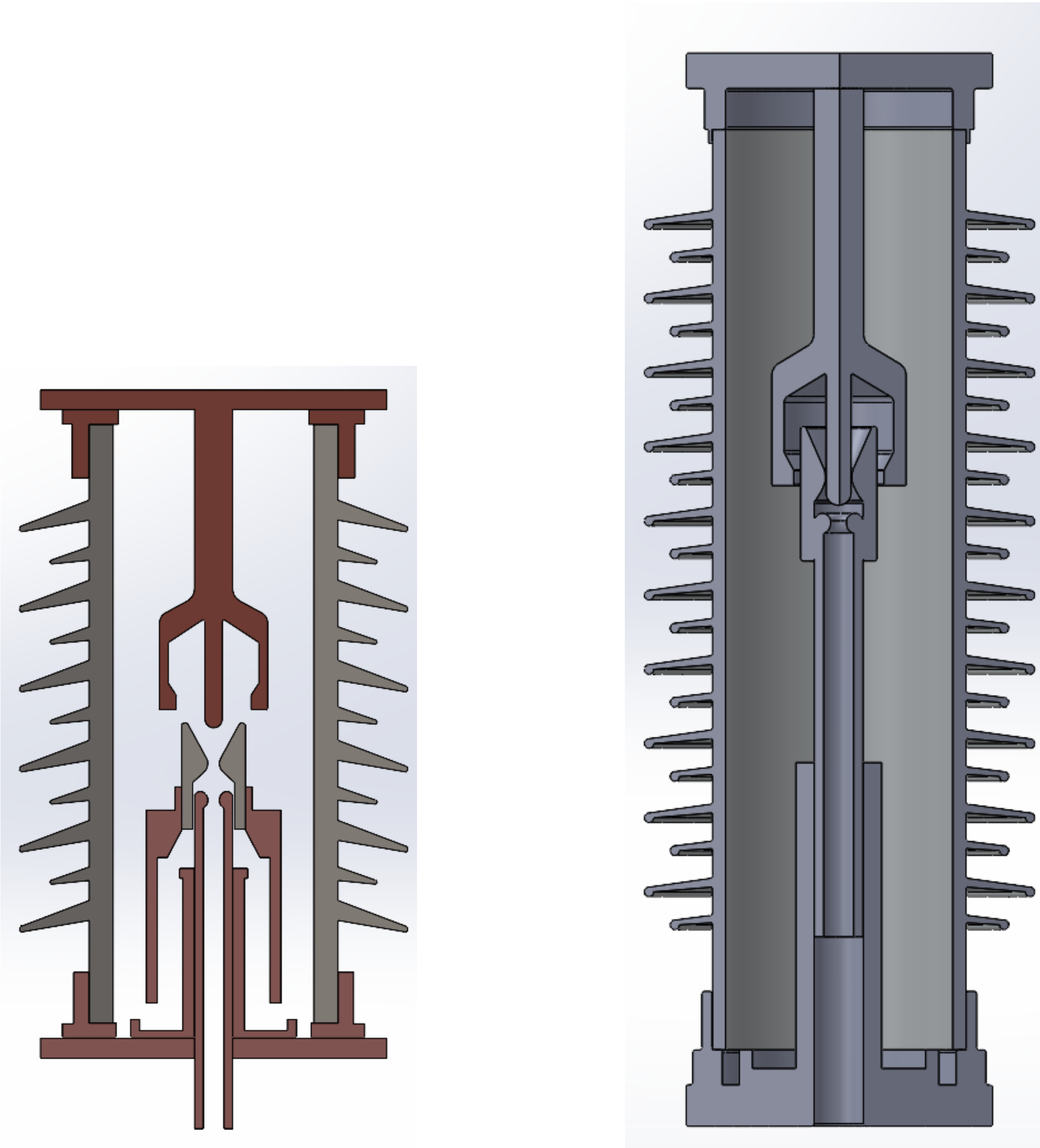


Figure 6.9: Power transformer

The interrupter unit from the CAD model is given in 2D in figure 6.10a, as well as in figure 6.10b as 3D.



(a) Interrupter 2D

(b) Interrupter 3D

Figure 6.10: Interrupter CAD model

6.2 Simulation results

The simulation uses the same geometry for SF_6 and the gas mixtures. Since the breakdown voltages (critical fields) are lower than SF_6, the gas mixtures are be operating closer to breakdown. The purpose of the simulation is to find *at what size* the gas mixtures will exhibit an equal electric field / breakdown ratio as SF_6.
The alternative gases used for the electrostatic simulation are, g^3, C4-FN-mixture and a CO_2-mixture. A C4-FN ratio of 3.5 % is selected as it yields lower dew

temperatures[83]. As the circuit breaker is operating outdoors, having a lower dew temperature is more suitable for Swedish climate.

6.3 Breakdown - bond energy

SF_6

$$U_{b,SF_6} = 6(S - F) = 6 * 3.39 = 20.34 \text{ eV}$$

C4-FN mix

The mixture ratio is, 3.5 % C4-FN, 10 % O_2, 86.5 % CO_2. Bond energy for C4-FN[97],

$$U_{b,C4FN} = 7(C - F) + 3(C - C) + (C \equiv N) = 7 * 4.6 + 3 * 3.6 + 9.23 = 52.23 \text{ eV}$$

$$U_{b,O_2} = (O = O) = 5.18 \text{ eV}$$

The total bond energy for the mixture

$$U_{b,C4FN-mix} = 3.5\% * 52.23 + 13\% * 5.18 + 86.5\% * 16.6 = 16.7 \text{ eV}$$

CO_2 mix

The CO_2-mix contains 90 % CO_2 mixed with 10 % O_2

$$U_{b,CO_2} = (O = C = O) = 2 * 8.3 = 16.6 \text{ eV}$$

$$U_{b,CO_2-mix} = 90\% * 16.6 + 10\% * 5.18 = 15.45 \text{ eV}$$

g^3 alternative

The mixture ratio is, 4 % C4-FN, 96 % CO_2,
The total bond energy for the mixture

$$U_{b,g^3} = 4\% * 52.23 + 96\% * 16.6 = 18 \text{ eV}$$

Breakdown - Critical field

3.1 gives the breakdown voltage at 1 cm and 1 atm. The critical electric field in kV/cm is given in table 6.2

Table 6.2: Bond energy and critical electric field for the gas mixtures

Gas	SF_6	C4-FN-mix	CO_2-mix	g^3	Unit
U_b	20.4	16.7	15.45	18.02	eV
E_{crit}	90.026	73.72	68.21	79.546	kV/cm

6.4 Electric fields

The upper and lower contact and terminal of the interrupter is simulated as copper. The insulating components, shed and nozzle are simulated as porcelain.

The permittivity for g^3 is simulated as $\epsilon_r = 0.88$[97]. Since the C4-FN-mix largely resembles the g^3 gas it is assumed that the permittivity of the C4-FN-mix is equal to that of g^3, $\epsilon_r = 0.88$. The permittivity for the materials used in the electrostatic simulation is provided in table 6.3.

Table 6.3: Values of relative permittivity used in the simulation

Material	Relative permittivity, ϵ_r
SF_6	1 [98]
CO_2-mix	1 [99]
C4FN-mix	0.88 [97]
g^3	0.88
Porcelain	5.5 [100]

The resulting electric field ratios ($\frac{E_{norm}}{E_{crit}}$) from the electrostatic simulation are given in figure 6.11, 6.12, 6.13, 6.14.

