CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of Electrical Engineering
Department of Electrical Power Engineering

Bachelor Thesis

New Trends in Field of Power Circuit Breakers

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May 2023

CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE

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Bachelor’s thesis title in English:

New trends in field of the Power Circuit Breakers

Bachelor’s thesis title in Czech:

Nové trendy v oblasti výkonových vypínačů

Guidelines:

1. Prepare the overview of topic focused on power circuit breakers (current technological solutions and new trends)
2. Perform a comparative overview of SF6-free technologies and describe the motivation of replacing SF6 technology.
3. Perform a case study for replacing SF6 circuit breakers in some specific application.
4. Evaluate the possibilities and ability of SF6-free technology for replacing SF6 technology in studied case.

Bibliography / sources:

1. Benjamin K. Sovacool, Steve Griffiths, Jinsoo Kim, Morgan Bazilian. Climate change and industrial F-gases: A critical and systematic review of developments, sociotechnical systems and policy options for reducing synthetic greenhouse gas emissions, Renewable and Sustainable Energy Reviews, Volume 141, 2021, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2021.110759.
2. Xiaofei Yao, Jianhua Wang, Shaogui Ai, Zhiyuan Liu, Yingsan Geng, Zhiguo Hao. Vacuum Switching Technology for Future of Power Systems, Engineering, Volume 13, 2022, Pages 164-177,ISSN 2095-8099, https://doi.org/10.1016/j.eng.2021.11.020.
3. Wen-Tien Tsai. The decomposition products of sulfur hexafluoride (SF6): Reviews of environmental and health risk analysis,Journal of Fluorine Chemistry, Volume 128, Issue 11, 2007, Pages 1345-1352, ISSN 0022-1139, https://doi.org/10.1016/j.jfluchem.2007.06.008.

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Date of bachelor’s thesis assignment: **03.02.2023** Deadline for bachelor thesis submission: **26.05.2023**

Assignment valid until: **22.09.2024**

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Declaration

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Abstract

SF6 is a potent greenhouse gas that is used as an insulating and arc-quenching medium in medium voltage, high-voltage, extra-high voltage and ultra-high voltage electrical systems. Due to its high global warming potential, there is a growing interest in developing SF6 free technologies for electrical power equipment. The use of SF6 alternatives is becoming increasingly popular and various technologies are being developed to meet the demand. These technologies include vacuum circuit breakers, gas-insulated switchgear and circuit breakers using alternative gases. The new technologies have their advantages and disadvantages, but they all share the common goal of reducing the environmental impact of electrical power equipment. The adoption of SF6 free technologies is expected to grow rapidly in the coming years driven by increasing regulatory pressure and the need to mitigate climate change.

Keywords:
Circuit breaker, SF6, SF6 free technologies, CO2 gas mixture, green house gas.

Abstrakt

SF6 je silný skleníkový plyn, který se používá jako izolační a zhášecí médium v elektrických systémech VN a vyšších. Vzhledem k jeho s vysokému potenciálu globálního oteplování roste zájem o vývoj technologií bez-SF6 pro elektrická energetické zařízení. Použití alternativ SF6 je stále oblíbenější a rozmanitější technologie jsou vyvíjeny, aby uspokojily poptávku. Mezi tyto technologie patří vakuové vypínače, plynem izolované rozváděče a vypínače využívající alternativní plyny. Nové technologie mají své výhody a nevýhody, ale všechny mají společný cíl snížit vliv elektrických zařízení na životní prostředí. Očekávané nasazování technologií bez-SF6 v nadcházejících letech souvisí novými nařízeními a potřebou zmírňovat klimatické změny.

Klíčová slova:

Vypínač, SF6, Technologie bez SF6, Směs plynu CO2, Skleníkový plyn.

Contents

List of abbreviations

Abbreviation	In English
3M	Minnesota Mining and Manufacturing
ACB	Air Circuit Breaker
Al	Aluminum
C4-FN	Fluoronitrile
C4F7N	Heptafluorobutyronitrile
CB	Circuit breaker
CF4	Carbon tetrafluoride
CO2	Carbon dioxide
COF2	Carbonyl fluoride
EHV	Extra High Voltage
F2	Difluorine
F2O	Oxygen difluoride
G3	Green Gas for Grid
GE	General Electric
H2S	Hydrogen sulfide
HF	Hydrogen fluoride
HFC-23	Hydrochlorofluorocarbon-23
HV	High Voltage
kg	Kilogram
kV	Kilovolts
LV	Low Voltage
mfg	manufacturing
Mg	Magnesium
MV	Medium Voltage
N2	Nitrogen
NF3	Nitrogen trifluoride
OHL	Overheadlines
Ref	Reference
S2F10	Disulfur decafluoride
S2O2F10	Disulfur dioxide decafluoride
S2OF10	Pentafluoro-sulfur oxide
SF4	Sulfur tetrafluoride
SF6	Sulfur Hexafluoride
SiF4	Silicon tetrafluoride
SO2	Sulfur Dioxide
SO2F2	Sulfuryl fluoride
SOF2	Thionyl fluoride
SOF4	Thionyl tetrafluoride
UHV	Ultra High Voltage
VCB	Vacuum Circuit Breaker
VI	Vacuum Interuptor

1 Introduction

1.1 Objectives

Our environment is getting more poluted each day, and humanity must try to find better, ecological friendly solutions in every industry, even in such important field like electrical power engineer.

The aim of this Bachelor Thesis is to explain how and by which technologies is possible to replace SF6 Circuit Breakers. In next chapters, F-gases, traditional types, and new types of circuit breakers will be focused on.

1.2 Thesis Organisation

In the next point of the introduction, the dangers of F-gases for our planet will be discussed. In the “Circuit Breaker” section, the operation of a circuit breaker will be explained. In the “Traditional Circuit Breaker Technologies” section, a description of traditional Technologies in this area will be provided. In the “SF6 Free Technologies” section, the operation of some new Technologies will be explained. For traditional technologies, air, oil, SF6, and vacuum CBs will be mentioned. However, for new technologies, examples of solutions found by leading companies in this industry, such as GE or Siemens, and others, will be chosen. The “Case Study” will focus on analyzing and comparing some of available CBs on the market. In the “Results and Discussion” section, the decision on whether the industry is able to replace SF6 CBs with the new Technologies will be determined. In the “Conclusion” section, the possible future of CBs will be discussed.

1.3 Overview

During the last centuries, hummanity has made significant advancements. The industry and inovations has resulted in a better quality of life. However, the negative consequence of all this progress is the polution of the planet’s environment. The primary issue is the dependence on “synthetic” substances that are manufactured for various industries and applications. In the field of electrical power engineering, one such synthetic substance is SF6 gas, which is used as quenching medium and insulation gas. Unfortunately, SF6 is highly detrimental greenhouse gas [1].

SF6 gas belongs to the category of F-gases, which are considered the most harmful greenhouse gases. They have the potential to be 140 to 23,500 times more damaging to our climate than CO2. Moreover, SF6 is the most potent greenhouse gas ever recorded [1].

Fluorinated gases (F-gases) are artificially created gases that were initially used due to their ozone-friendly properties. However, they are highly detrimental greenhouse gases [2]. The reason why F-gases are so hazardous is twofold. Firstly, they possess strong and persistent characteristics, enabling them to effectively absorb infrared radiation, greatly impacting the climate. Secondly, they have complex decomposition processes and can remain in the atmosphere for thousands of years. For instance, there are no known microbiological processes in soils or plants capable of breaking down the bonds in SF6 molecules. Due to being human-made and synthesized in laboratories, these gases are much more concentrated than other greenhouse gases like CO2 or methane [1].

SF6 is widely utilized in electrical power engineering applications as a dielectric medium and insulating material for a wide range of equipment, including switchgear and circuit breakers, spanning from medium voltage to ultra-high voltage levels. SF6 gas possesses excellent insulation properties and can withstand high electric fields, making it an ideal choice for high-voltage applications. Furthermore, SF6 gas engineering applications. However, it is important to note that the decomposition gases of SF6 can be toxic to humans [3].

However, it is crucial for everyone to understand that F-gases are utilized in a wide range of applications. It is evident from the diagram and graph below (Figure 1.1, Figure 1.2) that SF6 is not the most extensively used or emitted F-gas in the industry. Nonetheless, this does not dimish the importance of addressing its impact. It is imperative for people to actively seek alternative to SF6 [1].

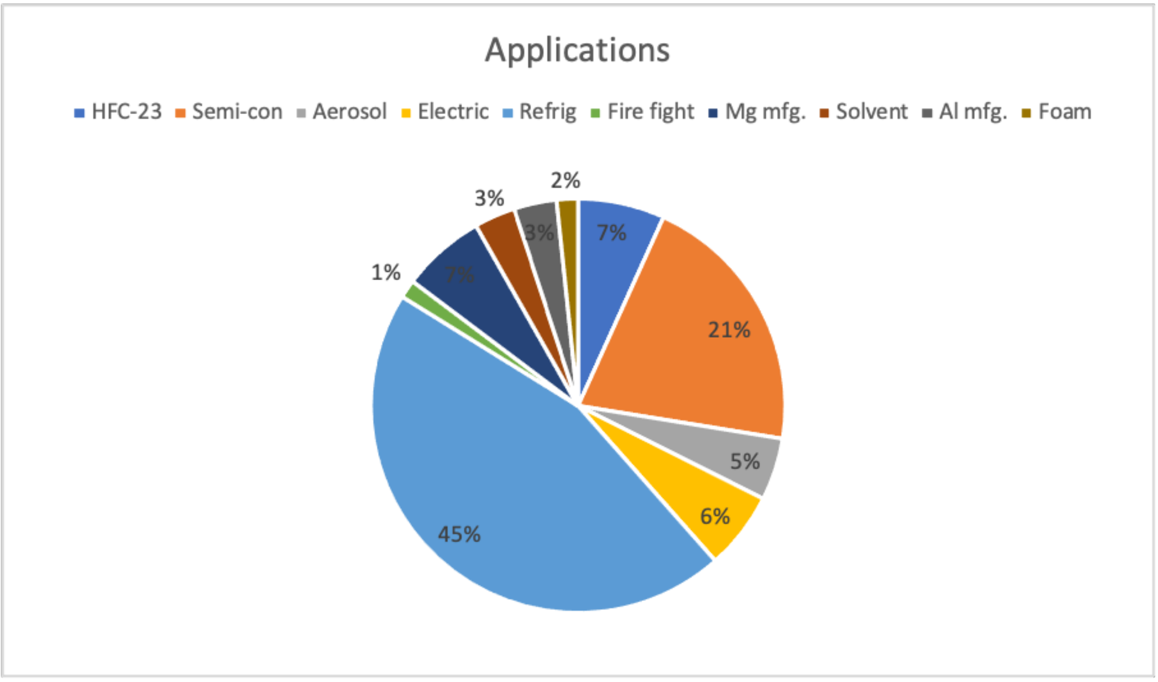


Figure 1.1: Percentage of F-gases used in different applications in USA.[1]

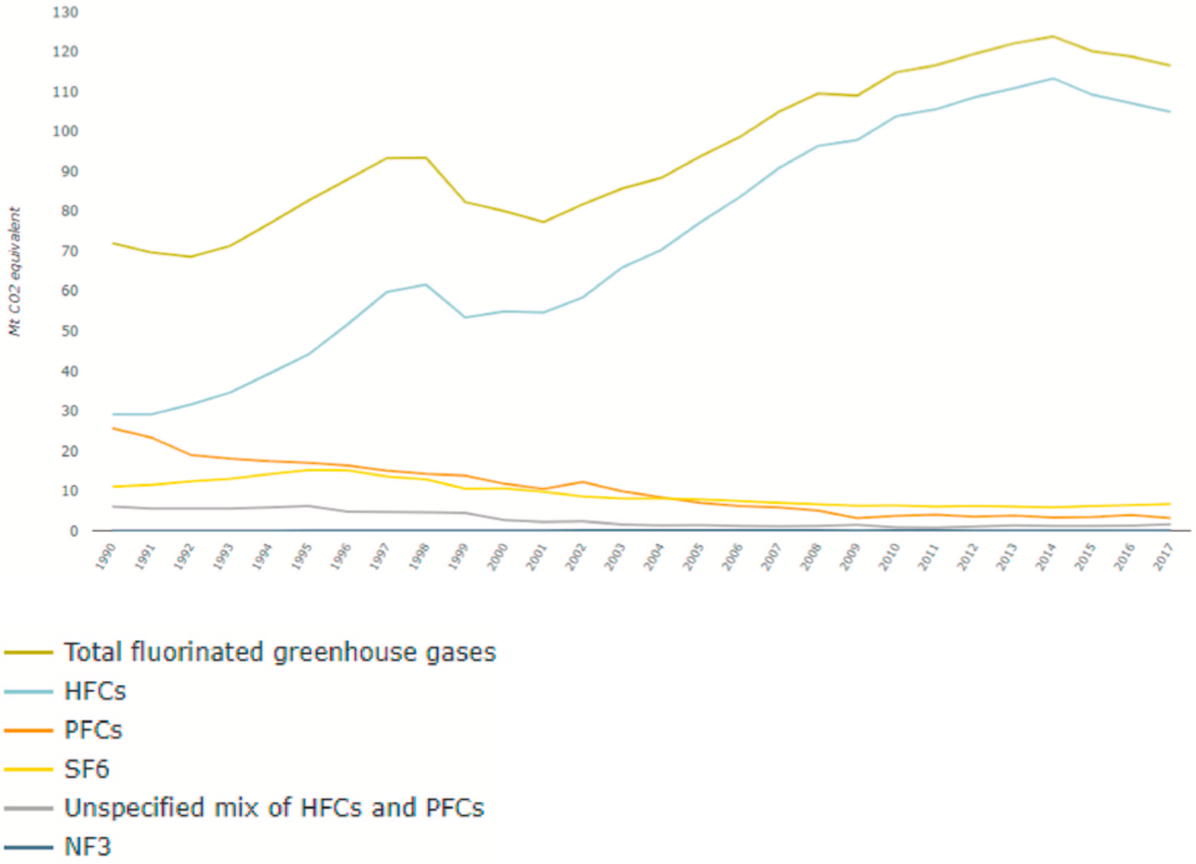


Figure 1.2: Global Emissions of F-gases from 1990 to 2017.[1]

The European Union has implemented several regulations to restrict the usage of SF6 gas in power engineering applications due to its high global warming potential. In 2014, Regulation number 517/2014 [4] was introduced, which limits the use of SF6 in new equipment. Subsequently, in 2018, Regulation number 842/2018 [5] was implemented to further restrict the use of SF6 gas in existing equipment, with a gradual phase-out by 2030 [6].