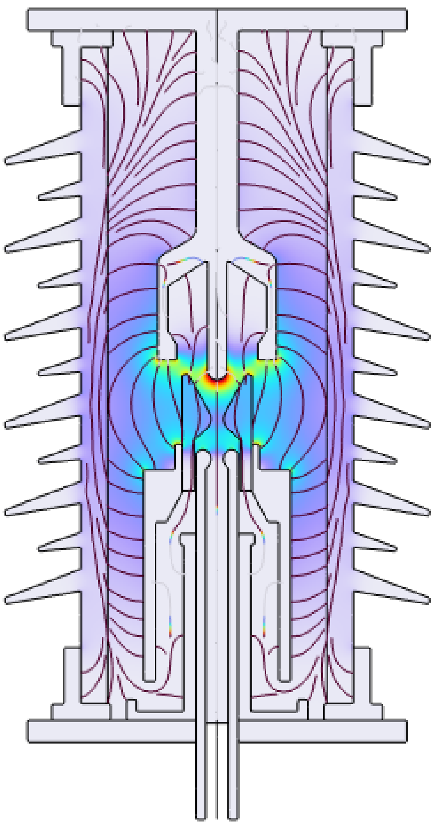


Figure 6.11: Interrupter electric field - SF_6

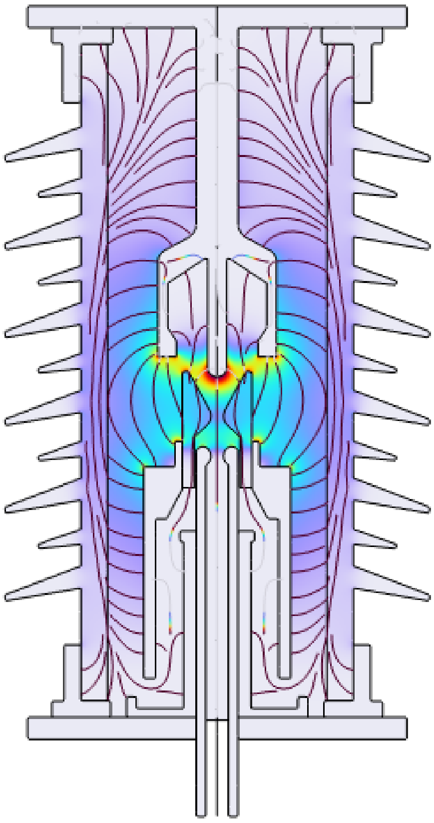


Figure 6.12: Interrupter electric field - 3.5 % C4-FN

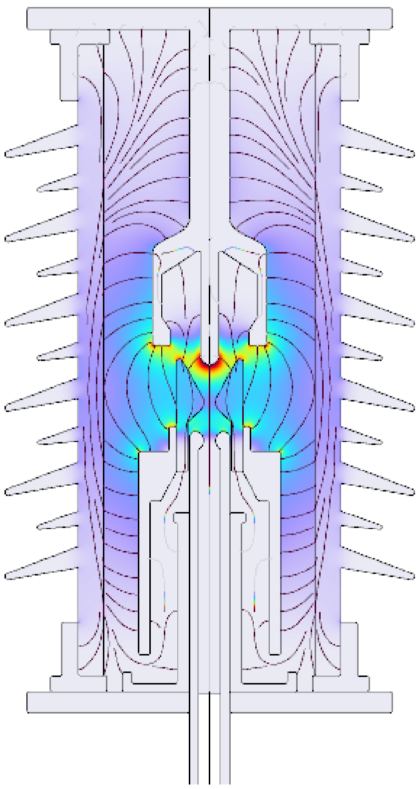


Figure 6.13: Interrupter electric field - g^3

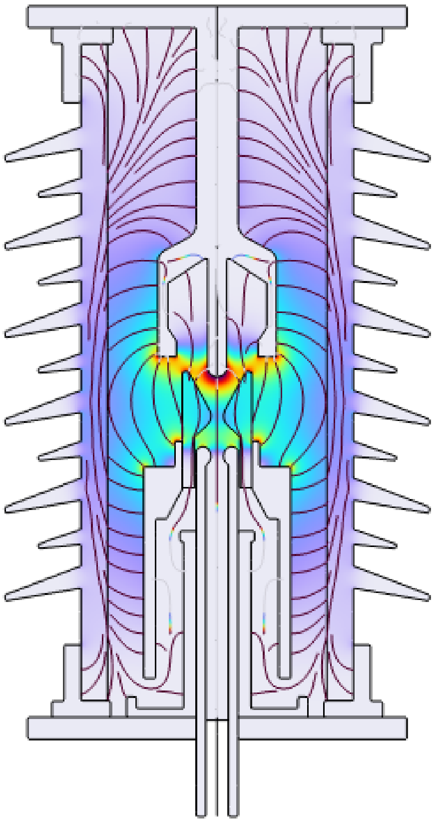


Figure 6.14: Interrupter electric field - CO_2

6.5 Scaling

The normal electric field along the symmetrical axis is extracted with a parametric sweep of the scaling factor, k, at different values until the local maximum of the alternative gas matches the SF_6 local maximum, meaning the gas alternative is operating as close to breakdown as SF_6 did originally. The field ratio along the symmetrical axis for SF_6 is provided in figure 6.15. The parametric sweeps for C4-FN, g^3 and CO_2 are provided in figure 6.16, 6.17 and 6.18, respectively.

The value of the scaling factor, k, are extracted from the figures. The scaling factor as well as the resulting widest distance of the interrupter is presented in table 6.4. The distance requirement refers to the distance between the circuit breaker and current transformer. Since the interrupter unit is scaled up, the distance between the devices will decrease. It can be observed that the CO_2 does not comply with the minimum distance requirement in the CAD model.

Table 6.4: Scale factor results

Gas alternative	Scaling	Length* [mm]	Distance to adjacent apparatus ** [mm]
SF_6	-	588	3115
CO_2-mix	1.5	882	2968
C4-FN-mix	1.2	706	3056
g^3	1.1	647	3086

*Widest distance of the interrupter

** Distance requirement 3000 mm [19]

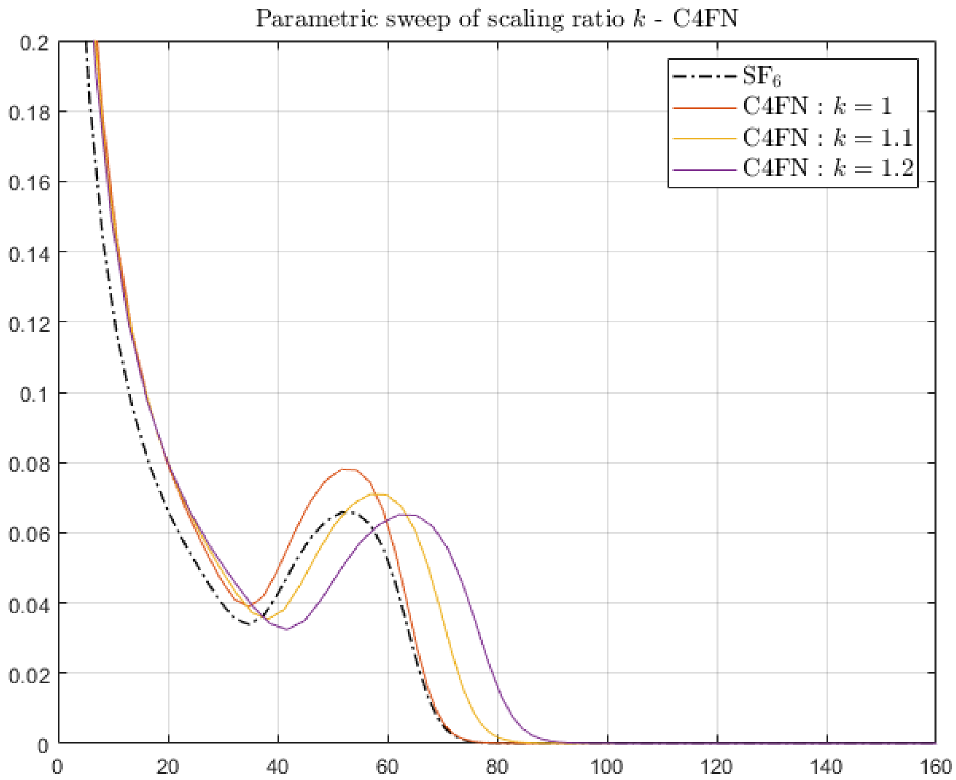


Figure 6.16: Ratio of normal and critical electric field along the symmetrical axis - C4-FN