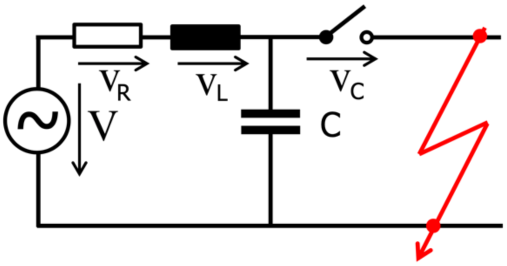
In response to these regulations, alternative technologies are being developed as potential replacements for SF6 gas in power engineering applications. Some of the contenders include clean air (a mixture of oxygen and nitrogen), g3 (green gas for grid), and CO2-based gas mixtures. However, further development is needed for these technologies to fully replace SF6 across all its applications. Another approach to replace SF6 technology is the utilization of vacuum technologies [7].

2 Circuit Breakers

A circuit breaker is an electrical switching device utilized to protect electrical circuits from damage caused by overloads, short circuits, or system faults. It serves the purpose of network reconfiguration as well. Essentialy, it acts as a switch capable of interrupting the flow of electrical current when abnormal conditions are detected, such as sudden current surges or short circuits. In cases where the voltage is low, circuit breakers also detect problems and automatically interrupt the flow. However, for medium to high voltages, a separate device is installed alongside the circuit breaker to detect faults and initiate the operation of circuit breaker. [8]

2.1 Principle of work

In each point of the network, where CB is installed, we can assume the following circuit[9]:



Short circuit equivalent is represented by R and L elements and also parasite capacity of the OHL and cables (parameter C) should be taken into account.

$$Ri + L\frac{di}{dt} + v_c = V\cos(\omega t) \qquad (1)$$

Where: i – current, t – time, V – voltage, ω - angular frequency, v_c – voltage at the circuit breker

$$i = C\frac{dv_c}{dt} \qquad (2)$$

$$RC\frac{dv_c}{dt} + LC\frac{d^2v_c}{dt^2} + v_c = V\cos(\omega t) \qquad (3)$$

$$\gamma = \frac{R}{L} \qquad (4)$$

$$\omega_0^2 = \frac{1}{LC} \qquad (5)$$

$$\frac{d^2v_c}{dt^2} + \gamma\frac{dv_c}{dt} + \omega_0^2 v_c = \frac{V}{LC}\cos(\omega t) \qquad (6)$$

Where: γ - Damping, ω_c – resonant frequency

We assume that there is a weak damping so $\gamma < 2\omega_0$. The general solution is:

$$v_{c0} = e^{-\frac{\gamma}{2}t}\sin(\sqrt{\omega_0^2 - \frac{\gamma^2}{4}}\,t + \varphi) \qquad (7)$$

Particular solution:

$$u_{Cp} = Bcos(\omega t + \psi) \qquad (9)$$

The characteristic equation shows what is used fort he following formulas

Characteristic equation:

$$p^2 + \gamma p + \omega_0^2 = 0 \qquad (10)$$

$$p_{1,2} = -\frac{\gamma}{2} \pm \sqrt{\frac{\gamma^2}{4} - \omega_0^2} \qquad (11)$$

Then the resulting voltage Vc will have the form:

$$v_c = v_{C0} + v_{Cp} = e^{-\frac{\gamma}{2}t} \sin\left(\omega_f t + \varphi\right) + Bcos(\omega t + \psi) \qquad (12)$$

If we substitute the particular solution into the differential equation for Vc, we have:

$$-B\omega^2 \cos(\omega t + \psi) - B\gamma\omega \sin(\omega t + \psi) + B\omega_0^2 \cos(\omega t + \psi) = \frac{V}{LC} \cos(\omega t) \qquad (13)$$

This expresion can be plotted using a phasor diagram:

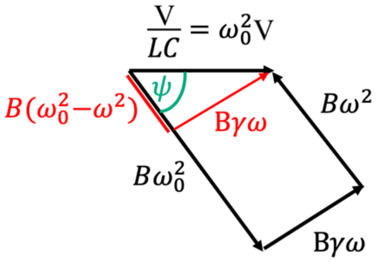


Diagram 2.1.1: Phasor diagram [9]

Then the constants B and Ψ of the particular solution are:

$$B = \frac{V\omega_0^2}{\sqrt{(\omega_0^2-\omega^2)^2+\gamma^2\omega^2}} \qquad (14)$$

$$\psi = arctg\left(\frac{\gamma\omega}{\omega_0^2-\omega^2}\right) \qquad (15)$$

When swithcing off the short-circuit current, we assume that the voltage Vc is 0 at the beginning of switching process:

$$v_c(0) = 0 \qquad (16)$$

From this initial condition we can determine the remaining constants and the resulting curve V at the contacts of the CB is (Figure 2.1.1) :

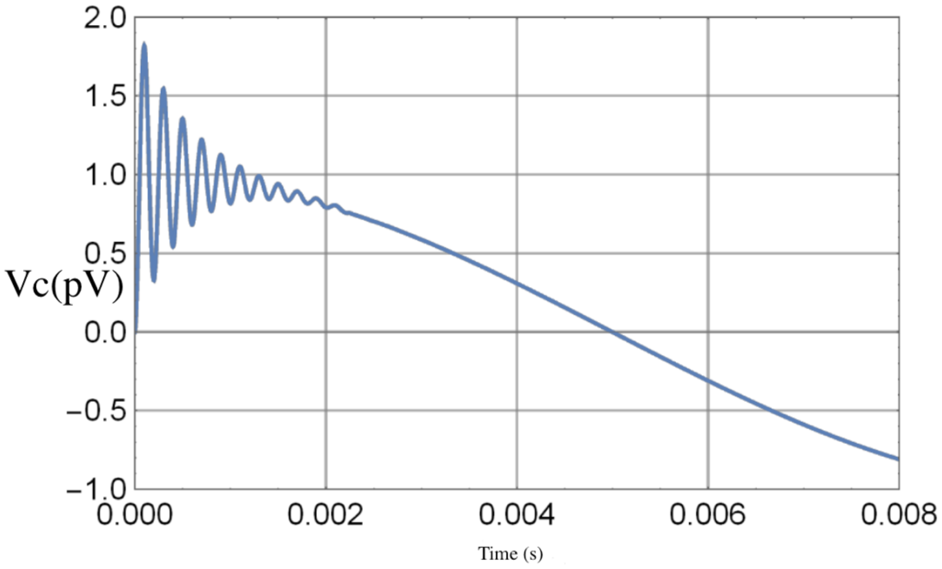


Figure 2.1.2 – Voltage transient that occurs during switching procedure. [9]

In the Figure 2.1.2 is shown the transient phenomena that occur when opening the circuit breaker. To effectively stop the current it is needed to increase the dielectric strength of the media where is the arc formed because the transient after swithcing can create a new arc that is a very dangerous situation.

2.2 Types of circuit breakers

Basically Circuit Breakers can be divided in some categories. The main of them are shown in **Table 1**.

Table 1: Types of Circuit breakers [10]

Criteria	Types				
Service	Outdoor		Indoor		
Operational mechanism	Spring operated	Pneumatic		Hydraulic	
Voltage level	LV	MV	HV	EHV	UHV
Arc extermination media	Air	Oil	SF6	Vacuum	SF6 free

The voltage level is a significabnt factor that determines the appropriate type of circuit breaker for specific application. In low voltage applications, indoor ACBs are generally sufficient. For medium voltage applications, there are several options available, ranging from air circuit breakers to SF6-free circuit breakers, including both indoor and outdoor types, In high voltage applications, SF6, vacuum, and SF6-free circuit breakers can be utilized, both for indoor and outdoor installations. Unfortunately, for extra and ultra-high voltage applications, SF6 technologies remain the primary choice.

The second important category is the arc extinguishing medium. Each dielectric mentioned in the table has its own advantages and disadvantages. Some are more effective than others in terms of arc quenching. Currently, SF6 circuit breaker are considered the most effective technology.

Operational mechanism has 3 types but the modern technologies are spring operated now.

Their service can be indoor or outdoor, and in most of the times if it is mentioned that a specific CB can operate outdoor this automatically means that it can be located indoors as it can be seen in the "Case Study".

Also it has to be said that in this thesis the chosen way of categorising the voltage levels is like in **Table 2**.

Table 2: Voltage Levels [11]

Voltage level	Range
Low Voltage	0 < V < 1000 V
Medium Voltage	1 < V < 100 kV
High Voltage	100 < V < 300 kV
Extra High Voltage	300 < V < 800 kV
Ultra High Voltage	800 kV < V

In this study there are going to be compared the circuit breakers by the voltage level where they can operate and by the arc quenching media.

3 Traditional Circuit Breaker Technologies

3.1 Air Circuit Breakers

An air circuit breaker (ACB) is a type of circuit breaker that utilizes compressed air to extinguish the arc that forms between the contacts when interrupting an electrical fault. When the contacts of the circuit breaker open, an arc is generated, and the ACB employs a blast of compressed air to cool and separate the contacts, thereby preventing the current from persisting [12]. Air circuit breakers are commonly employed in low and medium voltage power distribution systems and are well-suitable for applications with high fault currents, thanks to their capacity to interrupt substantial currents. They are also easy to maintain and repair, in addition to being environmentally friendly [13].

Arc extingushing can be done in 3 ways:

a) Increase the length of the arc;
b) Cooling the arc;
c) Splitting the arc into a number of series arcs. [14]

Usually there are used at least 2 of principles mentioned above.

Also there are two types of arc chute:

a) Insulated plate – It relies on stretching and cooling by using refractory plates of special shape.
b) Bare-metal-plate – This type splits the arc into some more arcs and also cools by conduction into the plates. [14]

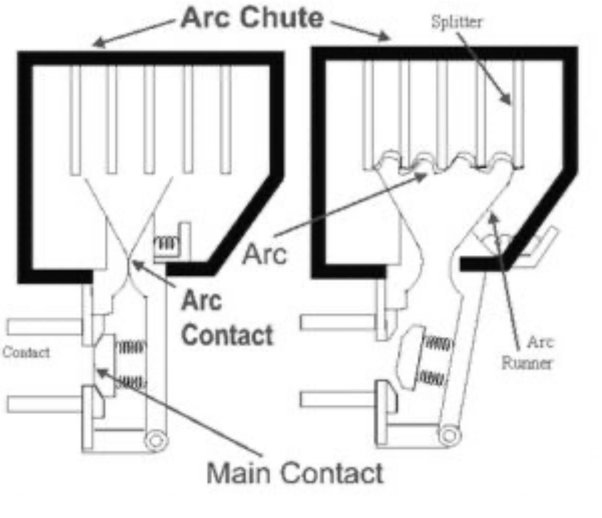


Figure 3.1.1: Air circuit breaker schematic. [15]

Nowadays the Air Circuit Breakers are used for protecting the plants where is a high risk of fire and explosions.[16]

3.2 Oil Circuit Breakers

In this type of circuit breaker, the fixed and moving contacts are immersed in mineral oil. The operational principle is as follows: when the contacts separate and an arc forms, the temperature causes the oil to vaporize and decompose, producing gases such as hydrogen, methane, ethylene, and acetylene. Of these gases, hydrogen gas is particularly crucial as it forms a hydrogen bubble around the arc. This condition facilitates the de-ionization process of the ionized gas medium between the contacts, rapidly increasing the dielectric strength and effectively extinguishing the arc [17].

The oil circuit breakers are designed for 11kV-765kV and are of two types: Bulk oil (Figure 3.2.1) and Minimum oil (Figure 3.2.2).[18]

The Bulk oil CB is where the oil is used as arc extinguishing media and insulating media between contacts and earth parts of a CB. However, the Minimum oil uses the oil just as interrupting media and this interrupting unit is located in an insulating chamber at live potential. [17]

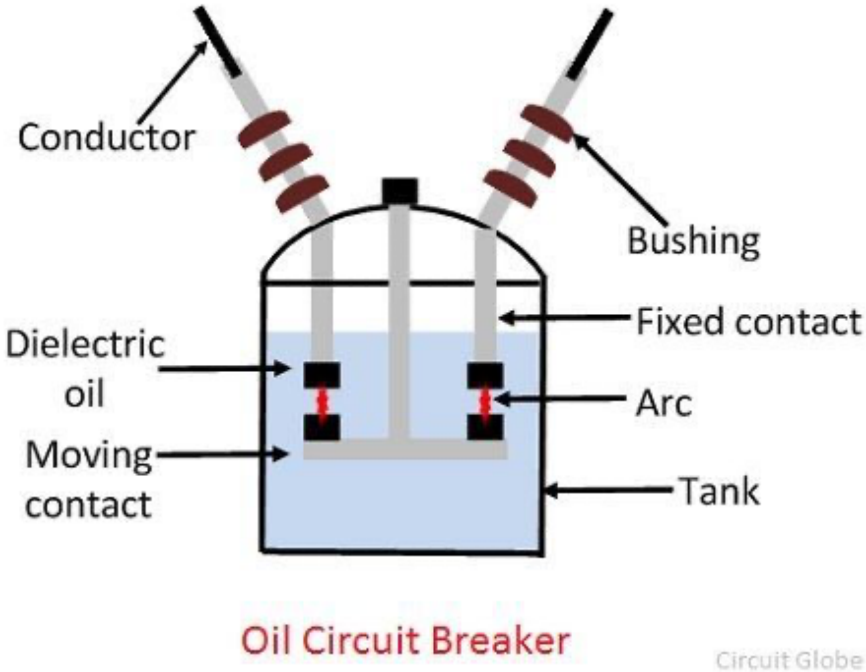


Figure 3.2.1: Bulk Oil Circuit Breaker Construction [19]