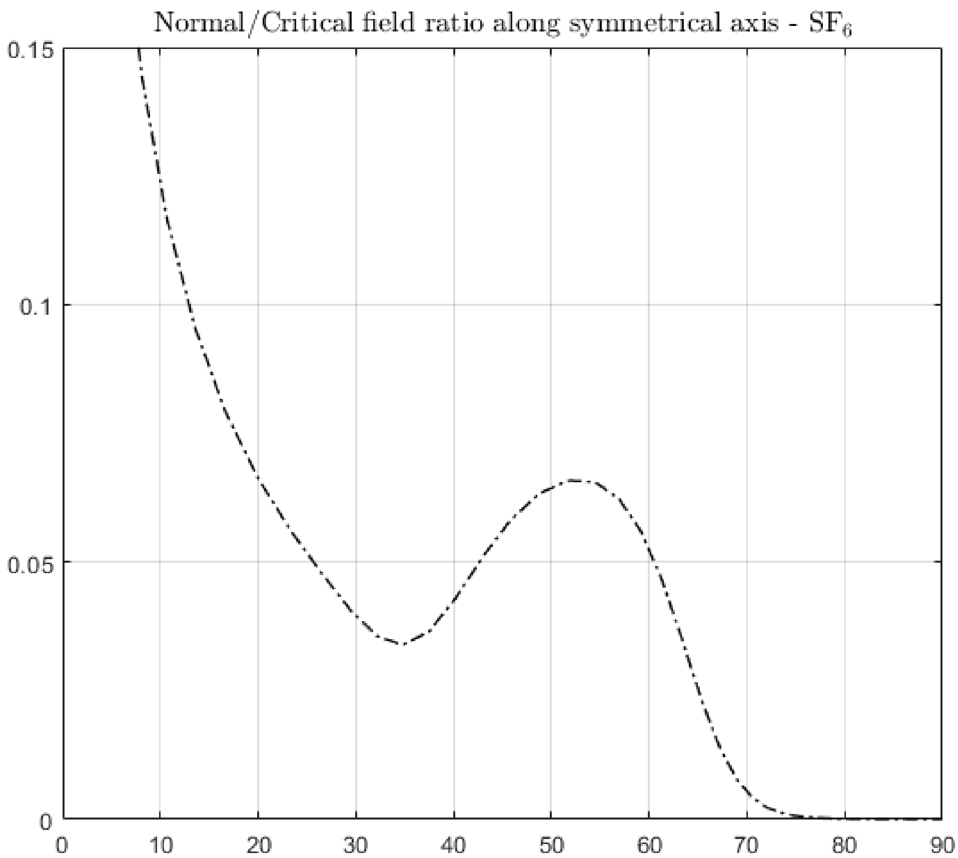


Figure 6.15: Ratio of normal and critical electric field along the symmetrical axis - SF_6

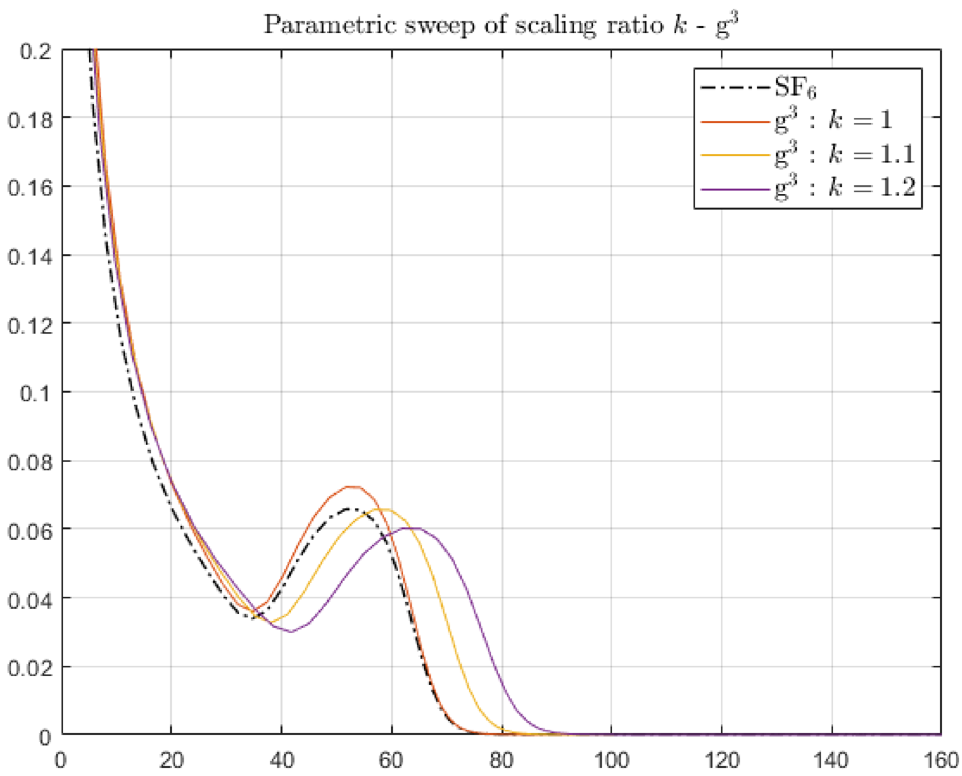


Figure 6.17: Ratio of normal and critical electric field along the symmetrical axis - g^3

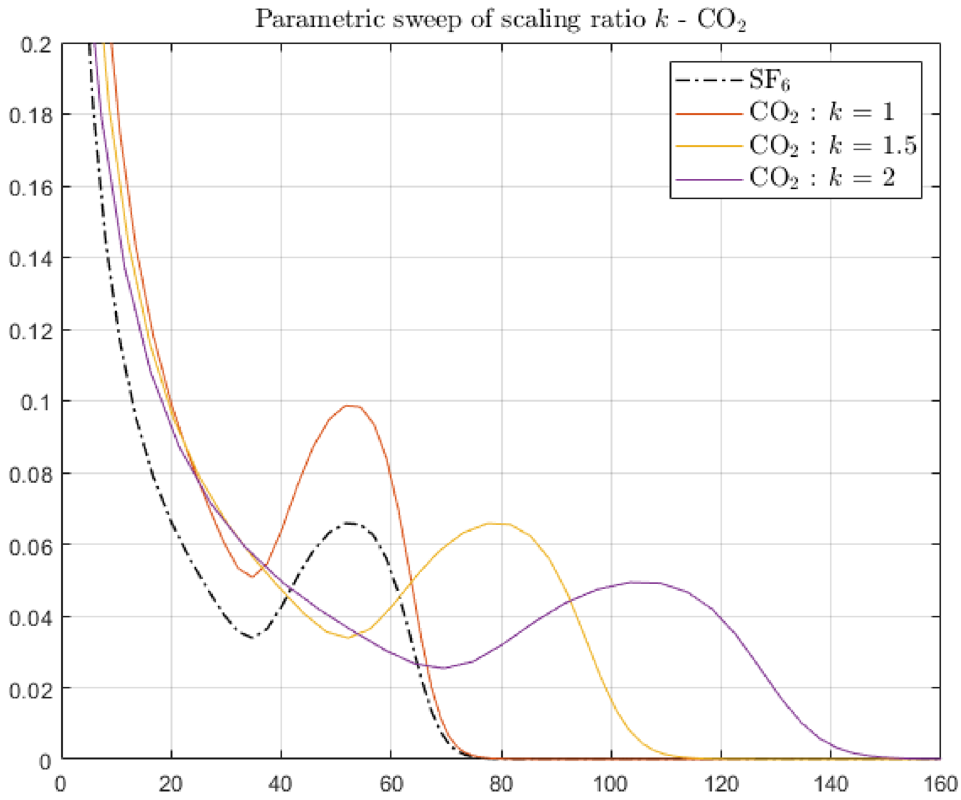


Figure 6.18: Ratio of normal and critical electric field along the symmetrical axis - CO_2

7
Discussion

7.1 Power system

The results point out that there are several issues following an integration of renewable energy into the power system. The results does not specify that what extent these issues will affect the power system. Without more data it is extremely difficult to predict the future power quality as well as the future stability of the system. Although no such prediction is made, it is still certain that the future power system will experience issues in power quality and stability.

From the future scenarios provided by the Swedish energy agency and SVK it can be observed that nuclear power is expected, in several scenarios, to increase in the coming future.

The penetration of RES depends on several factors. Future power demand and volume of nuclear power generation. From the future predictions and scenarios given by the TSO and Energy Agency it is clear that both future power demand and share of nuclear power is uncertain. There are substantial differences in the predictions made by the TSO from 2021 and 2024. One may argue that the increased share of nuclear power in the 2024 analysis as well as the analysis from the Energy agency is a direct result of the shift government from the 2022 Swedish election, where the current government is more significantly more friendly towards nuclear power than the prior. The ambition of the Kristersson cabinet is to expand the nuclear generation of Sweden with prolonged lifetime of current reactors and development of new nuclear power. If the ambition becomes reality remains to be seen, but current public opinion demonstrates a positive attitude towards the proposition.

Even though the future scenarios may conflicting, they all predict an increased power demand and heavily increased wind power production. The scenarios also predicts that Sweden will go from a large power exporter to a being more reliant on energy import. Combining the fact that the production/consumption ratio will be lower together with more wind power, which is by nature irregular in its power production, refer to figure 4.1, it is clear that the future will have negative consequences on frequency stability. The need for ancillary services will increase.

The integration of RES will inevitably affect the voltage/frequency stability negatively. It will also impose challenges related to protection of the power system.

Due to the future issues related to power quality and harmonic content the need for mitigating strategies will increase. FACTS have been demonstrated to posses several beneficial characteristics that will be able to alleviate future challenges for the power system by increasing, voltage stability, rotor-angle stability and mitigation of harmonics. If the FACTS devices will be play a major role in the future remains to be seen. Conclusively, such an expansion is driven by economical factors. If the economical advantages outweigh the negative, such an expansion is likely.

7.2 Environmental

In the literature three different adequate SF_6 alternatives for circuit breakers were found, C4-FN, C5-FK and vacuum breakers. Several articles highlights C4-FN and C5-FK as the most promising alternatives. But as can be observed in 5.2.2, it seems that C4-FN is the more favourable option as it sees usage by several manufacturers.

The greatest environmental footprint from substations was found to be power loss related. It was also concluded that energy mix in which the station is operating under plays a major role in the environmental footprint related to power losses. Since this project is related specifically to the Swedish power system, it can be concluded that SF_6 emissions is the dominant factor for the Swedish power system.

The original purpose of the substation model was to, apart from providing the circuit breaker geometry, simulate the electric field surrounding the station and evaluate the resulting electrical field after increasing the size. Unfortunately, this idea was never realized as it would require an extensive workload in the simulation part. The model itself should be considered realistic, as it is based upon real substation components and the distances and mechanical support structures are provided by a real CAD-model from a real substation.

There are several circumstances that make the results from the electrostatic simulation ambiguous. The internal interrupter geometry is selected from researching the subjected and then scaled to match the size of a real interrupter provided by Hitachi. If the geometry on which the simulation is based upon is accurate is doubtful. Additionally, the critical electric field calculation is based on calculating the bond energy for the compounds along with the required energy to break the compound, a method proposed by El-Zein[20] and used in a similar COMSOL study in [97]. In the article by El-Zein, the breakdown voltages are calculated accurately in comparison to traditional calculations and experimental results. The calculated critical fields in this thesis could very well be correct on a theoretical level under ideal conditions, but the results are applied to real applications. There are several physical entities that interplay during the breakdown phenomenon, pressure and distance, which we know from Paschen's law, field homogeneity and several material dependent properties. Furthermore, the interrupter is studied under a static condition, whereas in reality, the circuit breaker is a dynamic unit.

Atmospheric pressure is assumed in the critical field calculation, meaning that the values of the critical should be considerably lower than a real circuit breaker, where gas pressures are significantly higher. However, incorporating a lower pressure is beneficial as the studied circuit breaker needs to be able to operate under Swedish temperature conditions, meaning that the lowest ambient temperature in which the circuit breaker needs to able to operate under, is - 40 ° C (Southern Sweden). By adopting a lower pressure, the temperature ratings are improved.

There are uncertainties in the calculated results in the technical study, but this does not have to be of great concern. The purpose of the electrostatic simulation is not to extract precise results, but to find at which scale does the gas alternative give the same $\frac{E_{norm}}{E_{crit}}$ ratio as SF_6.

Furthermore, the simulation results concludes that the CO_2 circuit breaker does not achieve the necessary distance demands. This is an interesting topic from a future outlook. SF_6 will inevitably be banned, and once the SF_6 breakers in the substations are finally replaced, what happens if the substituting circuit breaker does not achieve the distance demands. Will the each apparatus in the substation have to be moved? If not, what are the electrical safety concerns?

Although the CO_2 mixture option does not comply with current distance regulation, the two other alternatives do. The C4-FN mixtures is able to maintain performance without resulting in over sizing the device. Originally, one of the strengths from SF_6 is the possibility of keeping a minimum size, which may also be realized by using the C4-FN mixtures while significantly reducing the GWP.

In the thesis, transformer insulation is briefly reflected upon. It may be observed that esters and dry-type transformer posses several beneficial qualities over mineral oil, mainly fire safety aspects and higher dielectric strength. As mineral oil has an undesirable environmental burden, it would be positive to be able to phase out the usage in transformers, which needs large volumes. Although phasing out mineral oil from the power system is desirable, it does not seem likely on a macroscopic scale. Dry-type transformers suffers in the high voltage ratings and esters displays poor performance in lower temperatures, which is inappropriate for application in the Swedish climate.

Something that is not reflected upon in this report is the price of the SF_6 alternatives. The reason for this is simply that such data is hard to find. However, since there is a limited amount of worldwide installations it can be assumed that the alternatives are significantly more expensive than the traditional circuit breakers. As SF_6 will be banned in the future the demand for the alternative breakers will increase and price decrease.

7.3 Future work

This main background question of the thesis is regarding the future challenges imposed on substations. The report covers a wide surface of that question, but merely scratches the surface on an array of subjects such as digitization, protection, etc. This thesis mainly covers SF_6 alternatives specifically for AIS circuit breakers. How the the proposed alternatives would perform in GIS applications is also an interesting topic as SF_6

As shortly reflected in the previous section in the discussion, what would happen if the distance demands are not met when substituting the SF_6 circuit breakers. This is an interesting topic that could be investigated in the future.

8
Conclusion

In conclusion, this thesis has examined the future challenges facing substations in the Swedish distribution and transmission system, particularly considering the anticipated surge in renewable energy production. The inevitable transition towards a power system characterized by a high penetration of renewable energy sources presents various issues that cannot be overlooked.

As highlighted throughout this report, integrating significant amounts of renewable energy into the power grid results in several negative effects. These include disruptions to frequency stability, rotor angle stability, voltage stability, and power system protection, in combination with the injection of harmonic content that further challenges the system's overall power quality.

Technologies such as energy storage systems and Flexible Alternating Current Transmission Systems (FACTS) devices have emerged as effective tools to mitigate the highlighted consequences of renewable energy integration.

Moreover, the impending ban on sulfur hexafluoride (SF_6), a highly potent greenhouse gas widely used in the electric power industry, necessitates the need of alternative insulation gases. Among these alternatives, C4-FN stands out for its high dielectric strength and significantly lower global warming potential. Its adoption could significantly contribute to reducing the environmental impact of substations in the Swedish power system.