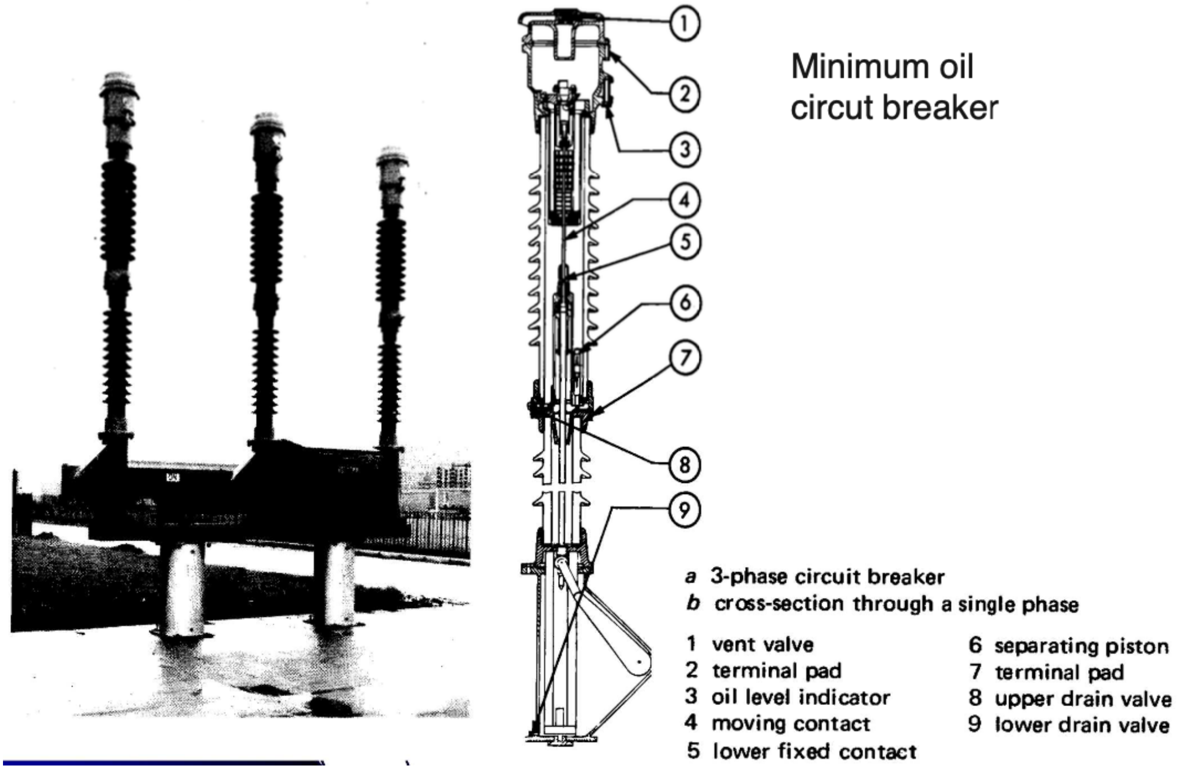


Figure 3.2.2: Minimum Oil Circuit Breaker Construction [18]

Nowadays, due to their high maintenance requirements and the environmental concerns associated with the use of oil, Oil CBs have been largely replaced by other types of CBs, such as air and vacuum circuit breakers. While OCBs are still used in some specialized applications, such as in large industrial and power generations systems, their use is becoming increasingly rare. Instead, alternative technologies are being developed that offer greater safety, reliability and sustainability, such as gas-insulated switchgear and solid-state circuit breakers. These technologies offer advantages such as smaller size, improved performance and reduced environmental impact, making them more suitable for modern electrical power systems. [20]

3.3 SF6 Circuit Breakers and SF6 gas:

SF6 gas offers numerous advantages for the power industry, making it highly suitable for systems with medium or high voltage. It possesses a constant dielectric strength, low viscosity, and high heat capacity. Additionally, it effectively prevents the occurrence of electric arcs due to its molecular fragments' ability to quickly recombine once arc source is eliminated. Other important properties of SF6 include its easy lequefaction, enabling compacts and cost-effective storage, its relatively affordable price of around 30$ per pound (0.45 kg), and its long lifespan of approximately 40 years. These exceptional characteristics make SF6 the preferred choice fort he power industry [21].

During fault conditions, when the contacts separate and an electric arc is formed, highly pressurized SF6 gas is rapidly released. As SF6 is an extremely electronegative gas, it readily absorbs free electrons, generating negative ions that have a slower mobility than free electrons. As a result, the dielectric strength of the gas increases, leading to the disappearance of the arc [22].

There are 3 types of SF6 CB according to the number of interruptors: [23]

a) Single interrupter (<245KV)
b) Two interrupter (<420KV)
c) Four interrupter(<800V)

There are also SF6 CBs of single (Figure 3.3.1) and double pressure systems (Figure 3.3.2). [23]

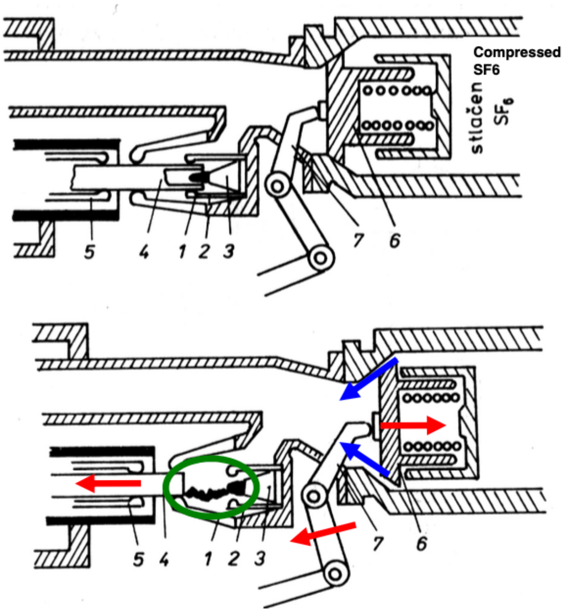


Figure 3.3.1: 1 - jet, 2 – fix contact lamella, 3 – sparking contact, 4 – moving contact, 5 – lamellas of moving contact, 6 – main closing valve, 7 – drive lever. [23]

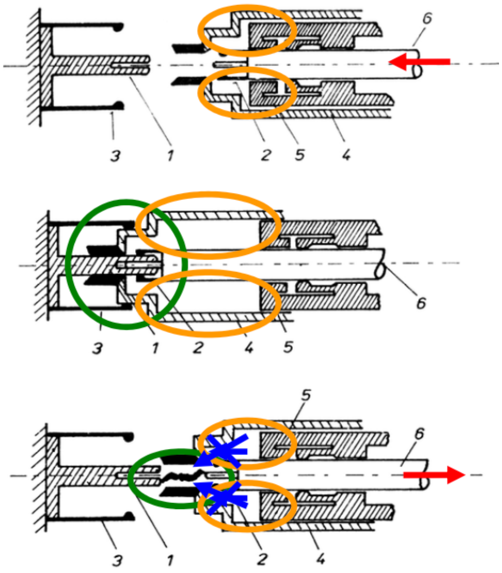


Figure 3.3.2: 1 – fix contact, 2 – moving contact, 3 – slippery contacts, 4 – moving tube chamber, 5 – fix piston, 6 – driving rod. [23]

The most used now SF6 CBs are of “puffer type” system (Figure 3.3.3)

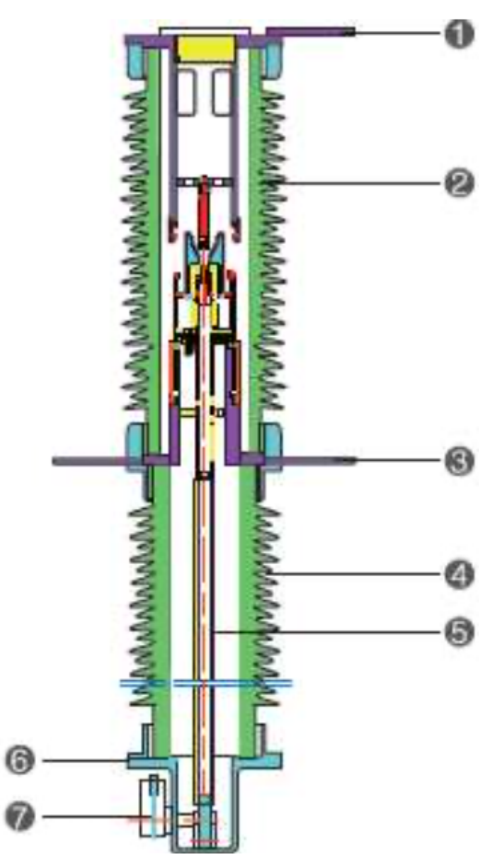


Figure 3.3.3: 1 – upper terminal plate, 2 – interrupter unit, 3 – lower terminal plate, 4 – porcelain insulator, 5 - insulating push rod, 6 - crank case, 7 – operating shaft [23]

No doubt SF6 CB is very effective technology, but it has several important disadvantages that motivates people to change them with other technologies:

a) It uses SF6 that is a very dangerous greenhouse gas with highly toxic decomposition (it can decompose in S_2OF_{10}, CF_4, COF_2, F_2, HF, H_2S, NF_3, F_2O, SiF_4, SO_2, S_2F_{10}, SF_4, SO_2F_2, SOF_2, SOF_4 and $S_2O_2F_{10}$);

b) Needs frequent maintenance during which usually most of the leakage happens;

c) Lower endurance of interrupters and contacts;

d) Needs a lot of energy to make the mechanism operating;

e) Has high opening and closing time;

f) High arc duration. [24]

3.4 Vacuum Circuit Breakers

Vacuum CB is one of the most ecological friendly switching technology and also is a pretendent for replacing the SF6 technology. [25]

The principle of vacuum circuit breaker operation is based on the use of vacuum as an arc quenching medium. When the circuit breaker contacts are separated, a high voltage arc is generated in the gap due to the ionization of the air. However, in a vacuum circuit breaker, the arc is rapidly extinguished by the absence of a medium to sustain it, as vacuum has a very dielectric strength. During the arc quenching process, the energy of the arc is absorbed by metal vapors, which contain both anode and cathode materials and formed due to intense heating of the contact material. The metal vapors are then condensed onto the contact surface, forming a metallic layer that provides insulation between the contacts. Vacuum CB's advantages are quick response time, high reliability and low maintenance. [26]

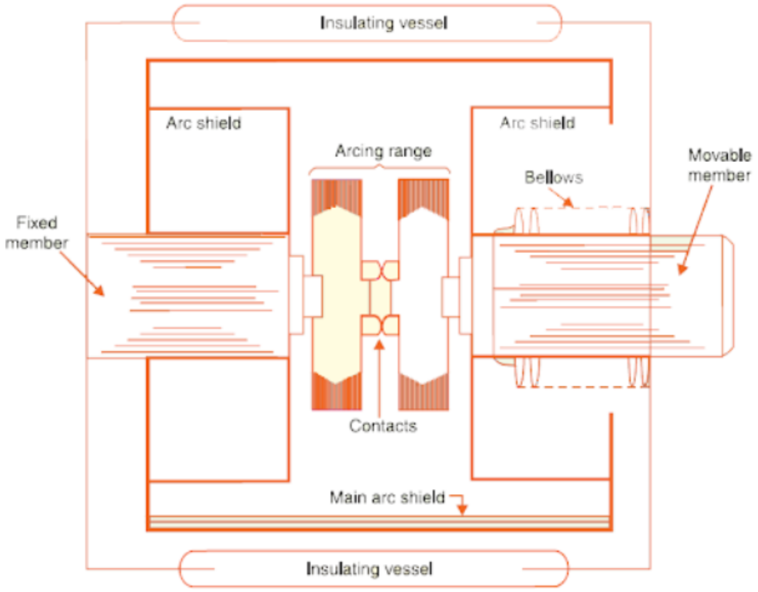


Figure 3.4.1: Schematic of Vacuum CB [25]

Vacuum Circuit Breakers are considered to be the best for medium voltage applications. There exists such technology and for HV application (>38kV) but it is very expensive. So, it is used mostly for medium voltage applications. [27]

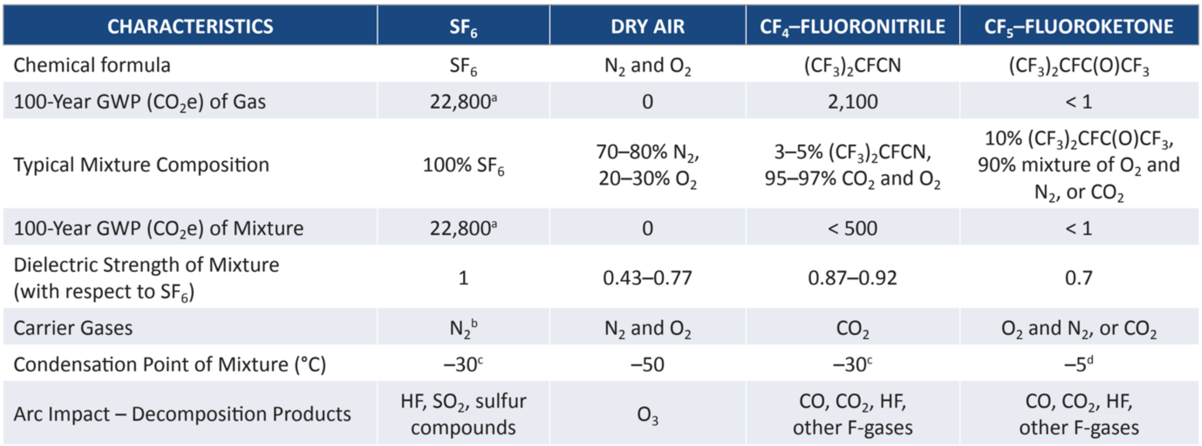
Mainly Vacuum technology is used in metal clad switchgear and also in porcelain housed CBs. [27]

4 SF6 Free Circuit Breakers

4.1 Alternatives

Because of the damage cause by SF6 gas for the atmosphere the European Union introduced new regulations that obligates companies to stop using SF6 technologies till 2030. So the last years companies that produce circuit breakers have worked on finding alternatives. After different researches in this field there have been found some alternative gas systems that can replace SF6 for some applications like distribution systems right now. These are: the Clean Air (Dry Air) and CO2 based gas mixtures (Novec 4710 and Novec 5110). [28]

Table 3. SF6 and alternative gases (SF6, Dry Air, Novec 4710, Novec 5110) [28]



CHARACTERISTICS	SF_6	DRY AIR	CF_4–FLUORONITRILE	CF_5–FLUOROKETONE
Chemical formula	SF_6	N_2 and O_2	$(CF_3)_2CFCN$	$(CF_3)_2CFC(O)CF_3$
100-Year GWP (CO_2e) of Gas	22,800[a]	0	2,100	< 1
Typical Mixture Composition	100% SF_6	70–80% N_2, 20–30% O_2	3–5% $(CF_3)_2CFCN$, 95–97% CO_2 and O_2	10% $(CF_3)_2CFC(O)CF_3$, 90% mixture of O_2 and N_2, or CO_2
100-Year GWP (CO_2e) of Mixture	22,800[a]	0	< 500	< 1
Dielectric Strength of Mixture (with respect to SF_6)	1	0.43–0.77	0.87–0.92	0.7
Carrier Gases	N_2[b]	N_2 and O_2	CO_2	O_2 and N_2, or CO_2
Condensation Point of Mixture (°C)	–30[c]	–50	–30[c]	–5[d]
Arc Impact – Decomposition Products	HF, SO_2, sulfur compounds	O_3	CO, CO_2, HF, other F-gases	CO, CO_2, HF, other F-gases

Also another technology that is able to replace SF6 is the Vacuum Shunt technology that uses a combination of Vacuum CB and a gas CB (usually air or Crean Air). It is a reasonable solution for MV systems. [29]

In the next subchapters we are going to discribe the new technologies by using as examples solutions created by main producers that deal with SF6 problem.

4.2 Siemens Energy “Blue Circuit Breaker”

Siemens Energy has developed a circuit breaker that utilizes a vacuum interrupter unit and utilizes a new insulating medium known as “clean air”. Clean air is composed of 80% nitrogen and 20% oxygen, and it is environmentally friendly with no harmful effects on humans. Currently, Siemens Energy offers circuit breakers for voltages up to 145 kV [30]. However, in 2023, Siemens Energy is planning to introduce the “Blue Circuit Breaker” designed for voltages up to 450 kV [31].

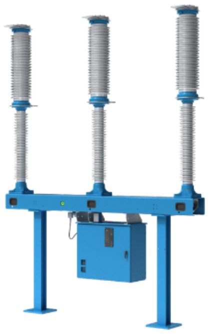
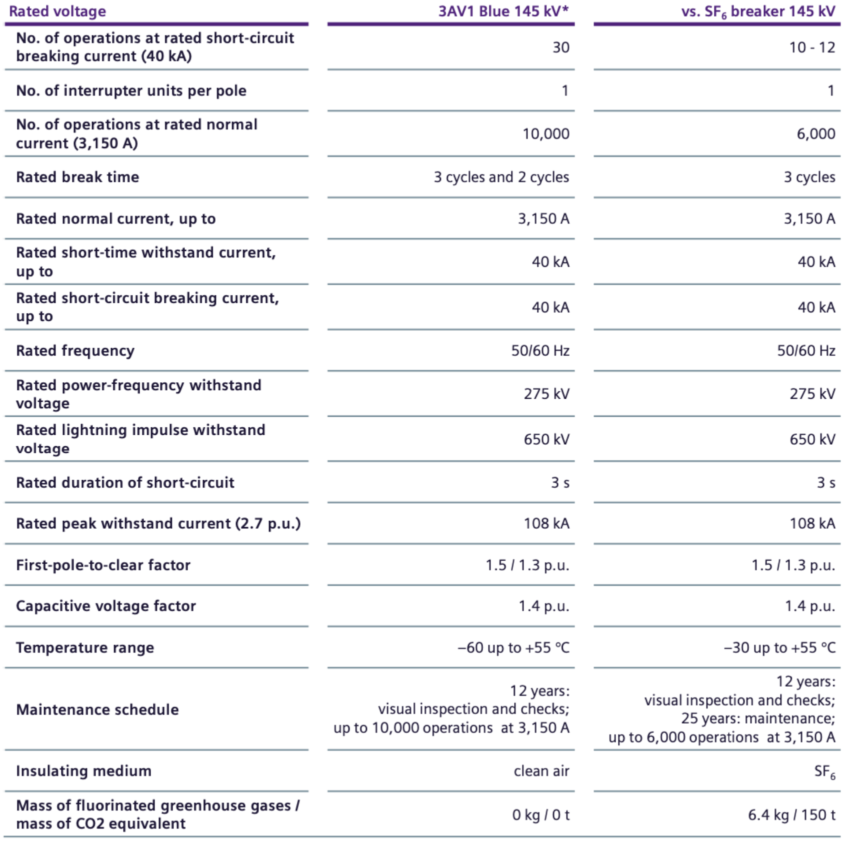


Figure 4.2.1. 3AV1 Blue Dead Tank CB[31] Figure 2.6.1.2 3AV1 Blue live Tank CB[31]

Table 4. 3AV1 Blue vs SF6 [31]

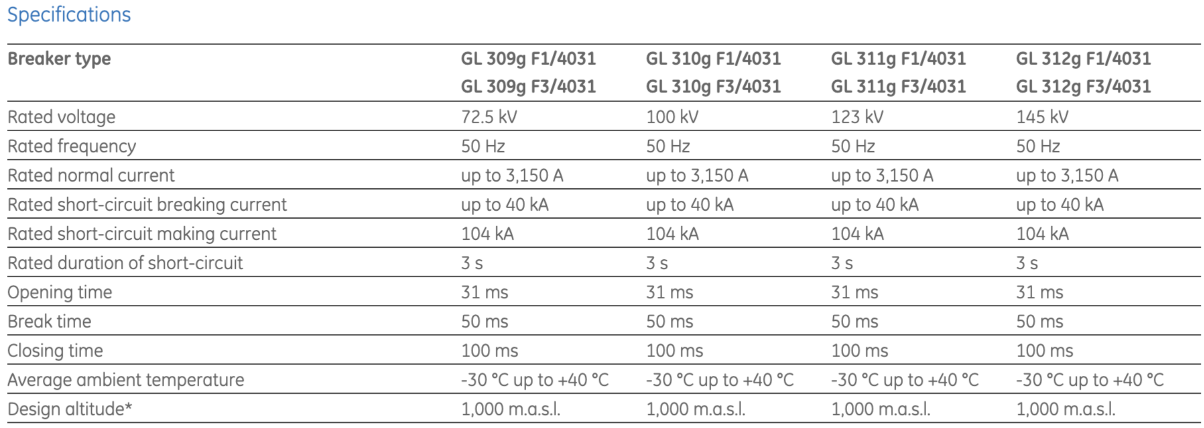


Rated voltage	3AV1 Blue 145 kV*	vs. SF$_6$ breaker 145 kV
No. of operations at rated short-circuit breaking current (40 kA)	30	10 - 12
No. of interrupter units per pole	1	1
No. of operations at rated normal current (3,150 A)	10,000	6,000
Rated break time	3 cycles and 2 cycles	3 cycles
Rated normal current, up to	3,150 A	3,150 A
Rated short-time withstand current, up to	40 kA	40 kA
Rated short-circuit breaking current, up to	40 kA	40 kA
Rated frequency	50/60 Hz	50/60 Hz
Rated power-frequency withstand voltage	275 kV	275 kV
Rated lightning impulse withstand voltage	650 kV	650 kV
Rated duration of short-circuit	3 s	3 s
Rated peak withstand current (2.7 p.u.)	108 kA	108 kA
First-pole-to-clear factor	1.5 / 1.3 p.u.	1.5 / 1.3 p.u.
Capacitive voltage factor	1.4 p.u.	1.4 p.u.
Temperature range	–60 up to +55 °C	–30 up to +55 °C
Maintenance schedule	12 years: visual inspection and checks; up to 10,000 operations at 3,150 A	12 years: visual inspection and checks; 25 years: maintenance; up to 6,000 operations at 3,150 A
Insulating medium	clean air	SF$_6$
Mass of fluorinated greenhouse gases / mass of CO2 equivalent	0 kg / 0 t	6.4 kg / 150 t

4.3 GE and 3M’s “G3 Circuit Breaker”

The new technology is based on g3 (g-cubed, green gas for grid). g3 is a gas based on 3M’s “Novec 4710” molecules that consist of Carbon, Fluor and Nitrogen (C_4F_7N). This gas has the same good qualities of SF_6 as a quenching media, but it reduces 98% of the emisions. [32] The Circuit Breaker itself has an interrupter chamber with integral double motion technology and self-blast system that uses g3 just as an extinguishing media. GE presents 4 CBs that are good for different voltage levels (Table 3). [33]

Table 5. Specifications of G3 Circuit Breakers [33]



Specifications

Breaker type	GL 309g F1/4031 GL 309g F3/4031	GL 310g F1/4031 GL 310g F3/4031	GL 311g F1/4031 GL 311g F3/4031	GL 312g F1/4031 GL 312g F3/4031
Rated voltage	72.5 kV	100 kV	123 kV	145 kV
Rated frequency	50 Hz	50 Hz	50 Hz	50 Hz
Rated normal current	up to 3,150 A	up to 3,150 A	up to 3,150 A	up to 3,150 A
Rated short-circuit breaking current	up to 40 kA	up to 40 kA	up to 40 kA	up to 40 kA
Rated short-circuit making current	104 kA	104 kA	104 kA	104 kA
Rated duration of short-circuit	3 s	3 s	3 s	3 s
Opening time	31 ms	31 ms	31 ms	31 ms
Break time	50 ms	50 ms	50 ms	50 ms
Closing time	100 ms	100 ms	100 ms	100 ms
Average ambient temperature	-30 °C up to +40 °C	-30 °C up to +40 °C	-30 °C up to +40 °C	-30 °C up to +40 °C
Design altitude*	1,000 m.a.s.l.	1,000 m.a.s.l.	1,000 m.a.s.l.	1,000 m.a.s.l.

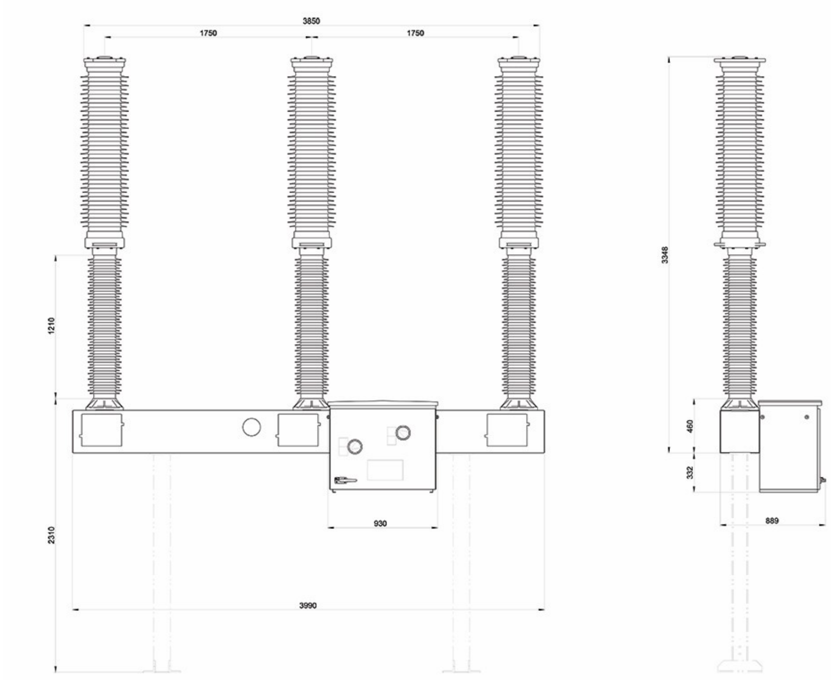
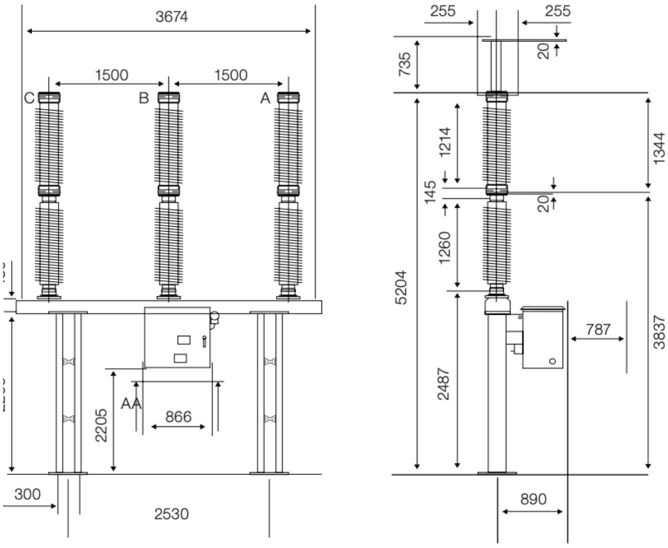


Figure 4.3.1. Schematic of G3 Circuit Breaker [33]

4.4 Hitachi “EconiQ DCB LTA”

Hitachi developes a Circuit Breaker for 72.5 and 145 kV applications that use as a quenching media a mixture of gases mostly based on CO2. Also in this gas mixture is included Fluoronitrile (C4-FN) and Oxygen (O2). Usage of such a CB can reduce the emisions by 65% comparing to SF6 systems. [34]



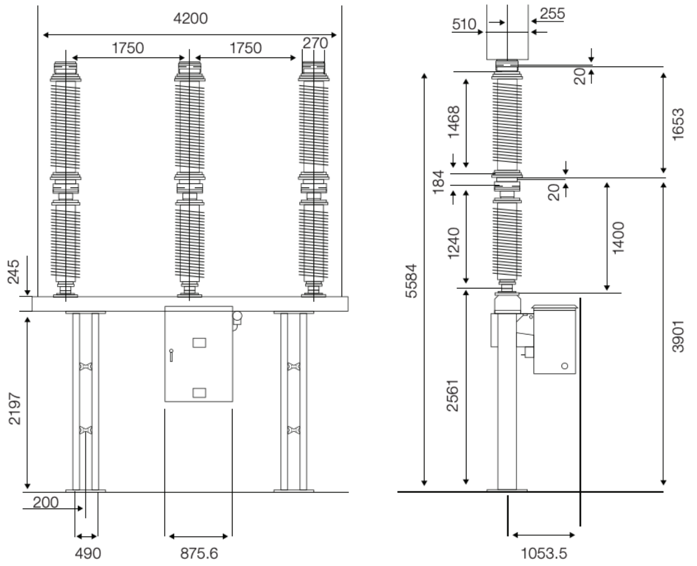
LTA circuit-breaker

Type		LTA 72.5D1
Voltage	kV	72.5 ... 84
Current	A	2750
Breaking current	kA	31.5
Frequency	Hz	50
Ambient temperature	°C	-50 ... +40
Operation		Three-pole

Disconnecting circuit-breaker (DCB) LTA

Type		DCB LTA 72.5D1
Voltage	kV	72.5 ... 84
Current	A	2750
Breaking current	kA	31.5
Frequency	Hz	50
Ambient temperature	°C	-50 ... +40
Operation		Three-pole

Figure 4.4.1. EconiQ DCB LTA Circuit Breaker for 72.5 kV Specifications [35]



LTA circuit-breaker

Type		LTA 145D1
Voltage	kV	145
Current	A	3150
Breaking current	kA	40
Frequency	Hz	50
Ambient temperature	°C	-50 ... +50
Operation		Three-pole

Figure 4.4.2. EconiQ DCB LTA Circuit Breaker for 145 kV Specifications [35]

4.5 Schneider Electric Solutions

Schneider Electric does not have any SF6 free technologies for High Voltage, however the company provides some solutions for Medium Voltage applications. They provide 3 main types of Circuit Breakers: Air, Vacuum and Shunt Vacuum CBs [36]. The chapter is not going to describe the Air and Vacuum Circuit breakers because their operation we explained in sections 3.1 and 3.4.