Bibliography

[1] SVK, “Tema - energiomställningen,” Available at https://www.svk.se/press-och-nyheter/temasidor/tema-energiomstallningen/ (2023/12/04).

[2] U. E. P. Agency, “Sulfur hexafluoride (sf6) basics,” Available at https://www.epa.gov/eps-partnership/sulfur-hexafluoride-sf6-basics (2024/04/29).

[3] ABB, “Förbud mot farlig gas i ställverk - så förbereder du ditt företag på eu:s nya planerade lag,” Available at https://new.abb.com/news/sv/detail/97608/forbud-mot-farlig-gas-i-stallverk-sa-forbereder-du-ditt-foretag-pa-eus-nya-planerade-lag (2023/11/21).

[4] P. Chen, “Inertial response and frequency containment process,” Lecture Notes, 2022.

[5] T. A. Le, “Small signal stability (sss),” Lecture Notes, 2023.

[6] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. Van Cutsem, and V. Vittal, “Definition and classification of power system stability ieee/cigre joint task force on stability terms and definitions,” *IEEE Transactions on Power Systems*, vol. 19, no. 3, pp. 1387–1401, 2004.

[7] T. A. Le, “Overview of power system stability; simplified models of synchronous generators,” Lecture Notes, 2023.

[8] ——, “Transient stability,” Lecture Notes, 2023.

[9] ——, “Voltage stability,” Lecture Notes, 2023.

[10] S. Direct, “Electrical breakdown,” Available at https://www.sciencedirect.com/topics/materials-science/electrical-breakdown.

[11] J. Blennow, “Electric breakdwon in gas under low presusure,” Lecture Notes, 2023.

[12] A. Küchler, *High voltage engineering*, 5th ed., ser. VDI-Buch. Wiesbaden, Germany: Springer, May 2017.

[13] K. Academy, “Electronegativity,” Available at https://www.khanacademy.org/science/hs-chemistry/x2613d8165d88df5e:states-of-matter/x2613d8165d88df5e:electronegativity-and-bond-polarity/v/electronegativity-trends.

[14] A. Hopf, J. A. Britton, M. Rossner, and F. Berger, “Dielectric strength of sf6 substitutes, alternative insulation gases and pfc-gas-mixtures,” in *2017 IEEE Electrical Insulation Conference (EIC)*, 2017, pp. 209–212.

[15] L. Lopez, “The 15 most frequently asked questions about sf6 gas and sf6 breakers,” Available at https://blog.wika.us/knowhow/15-most-frequently-asked-questions-about-sf6-gas-and-sf6-breakers/.

[16] W. M. Leeds, T. E. Browne, and A. P. Strom, “The use of sf6 for high-power arc quenching,” *Electrical Engineering*, vol. 76, no. 9, pp. 788–791, 1957.

[17] Liyond, “What is a high voltage circuit breaker?” Available at https://www.elecspare.com/what-are-high-voltage-circuit-breaker-types/ (2024/04/23).

[18] Savree, “Sf6 circuit breaker,” Available at https://savree.com/en/encyclopedia/sf6-circuit-breaker (2024/04/23).

[19] E.ON, “Anläggningsdirektiv,” Available at https://www.eon.se/content/dam/eon-se/swe-documents/leverantorer/swe-tb-d10-0015685-anlaggningsdirektiv-regionnat.pdf.

[20] A. El-Zein, M. Talaat, and A. Samir, “New approach to breakdown equation in gases based on energy concept from inception stage to arc condition,” *Vacuum*, vol. 194, p. 110614, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0042207X21005625

[21] SVK, “Elstatistik,” Available at https://www.svk.se/om-kraftsystemet/kraftsystemdata/elstatistik/ (2024/01/29).

[22] ——, “Elstatistik,” Available at https://www.svk.se/om-kraftsystemet/kraftsystemdata/elstatistik/ (2024/04/17).

[23] Elfakta, “Elanvändning,” Available at https://www.ekonomifakta.se/Fakta/elfakta/energianvandning/Elanvandning/ (2024/04/17).

[24] Hybrit, “En värdekedja för fossilfritt stål,” Available at https://www.hybritdevelopment.se/en-fossilfri-framtid/en-vardekedja-for-fossilfritt-stal/ (2024/04/17).

[25] LKAB, “Snabbare takt och högre mål i lkab:s omställning mot en hållbar framtid,” Available at https://lkab.com/press/snabbare-takt-och-hogre-mal-i-lkabs-omstallning-mot-en-hallbar-framtid/ (2024/01/23).

[26] Energiföretagen, “Elektrifiering,” Available at https://www.energiforetagen.se/energifakta/elsystemet/elektrifiering/ (2024/01/23).

[27] Vattenfall, “Elektrifiering av transporter – samarbeten för eldrivna fordon,” Available at https://group.vattenfall.com/se/var-verksamhet/vagen-mot-ett-fossilfritt-liv/elektrifiering-av-transporter (2024/01/23).

[28] S. E. Agency, “Scenarier över sveriges energisystem 2023,” Available at https://energimyndigheten.a-w2m.se/Home.mvc?ResourceId=213739 (2024/01/23).

[29] Vattenfall, “Scenarier över sveriges energisystem 2023,” Available at https://group.vattenfall.com/se/var-verksamhet/vagen-mot-ett-fossilfritt-liv/minska-industrins-koldioxidutslapp/fossilfri-vatgas?gad_source=1&gclid=EAIaIQobChMInrK927fzgwMVu1eRBR1H2wr3EAAYAyAAEgKHUPD_BwE (2024/01/23).

[30] SVK, “Scenarier över sveriges energisystem 2023,” Available at https://www.svk.se/om-kraftsystemet/energilagring-med-batterier-och-vatgas/ (2024/01/23).

[31] ——, “Långsiktig marknadsanalys 2021 - scenarier för elsystemets utveckling fram till 2050,” Sundbyberg, Tech. Rep., 2021.

[32] ——, “Långsiktig marknadsanalys,” Available at https://www.svk.se/siteassets/om-oss/rapporter/2024/lma_2024.pdf (2024/01/23).

[33] Regeringen, “Regeringen lanserar en färdplan för ny kärnkraft i sverige,” Available at https://www.regeringen.se/pressmeddelanden/2023/11/regeringen-lanserar-en-fardplan-for-ny-karnkraft-i-sverige/ (2024/01/22).

[34] Novus, “Allmänheten om kärnkraftnovember 2023,” Available at https://www.analys.se/wp-content/uploads/2023/11/20231112-analysgruppen-novus-allmanheten-om-karnkraft-1.pdf (2024/01/23).

[35] O. Lindström, “Bara en av tio vill avveckla kärnkraften,” *SVD*, 2022.

[36] Vattenfall, “Allmänheten om kärnkraftnovember 2023,” Available at https://group.vattenfall.com/se/nyheter-och-press/nyheter/2023/svenskarnas-stod-for-karnkraft-haller-starkt (2024/01/23).

[37] ——, “Vindkraftsprojekt kriegers flak,” Available at https://group.vattenfall.com/se/var-verksamhet/vindprojekt/kriegers-flak (2024/01/23).

[38] OX2, “Galene,” Available at https://www.ox2.com/sv/sverige/projekt/galatea-galene/ (2024/01/23).

[39] Vattenfall, “Vindkraftsprojekt kattegatt syd,” Available at https://group.vattenfall.com/se/var-verksamhet/vindprojekt/kattegatt-syd (2024/01/23).

[40] Regeringen, “Havsbaserad vindkraft,” Available at https://www.regeringen.se/regeringens-politik/miljo-och-klimat/havsbaserad-vindkraft/ (2024/01/23).

[41] X. Liang, “Emerging power quality challenges due to integration of renewable energy sources,” *IEEE Transactions on Industry Applications*, vol. 53, no. 2, pp. 855–866, 2017.