The shunt Vacuum technology is an innovative solutions for interrupting current in a circuit. It combines the functions of a vacuum interrupter and a disconnector in air, resulting in a reduced number of components and cost savings. Additionally, it operates as a conventional three-position switch. In this technology, the vacuum interrupter is connected in parallel with the disconnector. This arrangement allows the vacuum interrupter to operate only during the breaking phase when it needs to withstand the transient recovery voltage.

As depicted in the schematic below (Figure 2.5.1), when the circuit breaker is disconnected, the moving contact connects to the vacuum interrupter via the pivot lever. Once the electric arc is extinguished, the moving contact proceeds and connects to the earthing contact [36].

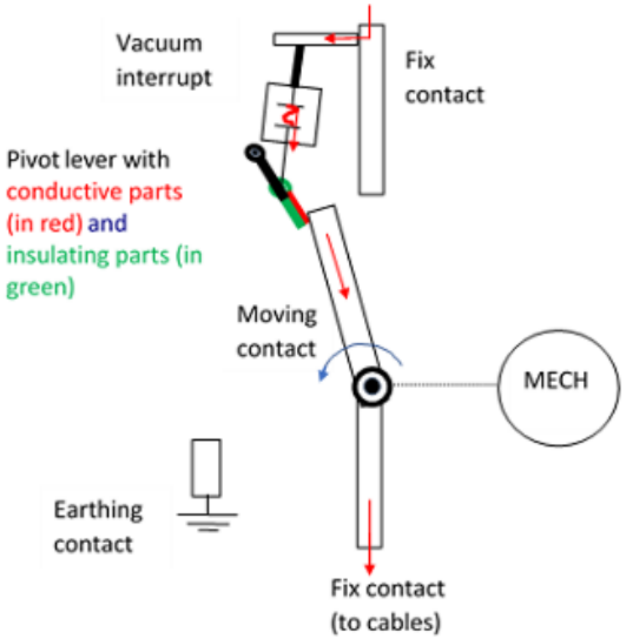


Figure 4.5.1. Shunt Vacuum operation schematic [36]

5 Case Study

In the table below, CB lines offered on the market by leading manufacturers are presented. The values listed, such as voltage and current, represent the maximum values for the respective product lines. The author compiled this table using information and documents obtained from the official websites of the manufacturers. In cases where certain data was not available on their websites, it was obtained by directly contacting a representative. To gather information on oil technology, the author reffered to old technical papers available on the internet and selected those that provided the necessary information for the table. The sections chosen for the main table are following:

a) Model Line Name;
b) Producer's Name;
c) Maximal Nominal Voltage [kV];
d) Voltage Level Category;
e) Maximal Nominal Current [kA];
f) Maximal Short Circuit Current [kA];
g) Breaking Time [ms];
h) Arc Quenching Material;
i) Frequency [Hz];
j) Volume of Oil [l per pole];
k) Number of Poles;
l) Expected Minimal Lifespan [years];
m) Type of Service;
n) Applications;
o) Reference.

However because the original table is too large it was decided to choose the main values and to make short tables for each voltage category (**Table 6**., **Table 7., Table 8., Table 9., Table 10.**). In these tables were included the following sections:

a) Model Line Name;
b) Producer's Name;
c) Maximal Nominal Voltage [kV];
d) Voltage Level Category;
e) Maximal Nominal Current [A];
f) Maximal Short Circuit Current [kA];
g) Breaking Time [ms];
h) Arc Quenching Material;
i) Reference.

Also so that the table is easier to read and find needed information it was decided to mark the types of technologies by using colors. It was used grey for ACB, green for VCB, orange for SF6 technology, yellow for oil CB and Blue for SF6-free Technologies that are created to replace the SF6 technology.

Table 6. Available on Market Circuit Breakers (Short Version) for Low Voltage

Model	Producer	Max Nominal Voltage [kV]	Voltage Level Category	Max Nominal Current [A]	Max Short Circuit Current [kA]	Breaking Time [ms]	Material	Ref
Masterpact MTZ	Schneider	1,15	LV	6300	150	30	Air	[37]
Masterpact NT	Schneider	0,277	LV	1600	150	50	Air	[37]
Masterpact UR	Schneider	0,69	LV	6000	150	8	Air	[37]
3VA MCCB	Siemens	1	LV	250	100	40	Air	[38]
Sentron MCCB	Siemens	0,415	LV	1600	150	40	Air	[38]
VL MCCB	Siemens	0,48	LV	1600	100	50	Air	[38]
WL PCB	Siemens	0,24	LV	1000	100	50	Air	[38]
F series	Hitachi	0,69	LV	1600	125	40	Air	[41]
L series	Hitachi	0,44	LV	800	175	40	Air	[41]
S series	Hitachi	0,44	LV	800	85	40	Air	[41]
M series	Hitachi	0,5	LV	225	50	40	Air	[41]
E series	Hitachi	0,44	LV	800	50	40	Air	[41]
R series	Hitachi	0,44	LV	1200	125	40	Air	[41]
BK63 series	Hitachi	0,4	LV	63	6	40	Air	[41]
BTK63 series	Hitachi	0,415	LV	63	10	40	Air	[41]
A series	Hitachi	0,5	LV	6300	150	40	Air	[41]

Table 7. Available on Market Circuit Breakers (Short Version) for Medium Voltage

Model	Producer	Max Nominal Voltage [kV]	Voltage Level Category	Max Nominal Current [A]	Max Short Circuit Current [kA]	Breaking Time [ms]	Material	Ref
Masterpact NW	Schneider	1,15	MV	6300	150	25	Air	[37]
Easypact EXE	Schneider	17,5	MV	2500	31,5	66	Vacuum	[37]
Evopact HVX	Schneider	24	MV	4000	50	15	Vacuum	[37]
Evopact LF	Schneider	17	MV	5000	50	50	SF6	[37]
Evopact SF	Schneider	40,5	MV	3150	40	60	SF6	[37]
VA	Schneider	38	MV	3150	50	60	Vacuum	[37]
VAH	Schneider	17,5	MV	8000	63	60	Vacuum	[37]
VXA and VXB	Schneider	27,5	MV	2500	40	60	Vacuum	[37]
VXC	Schneider	38	MV	4000	40	60	Vacuum	[37]
Evolis	Schneider	24	MV	2500	40	50	Vacuum	[37]
GM-SG	Siemens	15	MV	1200	50	80	Vacuum	[39]
EDF SK	Hitachi	72,5	MV	2500	31,5	55	SF6	[42]
EDI SK	Hitachi	72,5	MV	2500	31,5	55	SF6	[42]
GL 107X	GE	40,5	MV	2000	31,5	50	SF6	[43]
GL 308	GE	52	MV	2000	31,5	50	SF6	[43]
GL 309	GE	72,5	MV	2000	31,5	50	SF6	[43]
GL 309g	GE	72,5	MV	3150	40	50	g3	[43]
GL 310g	GE	100	MV	3150	40	50	g3	[43]
GL 310 S	GE	100	MV	3150	40	60	SF6	[43]
FKG2S	GE	24	MV	6800	63	50	SF6	[43]
FKG2M	GE	24	MV	8400	80	50	SF6	[43]
FKG1N	GE	27	MV	10800	120	75	SF6	[43]
FKG1F	GE	27	MV	13500	120	75	SF6	[43]
FKGA2	GE	27	MV	14100	100	75	SF6	[43]
FKG1X	GE	32,4	MV	17000	160	75	SF6	[43]
FKG1XV	GE	32,4	MV	24000	160	75	SF6	[43]
FKG1XP	GE	32,4	MV	21000	160	75	SF6	[43]
FKG1XW	GE	32,4	MV	24000	160	75	SF6	[43]
FKGA8	GE	33	MV	30000	210	75	SF6	[43]

SBS Minimum Oil CB	BBC Brown Boveri	12	MV	1600	43	100	Oil	[44]
T type	Fuji Electric	12	MV	2000	36	100	Oil	[45]
SM AirSeT	Schneider	24	MV	1250	25	50	Clean Air, vacuum	[46]
GM AirSeT	Schneider	24	MV	1250	25	50	Clean Air, vacuum	[46]
RM AirSeT	Schneider	24	MV	630	20	50	Clean Air	[46]
Xpert UX	Eaton	24	MV	4000	50	50	Air, vacuum	[47]
Xpert FMX	Eaton	24	MV	2000	25	50	Air, vacuum	[47]
N2 Blue	SGC	17,5	MV	2500	25	50	N2 gas	[48]
DF2	SGC	24	MV	1250	25	50	Air	[48]

Table 8. Available on Market Circuit Breakers (Short Version) for High Voltage

Model	Producer	Max Nominal Voltage [kV]	Voltage Level Category	Max Nominal Current [A]	Max Short Circuit Current [kA]	Breaking Time [ms]	Material	Ref
3AV1FG Blue live tank	Siemens	145	HV	3150	40	40	Vacuum, clean air	[40]
3AV1DT Blue dead tank	Siemens	145	HV	3150	63	40	Vacuum, clean air	[40]
3AP1 DTC	Siemens	245	HV	4000	63	60	SF6	[40]
ELK04	Hitachi	170	HV	4000	63	60	SF6	[42]
BLF/PASS	Hitachi	170	HV	3150	40	60	SF6	[42]
ELK-14	Hitachi	300	HV	4000	63	60	SF6	[42]
LTB D	Hitachi	170	HV	3150	40	40	SF6	[42]
COMPASS	Hitachi	170	HV	2000	40	50	SF6	[42]
Econiq LTA	Hitachi	145	HV	2700	40	50	CO2 based gas mix	[42]
GL 311g	GE	123	HV	3150	40	50	g3	[43]
GL 312g	GE	145	HV	3150	40	50	g3	[43]
GL 311 S	GE	123	HV	3150	40	60	SF6	[43]
GL 312 S	GE	145	HV	3150	40	60	SF6	[43]
GL 313	GE	170	HV	3150	40	50	SF6	[43]
GL 314	GE	252	HV	4400	137	38	SF6	[43]
GL 314X	GE	300	HV	4000	173	40	SF6	[43]

Table 9. Available on Market Circuit Breakers (Short Version) for Extra High Voltage

Model	Producer	Max Nominal Voltage [kV]	Voltage Level Category	Max Nominal Current [A]	Max Short Circuit Current [kA]	Breaking Time [ms]	Material	Ref
3AP dead tank	Siemens	550	EHV	5000	90	40	SF6	[40]
3AP DCB	Siemens	420	EHV	4000	50	60	SF6	[40]
ELK-3	Hitachi	550	EHV	6300	80	60	SF6	[42]
LTB E	Hitachi	420	EHV	4000	50	40	SF6	[42]
DCB	Hitachi	550	EHV	4000	63	50	SF6	[42]
GL 315	GE	362	EHV	4000	137	38	SF6	[43]
GL 315X	GE	362	EHV	5500	173	40	SF6	[43]
GL 316	GE	420	EHV	4000	137	38	SF6	[43]
GL 316X	GE	420	EHV	5500	173	40	SF6	[43]
GL 317	GE	550	EHV	4000	137	38	SF6	[43]
GL 317X	GE	550	EHV	5500	173	40	SF6	[43]
DT1	GE	362	EHV	5000	63	33	SF6	[43]
DT2	GE	550	EHV	5000	60	42	SF6	[43]

Table 10. Available on Market Circuit Breakers (Short Version) for Ultra High Voltage

Model	Producer	Max Nominal Voltage [kV]	Voltage Level Category	Max Nominal Current [A]	Max Short Circuit Current [kA]	Breaking Time [ms]	Material	Ref
3AP live tank	Siemens	1100	UHV	5000	63	40	SF6	[40]
ELK-4	Hitachi	800	UHV	6300	63	60	SF6	[42]
ELK-5	Hitachi	1200	UHV	8000	63	60	SF6	[42]
HPL B	Hitachi	1100	UHV	6300	80	40	SF6	[42]
DTB	Hitachi	800	UHV	5000	63	40	SF6	[42]
GL 318	GE	800	UHV	4000	137	38	SF6	[43]
GL 318X	GE	800	UHV	5500	173	40	SF6	[43]

6 Results and Discussion

To see better the difference between the models presented in the “Case Study” the points on some graphs are plotted. First all technologies are compared by such parameters as Short Circuit Current over Nominal Current, Breaking Time over Nominal Current and Breaking Time over Short Circuit Current for all voltage levels. There are two types of graphs, the first are for division on just SF6 and SF6-free, and the second type is showing every type of technology divided by colors.

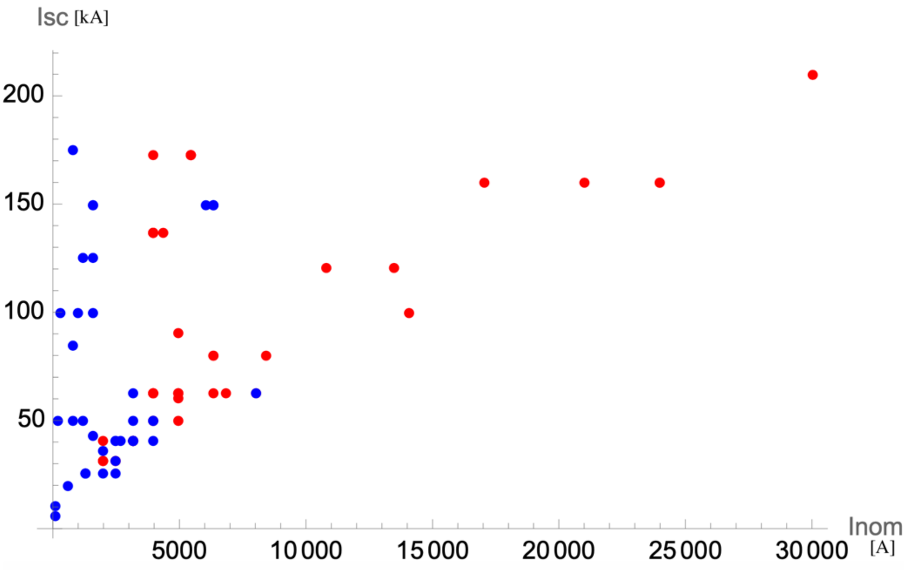


Figure 6.0.1: All Voltage Levels Circuit Breakers Current Parameters: Red – SF6 technologies, Blue – SF6 Free technologies

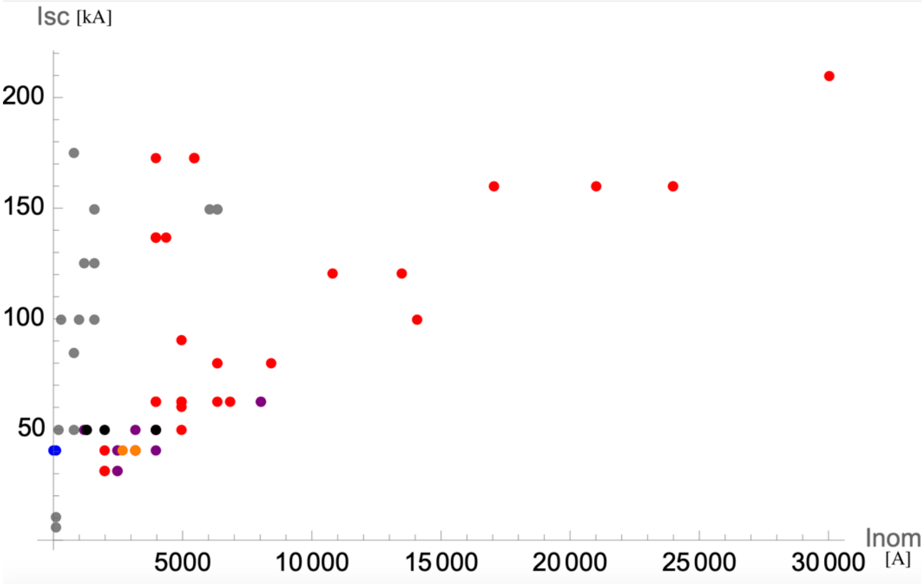


Figure 6.0.2: All Technologies Current Parameters: Grey – ACB, Blue – Clean Air CB, Red – SF6 CB, Purple – VCB, Orange – CO2 gas mixture CB, Black – Vacuum/Clean Air CB

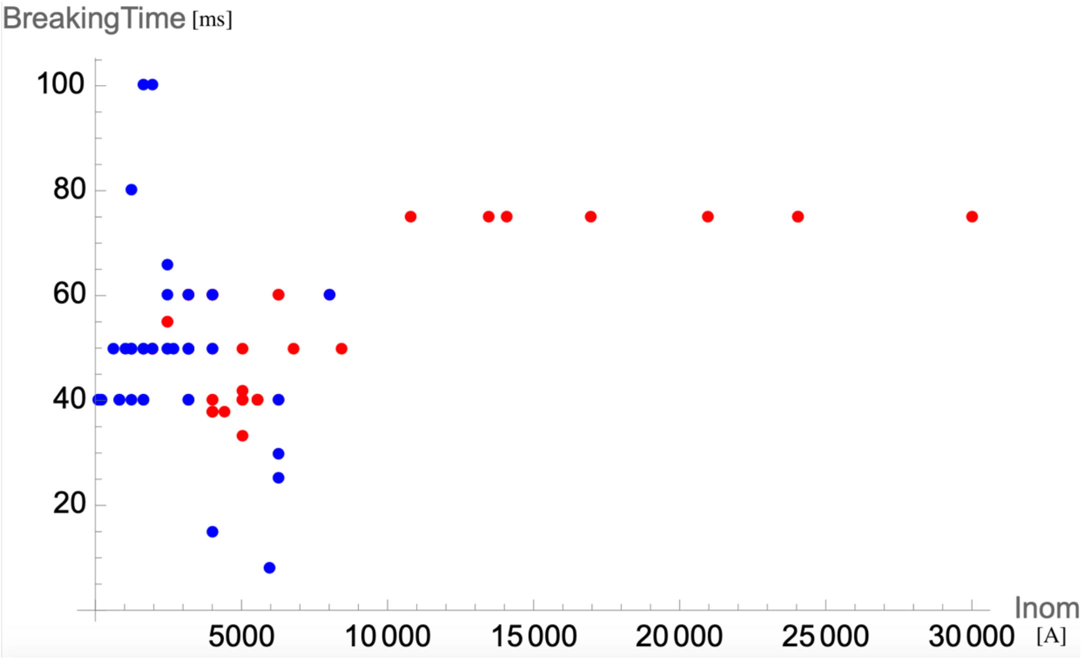


Figure 6.0.3: All Voltage Levels Breaking Breaking Time(Inom): Red – SF6 technologies, Blue – SF6 Free technologies

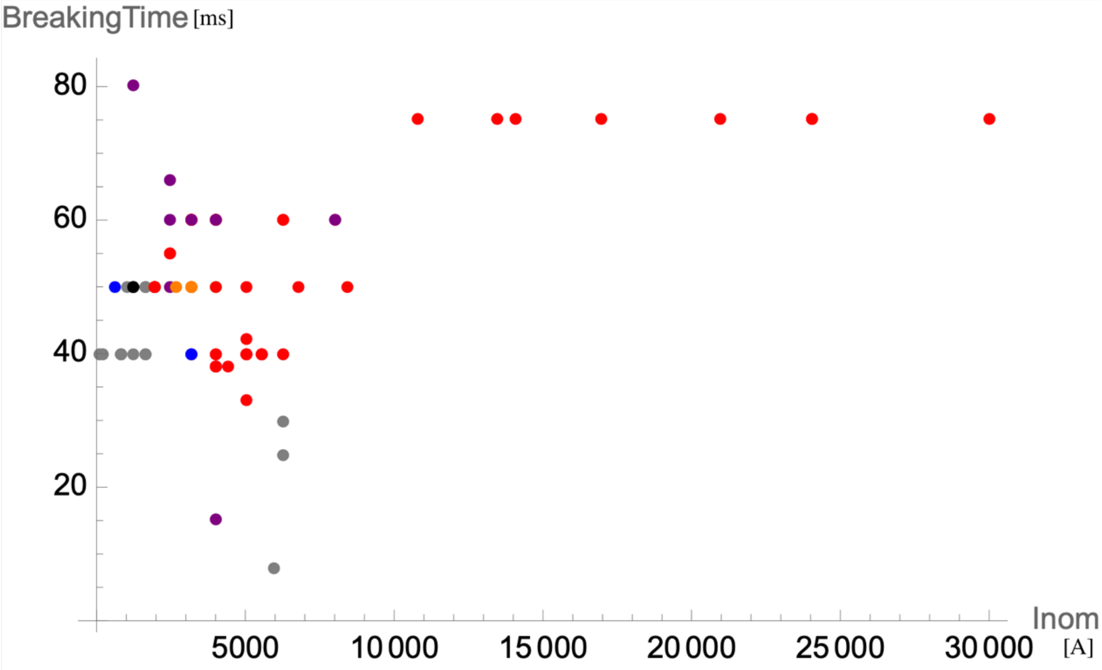


Figure 6.0.4: All Technologies Breaking Time(Inom): Grey – ACB, Blue – Clean Air CB, Red – SF6 CB, Purple – VCB, Orange – CO2 gas mixture CB, Black – Vacuum/Clean Air CB

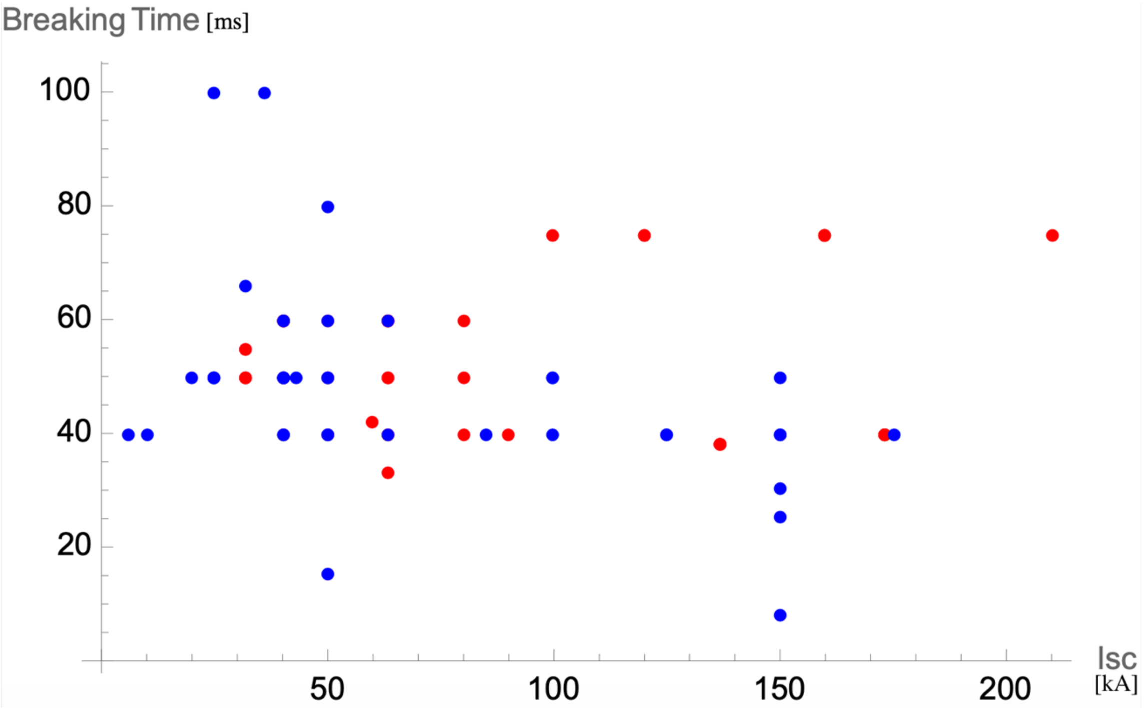


Figure 6.0.5: All Voltage Levels Breaking Time(Isc): Red – SF6 technology, Blue – SF6 Free technology

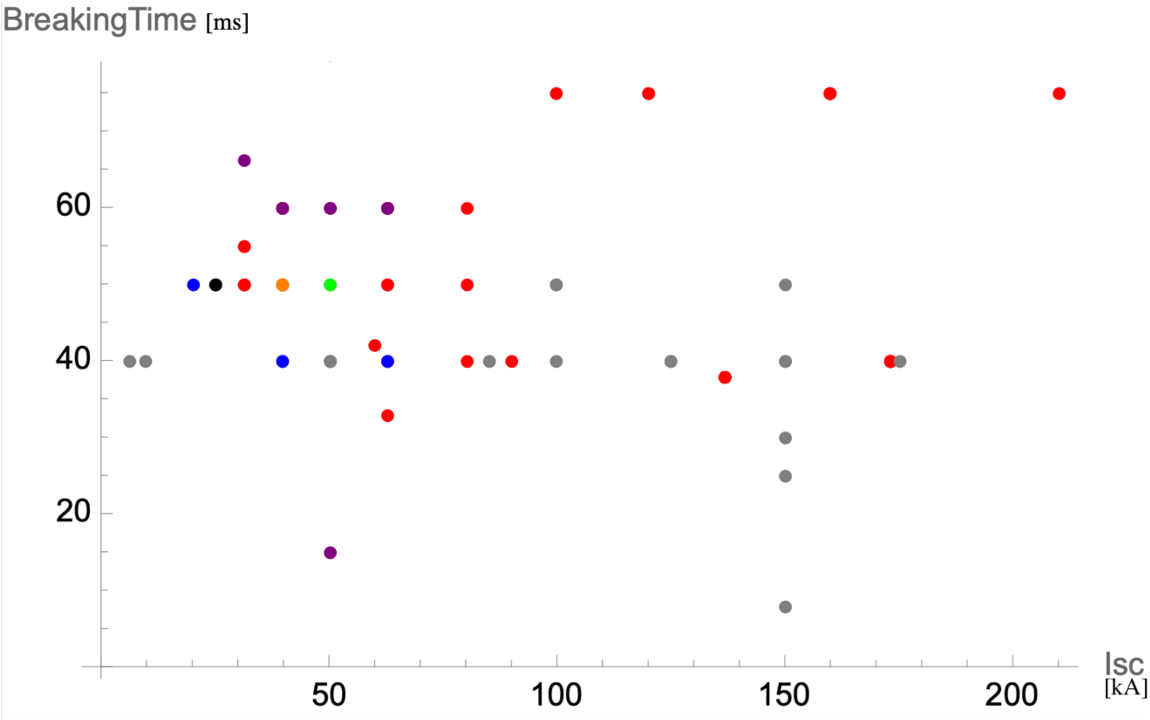


Figure 6.0.6: All Technologies Breaking Time(Isc): Grey – ACB, Blue – Clean Air CB, Red – SF6 CB, Purple – VCB, Orange – CO2 gas mixture CB, Black – Vacuum/Clean Air CB

6.1 Medium Voltage

The next few graphs show the same parameters but only for medium voltage category only.