[42] H. Eroğlu, E. Cuce, P. Mert Cuce, F. Gul, and A. Iskenderoğlu, “Harmonic problems in renewable and sustainable energy systems: A comprehensive review,” *Sustainable Energy Technologies and Assessments*, vol. 48, p. 101566, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2213138821005804

[43] elspec, “Power harmonics in electrical systems,” Available at https://www.elspec-ltd.com/what-are-harmonics/ (2024/01/29).

[44] H. Eroğlu, E. Cuce, P. Mert Cuce, F. Gul, and A. Iskenderoğlu, “Harmonic problems in renewable and sustainable energy systems: A comprehensive review,” *Sustainable Energy Technologies and Assessments*, vol. 48, p. 101566, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2213138821005804

[45] X. Liang and C. Andalib Bin-Karim, “Harmonics and mitigation techniques through advanced control in grid-connected renewable energy sources: A review,” *IEEE Transactions on Industry Applications*, vol. 54, no. 4, pp. 3100–3111, 2018.

[46] C. D. Iweh, S. Gyamfi, E. Tanyi, and E. Effah-Donyina, “Distributed generation and renewable energy integration into the grid: Prerequisites, push factors, practical options, issues and merits,” *Energies*, vol. 14, no. 17, 2021. [Online]. Available: https://www.mdpi.com/1996-1073/14/17/5375

[47] M. Meskin, A. Domijan, and I. Grinberg, “Impact of distributed generation on the protection systems of distribution networks: analysis and remedies – review paper,” *IET Generation, Transmission & Distribution*,

vol. 14, no. 24, pp. 5944–5960, 2020. [Online]. Available: https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/iet-gtd.2019.1652

[48] G. Kaur and M. Vaziri, "Effects of distributed generation (dg) interconnections on protection of distribution feeders," in *2006 IEEE Power Engineering Society General Meeting*, 2006, pp. 8 pp.–.

[49] SVK, "Stödtjänster och avhjälpande åtgärder," Available at https://www.svk.se/om-kraftsystemet/om-systemansvaret/verktyg-for-systemdrift/stodtjanster-och-avhjalpande-atgarder/ (2024/02/02).

[50] ——, "Om olika reserver," Available at https://www.svk.se/aktorsportalen/bidra-med-reserver/om-olika-reserver/ (2024/02/07).

[51] ——, "Snabb frekvensreserv (frr)," Available at https://www.svk.se/aktorsportalen/bidra-med-reserver/om-olika-reserver/ffr/ (2024/02/07).

[52] ——, "Frekvenshållningsreserv normaldrift (fcr-n)," Available at https://www.svk.se/aktorsportalen/bidra-med-reserver/om-olika-reserver/fcr-n/ (2024/02/07).

[53] ——, "Frekvenshållningsreserv störning uppreglering (fcr-d upp)," Available at https://www.svk.se/aktorsportalen/bidra-med-reserver/om-olika-reserver/fcr-n/ (2024/02/07).

[54] Vattenfall, "Batterilagringssystems," Available at https://group.vattenfall.com/se/var-verksamhet/vagen-mot-ett-fossilfritt-liv/batterilagringssystem (2024/03/04).

[55] J. WICKSTRÖM, "Därför satsar energibolagen på batterilager," Available at https://www.energi.se/artiklar/2023/maj-2023/darfor-satsar-energibolagen-pa-batterilager/ (2024/03/04).

[56] J. A. P. Lopes, A. G. Madureira, M. Matos, R. J. Bessa, V. Monteiro, J. L. Afonso, S. F. Santos, J. P. S. Catalão, C. H. Antunes, and P. Magalhães, "The future of power systems: Challenges, trends, and upcoming paradigms," *WIREs Energy and Environment*, vol. 9, no. 3, p. e368, 2020. [Online]. Available: https://wires.onlinelibrary.wiley.com/doi/abs/10.1002/wene.368

[57] K. Divya and J. Østergaard, "Battery energy storage technology for power systems—an overview," *Electric Power Systems Research*, vol. 79, no. 4, pp. 511–520, 2009. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378779608002642

[58] M. Bongiorno, "Lectures 5 6: Shunt-connected facts - tcr," Lecture Notes, 2023.

[59] ——, "Lecture 9/10: Series-connected facts devices – tcsc and sssc," Lecture Notes, 2023.

[60] ——, "Lecture 4: Concepts of power system control and operation," Lecture Notes, 2023.

[61] ——, "Lecture 13: Custom power controllers," Lecture Notes, 2023.

[62] E. Technology, "Facts – flexible ac transmission system – types of facts controllers devices," Available at https://www.electricaltechnology.org/2020/06/facts-flexible-ac-transmission-system.html (2024/02/29).

[63] M. Bongiorno, "Lecture 11: Power quality and custom power," Lecture Notes, 2023.

[64] G. M. Shafiullah and A. M. T. Oo, "Analysis of harmonics with renewable energy integration into the distribution network," in *2015 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)*, 2015, pp. 1–6.

[65] T. A. Le, "Lecture 7: Overcurrent protection (2/2)," Lecture Notes, 2023.

[66] COPADATA, "What is a digital substation?" Available at https://www.copadata.com/sv/industrier/energi-infrastruktur/energy-insights/what-is-a-digital-substation/energy-infrastructure-2/ (2024/03/08).

[67] R. Hunt, B. Flynn, and T. Smith, "The substation of the future: Moving toward a digital solution," *IEEE Power and Energy Magazine*, vol. 17, no. 4, pp. 47–55, 2019.

[68] A. G. Palumberi, M. Rebolini, P. Bonci, A. Giorgi, and F. Grasso, "Life cycle assessment of a 132 kv gas insulated switchgear substation using lca methodology," in *2018 AEIT International Annual Conference*, 2018, pp. 1–6.

[69] C. G. B. I. P. A. T. Turconi, Roberto. Simonsen, "Life cycle assessment of the danish electricity distribution network," *The International Journal of Life Cycle Assessment*, vol. 19, pp. 100–108, 2014. [Online]. Available: https://doi.org/10.1007/s11367-013-0632-y

[70] P. T. A. Gargiulo, Alessia. Girardi, "Lca of electricity networks: a review," *The International Journal of Life Cycle Assessment*, vol. 22, pp. 1502–1513, 2017. [Online]. Available: https://doi.org/10.1007/s11367-017-1279-x

[71] T. R. H. E. G. Jorge, Raquel Santos. Hawkins, "Life cycle assessment of electricity transmission and distribution—part 2: transformers and substation equipment," *The International Journal of Life Cycle Assessment*, vol. 17, pp. 184–191, 2012. [Online]. Available: https://doi.org/10.1007/s11367-011-0336-0

[72] Y. Serdyuk, "L5: Gas discharges and breakdown in gases," Lecture Notes, 2023.

[73] C. T. Dervos and P. Vassiliou, "Sulfur hexafluoride (sf6): Global environmental effects and toxic byproduct formation," *Journal of the Air & Waste Management Association*, vol. 50, no. 1, pp. 137–141, 2000. [Online]. Available: https://doi.org/10.1080/10473289.2000.10463996

[74] Y. K. Edgar Dullni, Thor Endre and R. Coccioni, "Reducing sf6 emissions from electrical switchgear," *Carbon Management*, vol. 6, no. 3-4, pp. 77–87, 2015. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/17583004.2015.1090056

[75] M. U. K. . M. N. A. T. Ahmad Raza, M. Kamran, "Potential of eco-friendly gases to substitute sf6 for electrical hv applications as insulating medium: A review," *TEPES*, vol. 2, pp. 94–102, 2022. [Online]. Available: https://www.tepesjournal.org/Content/files/TEPES%20April%202022-s%C4%B1k%C4%B1%C5%9Ft%C4%B1r%C4%B1ld%C4%B1.pdf#page=100

[76] P. Billen, B. Maes, M. Larrain, and J. Braet, "Replacing sf6 in electrical gas-insulated switchgear: Technological alternatives and potential life cycle greenhouse gas savings in an eu-28 perspective," *Energies*, vol. 13, no. 7, 2020. [Online]. Available: https://www.mdpi.com/1996-1073/13/7/1807

[77] M. S. et al, “Recent trends in development of high voltage circuit breakers with sf6 alternative gases,” *Plasma Physics and Technology*, vol. 4, no. 1, pp. 8–12, 2018.