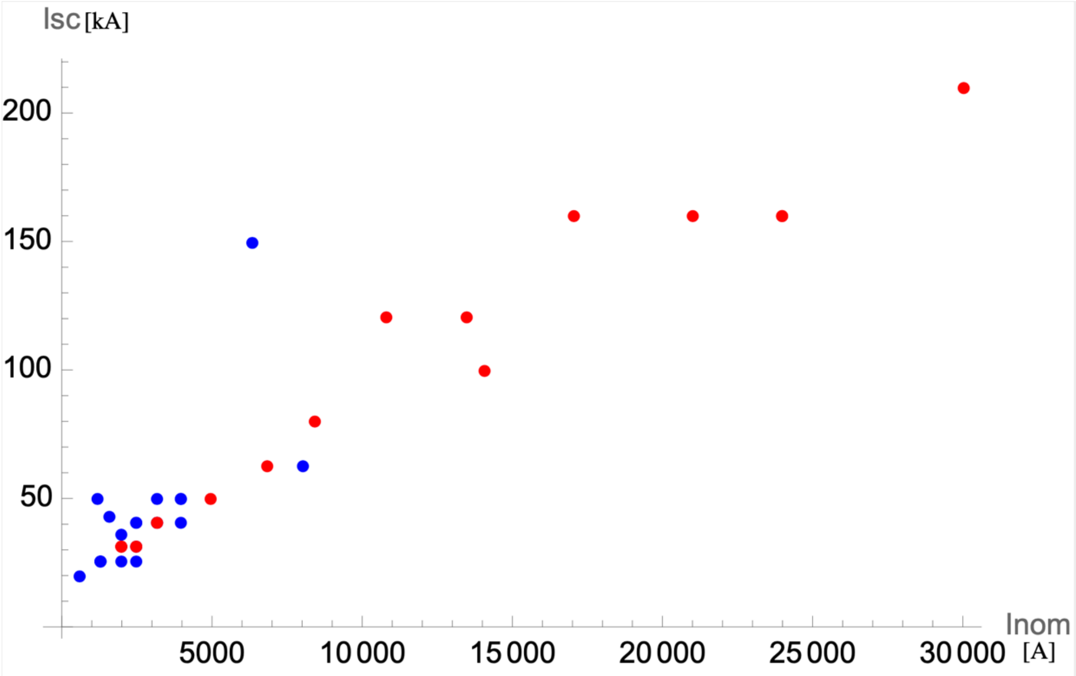


Figure 6.1.1: MV Circuit Breakers Current Parameters: Red – SF6 technologies, Blue - SF6 Free technologies

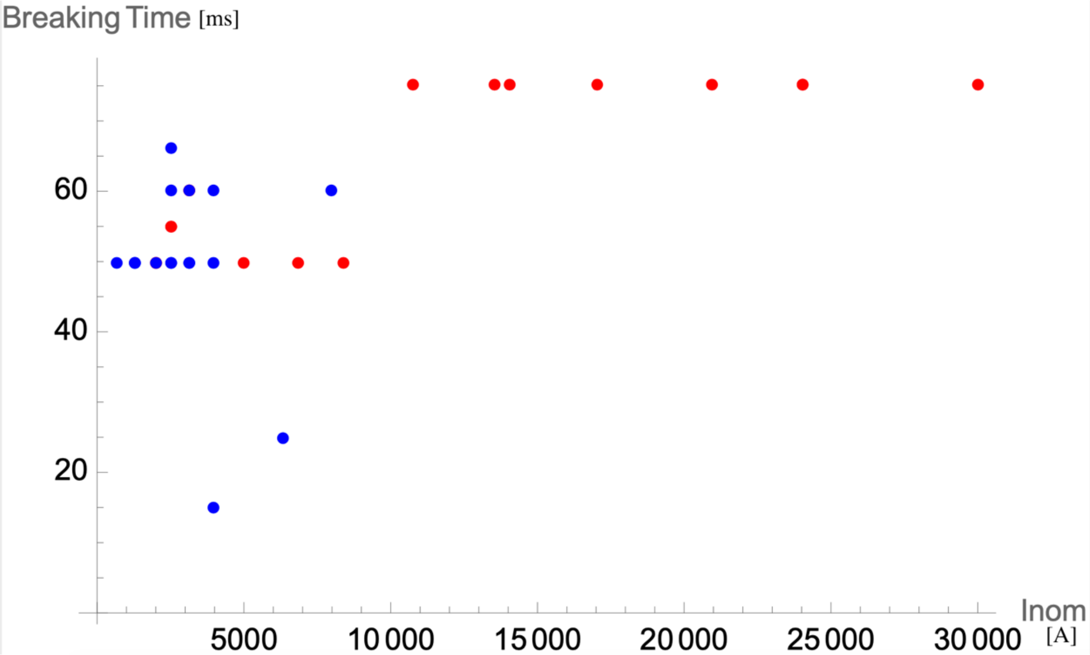


Figure 6.1.2: MV Breaking Time(Inom): Red – SF6 technologies, Blue – SF6 Free technologies

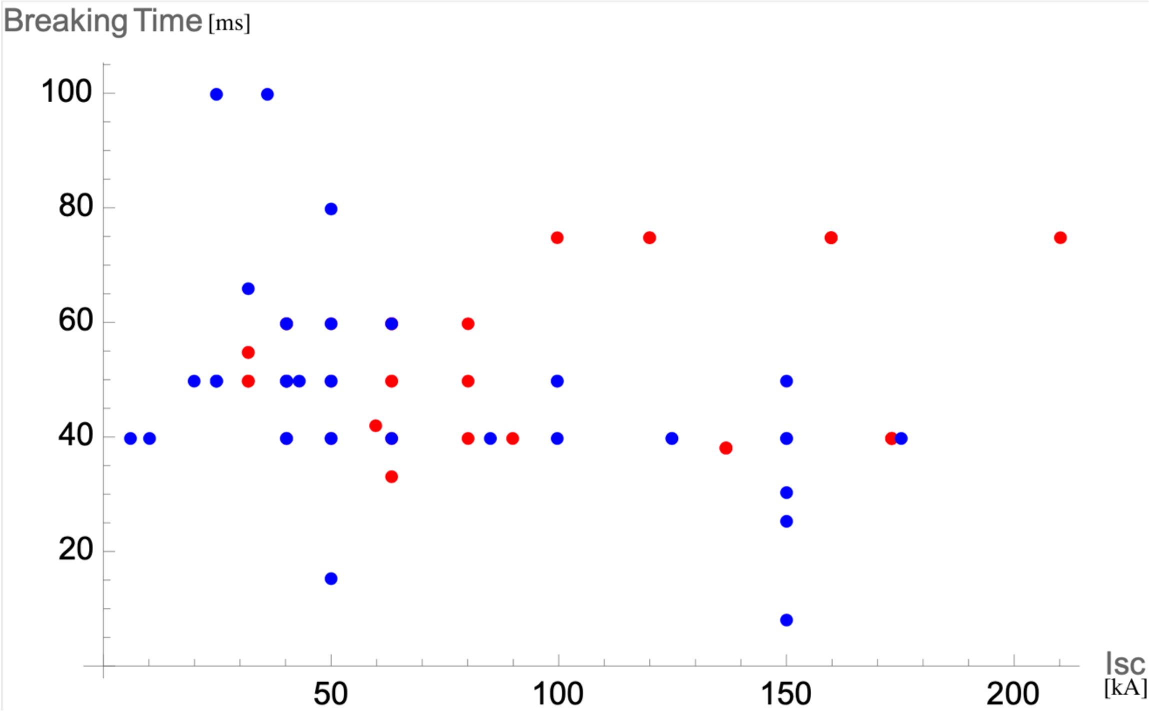


Figure 6.1.3: MV Breaking Time(Isc): Red – SF6 technology, Blue – SF6 Free technologies

6.2 High Voltage

The following graphs are plotted only for high voltage technologies:

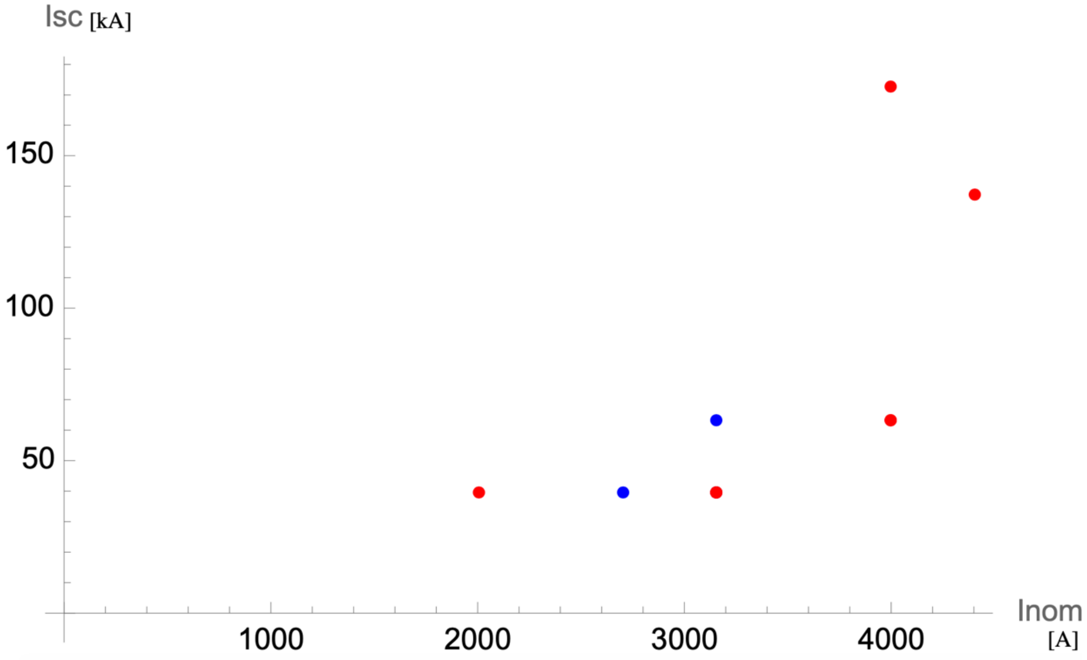


Figure 6.2.1: HV Circuit Breakers Current Parameters: Red – SF6 technologies, Blue – SF6 Free technologies

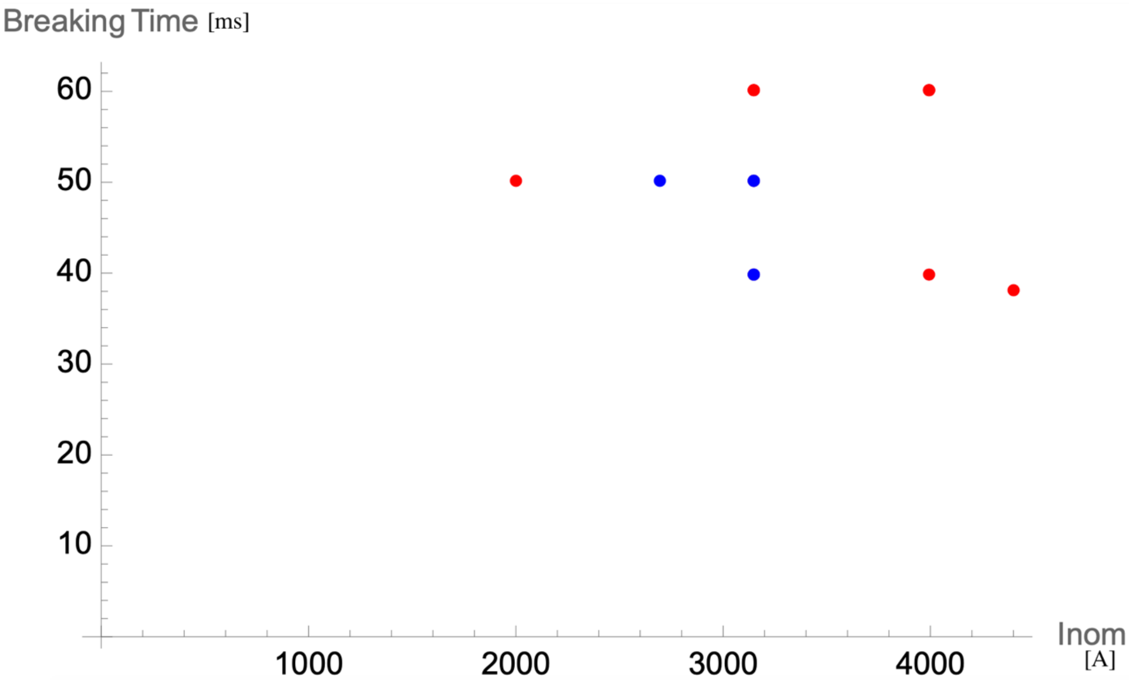


Figure 6.2.2: HV Breaking Time(Inom): Red – SF6 technologies, Blue – SF6 Free technologies

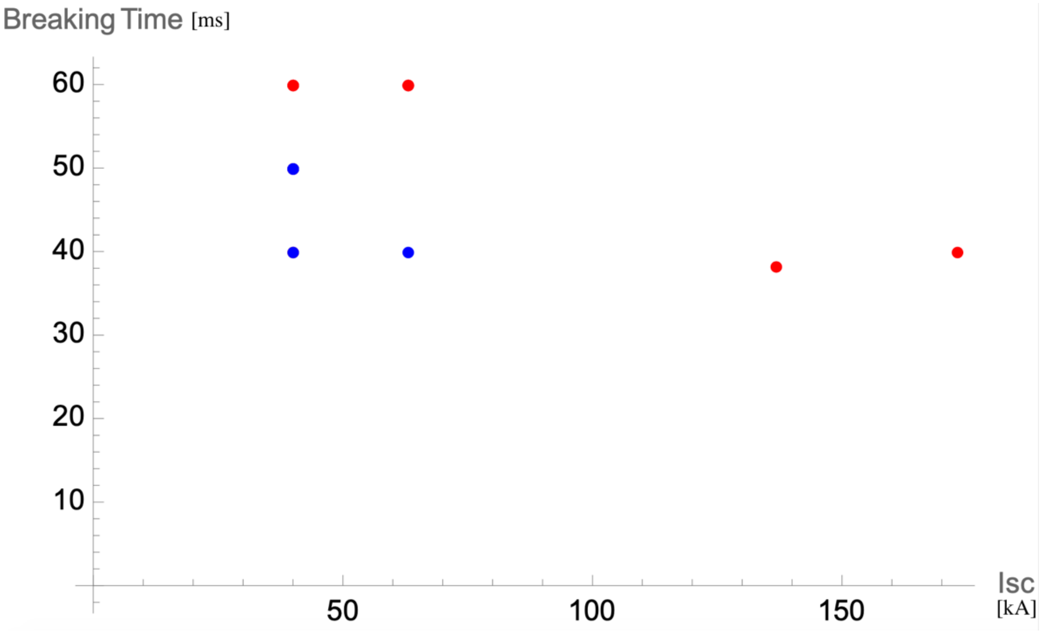


Figure 6.2.3: HV Breaking Time(Isc): Red – SF6 technology, Blue – SF6 Free technology

6.3 Extra High Voltage

The last 3 graphs are for extra high voltage and it was decided that graphs for UHV is not necessary because it is enough to see that SF6 free Technologies can not be used in systems with such high voltage

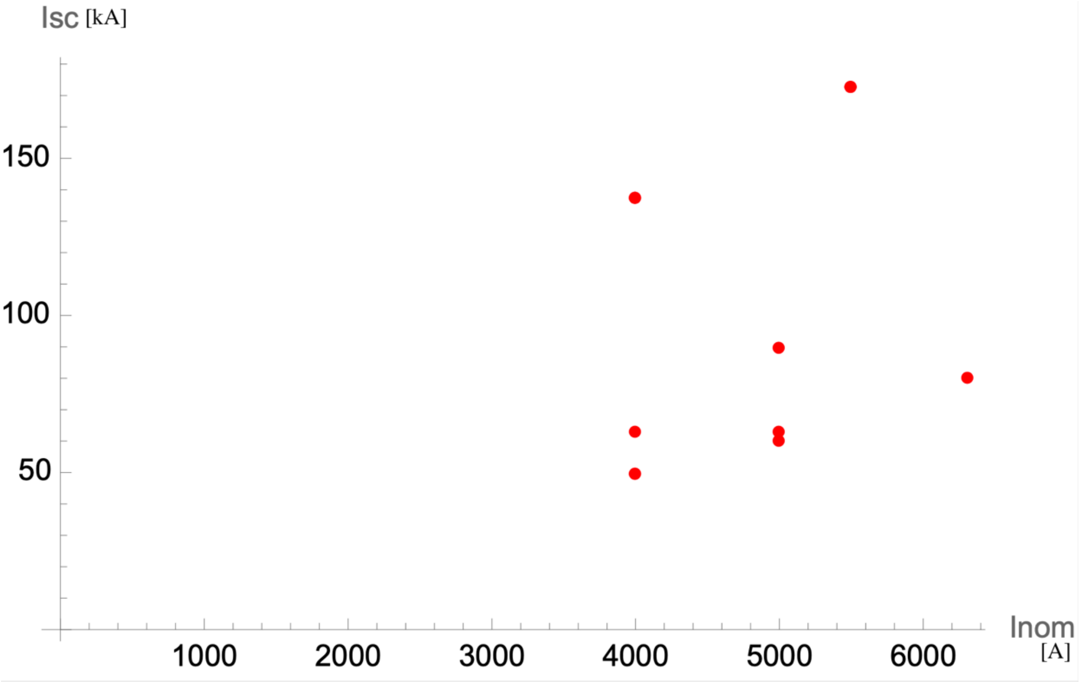


Figure 6.3.1: EHV Circuit Breakers Current Parameters: Red – SF6 technologies, Blue – SF6 Free technologies

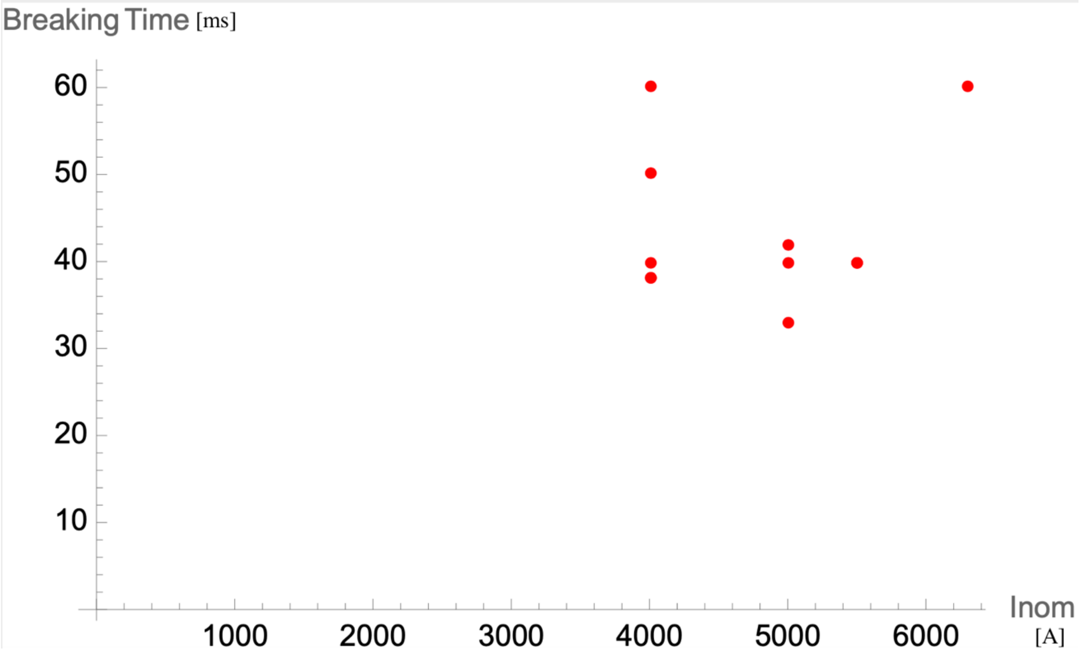


Figure 6.3.2: EHV Breaking Time(Inom): Red – SF6 technology, Blue – SF6 Free technology

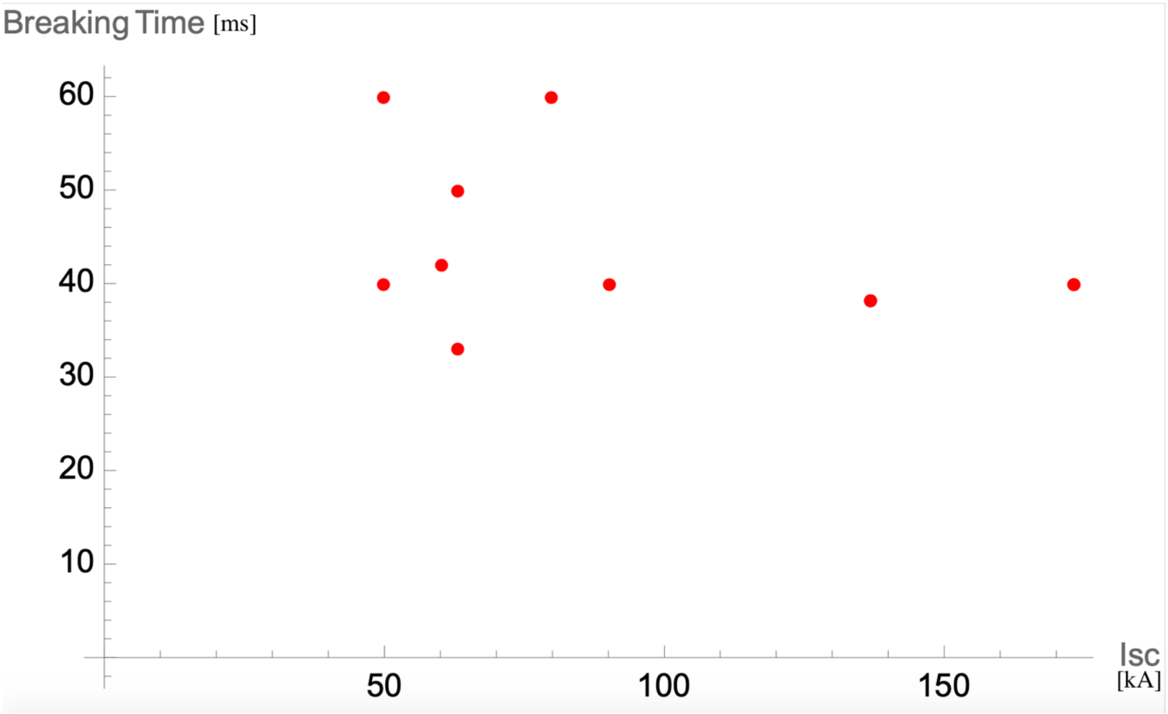


Figure 6.3.3: EHV Breaking Time(Isc): Red – SF6 technology, Blue – SF6 Free technology

6.4 Discussion

From the graphs in the previous chapter has to be mentioned that SF6 free technologies are limited not only for voltage but also for nominal current and short circuit current. Largest parameters for SF6 free technologies are:

a) Nominal Voltage = 145 kV;
b) Nominal Current = 6,3 kA;
c) Short Circuit Current = 175 kA.

Largest parameters for SF6 CBs:

a) Nominal Voltage = 1200 kV;
b) Nominal Current = 30 kA;
c) Short Circuit Current = 210 kA.

The other characteristics are similar. Most of CBs are in the same range if comparing Breaking Time, and it is between 20 to 75 ms. The minimal expected lifetime for small indoor CBs is usually 10 years, and for the rest is 30 years and higher. There are lots of indoor and outdoor products, and there is a large variety of applications for SF6 and SF6 free technologies.

Basically if everyone in year 2023 switched to SF6 free technologies then because of lots limits there wouldn't be possible to cover some of the applications.

The main application were we can use SF6 free Technologies are:

a) LV applications;
b) Primary and Secondary distribution systems;
c) Switching applications;
d) Connecting building infrastructure and industrial buildings to the grid;
e) HV applications for systems lower then 145 kV.

Applications where we are not able to use SF6 free technologies:

a) Generators CB for powerplants from 50 to 1500 MW;
b) High voltage applications for systems higher then 145 kV;
c) EHV applications;
d) UHV applications.

As it is mentioned by changing to SF6 free technologies in 2023, people won't be able to move large amount of power across long lines because without protection it would be very dangerous. Also people won't be able to use powerplants that produce more then 50 MW.

7 Conclusion

In conclusion, it is evident that as of 2023, the complete replacement of SF6 technologies is not yet feasible. For low voltage applications, SF6 is unnecessary, while for medium voltage, it can be replaced if the nominal current is below 6.3 kA and the short circuit current is below 150 kA. For high voltage, SF6 can be replaced if the voltage is below 145 kV, the nominal current is below 3.15 kA, and the short circuit current is below 63 kA.

However, companies like GE, Siemens, and Hitachi have announced the development of the next generation of SF6-free CBs and switchgears, aiming to expand the limited voltage range. Siemens plans to expand its SF6-free HV technology portfolio untill 2030 [49]. GE has introduced a CB for applications up to 420 kV, set to be commercially available in 2023 [50]. Hitachi aims to offer a 420 kV solution by 2024, as well as a CB for power plant generators up to 220 MW by 2026 [51].

Engineers are diligently working on addressing the SF6 issue, and companies regularly announce advancements in their technologies. However, more time is needed for comprehensive solutions. The challenge lies in EU regulations that mandate a transition to SF6-free alternatives by 2030. From the author's perspective, it would be beneficial for the EU to revise these regulations and provide companies with more time to develop even better solutions. For instance, extending the deadline to 2050 aligns with the EU's goal of achieving full climate neutrality.

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List of Appendixes

Appendix A

Model	Company	Max Vominal Voltage [kV]	Voltage level category	Frequency [Hz]	Material	Volume of oil [l per pole]	Number of Poles	Short-circuit time [s]	Expected Minimal Lifetime [years]	Breaking Time [ms]	Type of Service	Application	Max Nominal Current [A]	Short Circuit Current [kA]	Ref
Masterpact MTZ	Schneider	1,15	LV	50/60	Air		4	3	10	30	Indoor	Designed for most of LV applications	6300	150	[37]
Masterpact NT	Schneider	0,277	LV	50/60	Air		4	3	10	50	Indoor	Designed for motor and generator protection	1600	150	[37]
Masterpact NW	Schneider	1,15	MV	50/60	Air		4	3	10	25	Indoor	Designed to work for AC and DC applications	6300	150	[37]
Masterpact UR	Schneider	0,69	LV	50/60	Air		3	3	10	8	Indoor	Designed for high short circuit values	6000	150	[37]
Easypact EXE	Schneider	17,5	MV	50/60	Vacuum		3	3	10	66	Indoor	Designed to connect building infrastructure or industrial plant processes to the power grid	2500	31,5	[37]
Evopact HVX	Schneider	24	MV	50/60	Vacuum		3	3	30	15	Indoor	For medium voltage applications	4000	50	[37]
Evopact LF	Schneider	17	MV	50/60	SF6		3	3	30	50	Indoor	Designed to be sensitive for over voltage	5000	50	[37]
Evopact SF	Schneider	40,5	MV	50/60	SF6		3	3	30	60	Indoor	Designed to be sensitive for over voltage	3150	40	[37]
VA	Schneider	38	MV	50/60	Vacuum		4	3	30	60	Indoor	Designed fo MV systems applications	3150	50	[37]
VAH	Schneider	17,5	MV	50/60	Vacuum		3	3	30	60	Indoor	Design for high mechanical and electrical switching applications	8000	63	[37]
VXA and VXB	Schneider	27,5	MV	50/60	Vacuum		2	3	30	60	Indoor	Designed to meet the specific requirements of AC traction power supply systems	2500	40	[37]
VXC	Schneider	38	MV	50/60	Vacuum		3	3	30	60	Indoor	For intense industrial applications at very high ratings	4000	40	[37]
Evolis	Schneider	24	MV	50/60	Vacuum		3	3	30	50	Indoor	Protection for industrial and tertiary distribution	2500	40	[37]
3VA MCCB	Siemens	1	LV	50/60	Air		4	3	30	40	Indoor	Used in LV power distribution systems	250	100	[38]
Sentron MCCB	Siemens	0,415	LV	50/60	Air		4	3	30	40	Indoor	Applications with low currents	1600	150	[38]
VL MCCB	Siemens	0,48	LV	50/60	Air		3	3	30	50	Indoor	Applications with low currents	1600	100	[38]
WL PCB	Siemens	0,24	LV	50/60	Air		4	3	30	50	Indoor	Designed for protecting electrical distribution applications	1000	100	[38]
GM-SG	Siemens	15	MV	50/60	Vacuum		3	3	30	80	Indoor	Designed for protection and switching	1200	50	[39]
3AV1FG Blue live tank	Siemens	145	HV	50/60	Vacuum, clean air		3	3	50	40	Outdoor	High voltage applications up to 145 kV	3150	40	[40]
3AP live tank	Siemens	1100	UHV	50/60	SF6		3	3	50	40	Outdoor	High voltage applications up to 800 kV	5000	63	[42]
3AV1DT Blue dead tank	Siemens	145	HV	50/60	Vacuum, clean air		3	3	50	40	Outdoor	High voltage applications up to 145 kV	3150	63	[40]
3AP dead tank	Siemens	550	EHV	50/60	SF6		3	3	50	40	Outdoor	High voltage applications up to 550 kV	5000	90	[40]
3AP1 DTC	Siemens	245	HV	50/60	SF6		3	3	50	60	Outdoor	High voltage applications up to 245 kV	4000	63	[40]
3AP DCB	Siemens	420	EHV	50/60	SF6		1, 2	3	50	60	Outdoor	High voltage applications up to 420 kV	4000	50	[40]
F series	Hitachi	0,69	LV	50/60	Air		3, 4	3	30	40	Indoor	Standard low voltage indoor applicatins	1600	125	[41]
L series	Hitachi	0,44	LV	50/60	Air		3, 4	3	30	40	Indoor	Designed for applications that need high interrupting capacity	800	175	[41]
S series	Hitachi	0,44	LV	50/60	Air		2, 3	3	30	40	Indoor	Small cheaper CBs for LV applications	800	85	[41]
M series	Hitachi	0,5	LV	50/60	Air		3	3	30	40	Indoor	LV general applications	225	50	[41]
E series	Hitachi	0,44	LV	50/60	Air		3	3	30	40	Indoor	Standard indoor LV applications	800