[78] E. Yedinak, K. Lentijo, and I. C. Kizilyalli, *Eliminating SF6 from Switchgear*. Cham: Springer International Publishing, 2023, pp. 409–427. [Online]. Available: https://doi.org/10.1007/978-3-031-26572-3_18

[79] H. Duzkaya, S. S. Tezcan, A. Ocak, A. K. Ozmen, O. Kilic, and V. Akbucak, “Comparison of electromechanical properties of medium voltage sf6 and vacuum circuit breakers,” in *2022 International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT)*, 2022, pp. 583–586.

[80] M. Hyrenbach and S. Zache, “Alternative insulation gas for medium-voltage switchgear,” in *2016 Petroleum and Chemical Industry Conference Europe (PCIC Europe)*, 2016, pp. 1–9.

[81] 3M, “3m™ novec™ 4710 insulating gas,” Available at https://multimedia.3m.com/mws/media/1132124O/3m-novec-4710-insulating-gas-tech-data-sheet.pdf?&fn=Novec-4710-Insulating-Gas-TDS_R13.pdf (2024/02/16).

[82] ——, “3m™ novec™ 5110 insulating gas,” Available at https://multimedia.3m.com/mws/media/1132123O/3m-novec-5110-insulating-gas.pdf?&fn=3M-Novec-5110-Insulating-Gas-TDS-FINAL_R6.pdf (2024/02/16).

[83] M. Perret, “C4-fn mixtures for high-voltage equipment,” Available at https://library.e.abb.com/public/283e290ba5624c9e8ba4c979db4c39cf/Handbook_C4-FN_Mixtures_for_High-Voltage_Equipment_V1.1.pdf?x-sign=AqUgEsKJW0W3GLQ6iukoeYokkztl9BS/jSk2NJGPeMRI+JL4NAmn4uhKs3TiH3es.

[84] Hitach, “Econiq™ 420pm63-ha,” Available at https://publisher.hitachienergy.com/preview?DocumentID=9AKK108468A2665&LanguageCode=en&DocumentPartId=&Action=launch&DocumentRevisionId=C (2024/02/19).

[85] ——, “Econiq™ - eco-efficient high-voltage portfolio,” Available at https://www.hitachienergy.com/products-and-solutions/high-voltage-switchgear-and-breakers/econiq-eco-efficient-hv-portfolio (2024/02/19).

[86] B. Pan, G. Wang, H. Shi, J. Shen, H.-K. Ji, and G.-S. Kil, “Green gas for grid as an eco-friendly alternative insulation gas to sf6: A review,” *Applied Sciences*, vol. 10, no. 7, 2020. [Online]. Available: https://www.mdpi.com/2076-3417/10/7/2526

[87] GE, “g^3 g3- ge’s sf sf6alternative for high voltage applications,” Available at https://www.gegridsolutions.com/hvmv_equipment/catalog/g3/ (2024/02/19).

[88] Siemens, “The blue portfolio – a cleaner future is here,” Available at https://www.siemens-energy.com/global/en/home/products-services/product-offerings/blue-high-voltage-products.html (2024/02/19).

[89] T. K. Saha and P. Purkait, *Transformer Insulation Materials and Ageing*, 2017, pp. 1–33.

[90] C. Krause, “Power transformer insulation – history, technology and design,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 19, no. 6, pp. 1941–1947, 2012.

[91] K. Mukhopadhyaya, A. Aryan, and A. Rajeev, “Analysis and comparison of characteristics of biodegradable transformer oils,” in *2021 7th International Conference on Advanced Computing and Communication Systems (ICACCS)*, vol. 1, 2021, pp. 90–94.

[92] A. K. Das, D. Ch Shill, and S. Chatterjee, “Coconut oil for utility transformers – environmental safety and sustainability perspectives,” *Renewable and Sustainable Energy Reviews*, vol. 164, p. 112572, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032122004683

[93] T. K. Saha and P. Purkait, *Transformer Insulation Materials and Ageing*, 2017, pp. 1–33.

[94] S. O. Oparanti, U. M. Rao, and I. Fofana, “Natural esters for green transformers: Challenges and keys for improved serviceability,” *Energies*, vol. 16, no. 1, 2023. [Online]. Available: https://www.mdpi.com/1996-1073/16/1/61

[95] T. Nunn, “A comparison of liquid-filled and dry-type transformer technologies,” in *2000 IEEE-IAS/PCA Cement Industry Technical Conference. Conference Record (Cat. No.00CH37047)*, 2000, pp. 105–112.

[96] Hitachi, “Live tank circuit breaker type edf sk 1-1,” Available at https://publisher.hitachienergy.com/preview?DocumentID=1HYB800001-005&LanguageCode=en&DocumentPartId=&Action=launch&DocumentRevisionId=F.

[97] A. El-Zein and A. Ibrahim, “Modelling g3 gas as an alternative gas for sf6 using comsol multiphysics,” *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 13, p. 1101, 06 2022.

[98] Solvay, “Sulphur hexafluoride,” Available at https://www.solvay.com/sites/g/files/srpend221/files/2018-08/SF6-Sulphur-Hexafluoride_0.pdf.

[99] E. toolbox, “Relative permittivity - the dielectric constant,” Available at https://www.engineeringtoolbox.com/relative-permittivity-d_1660.html.

[100] C. Nordling and Österman Jonny, *Physics Handbook for Science and Engineering*, 9th ed. Lund: Studentlitteratur ab, 2020.

A

Appendix 1

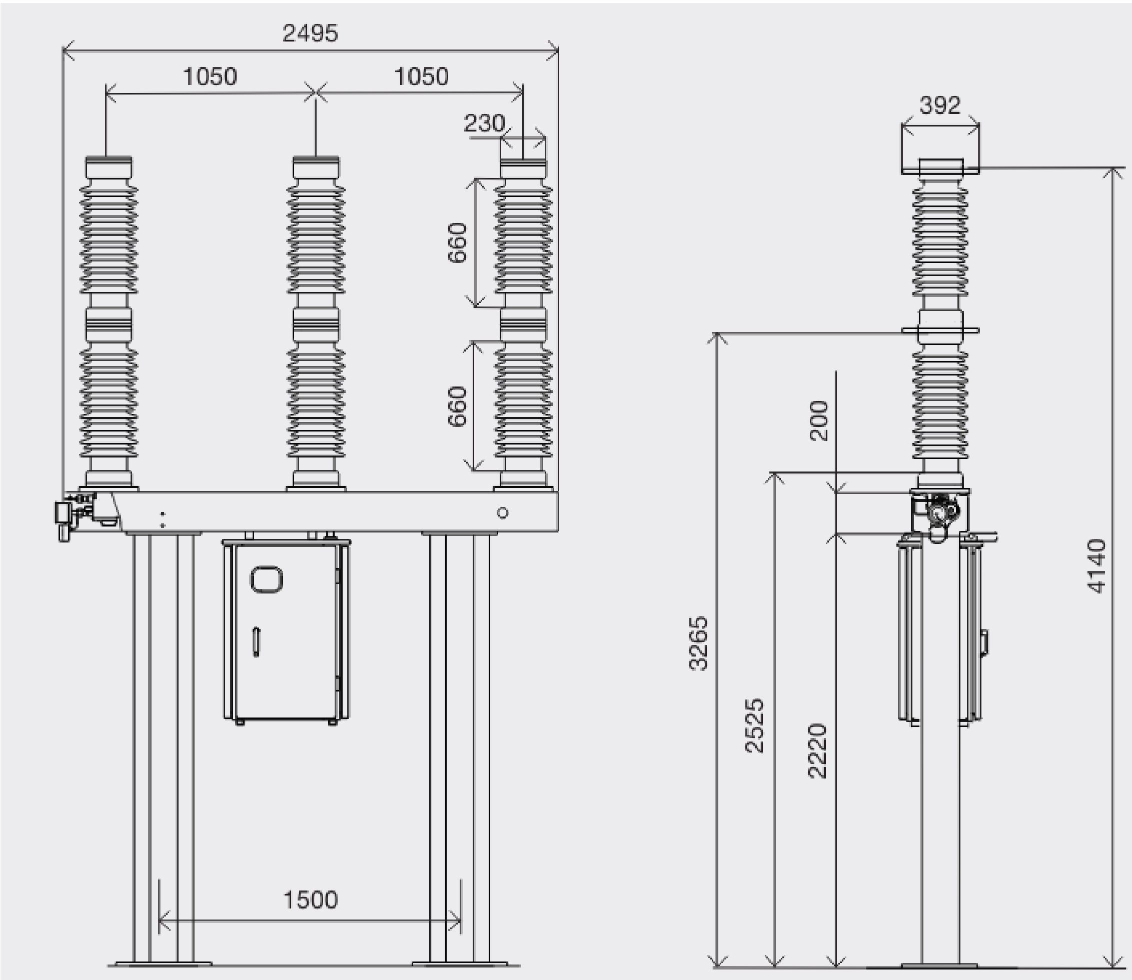


Figure A.1: LTB from Hitachi [96]

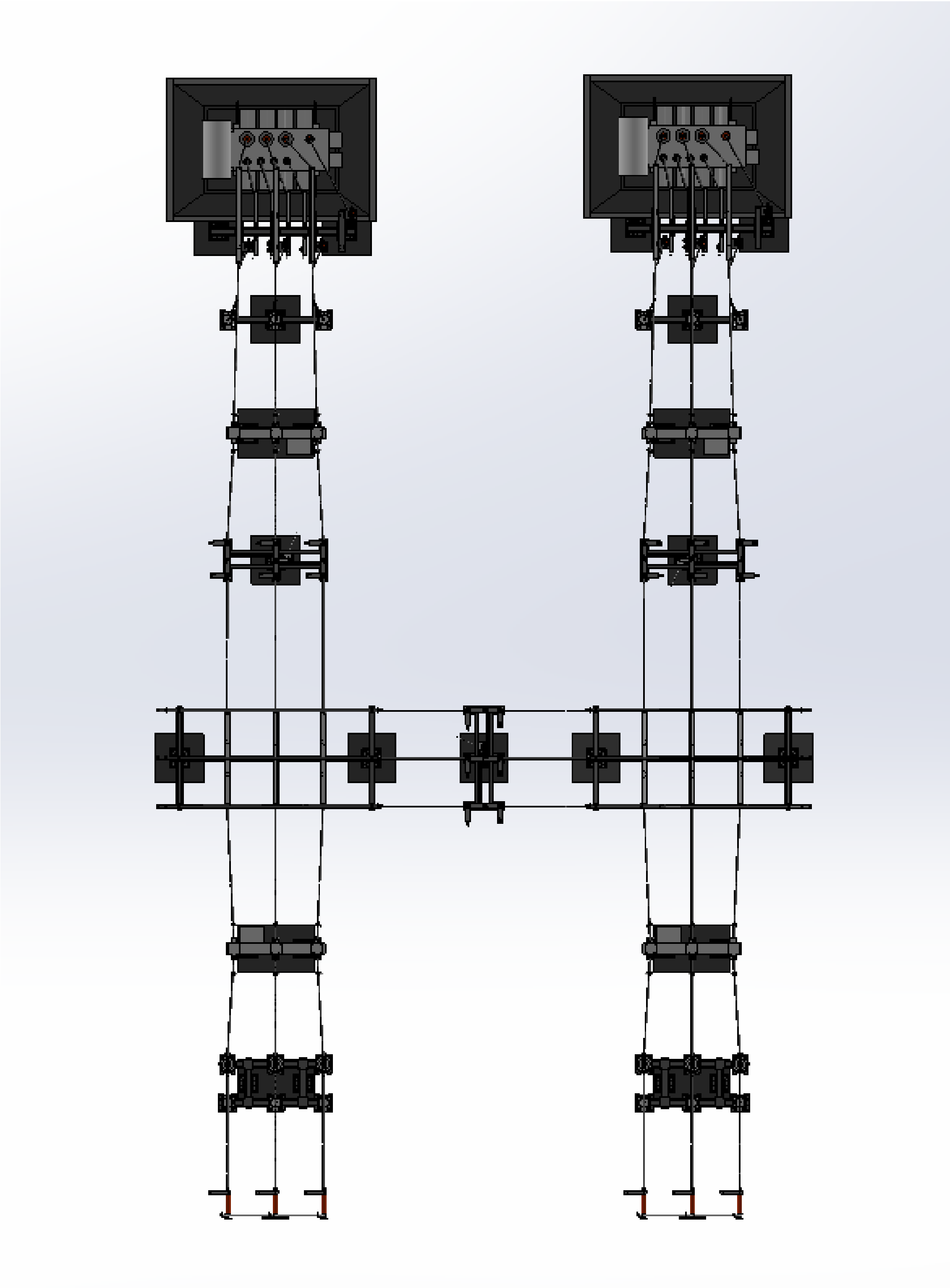


Figure A.2: Model from real substation of H-type configuration - top view

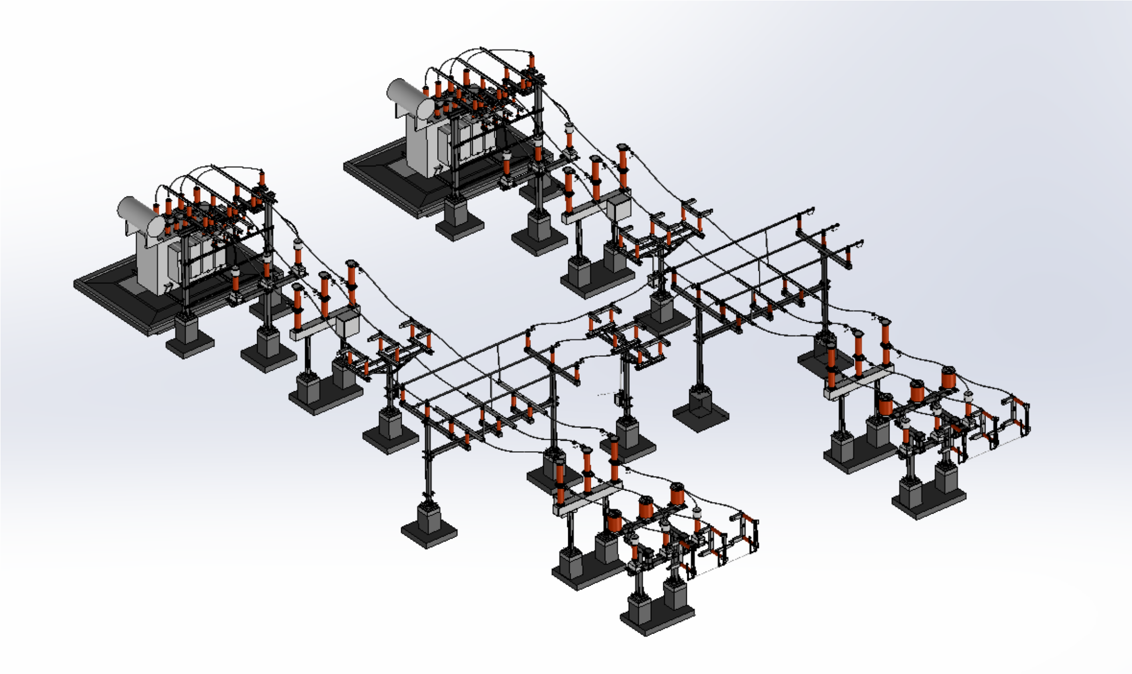


Figure A.3: Model from real substation of H-type configuration - isometric view

DEPARTMENT OF SOME SUBJECT OR TECHNOLOGY
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY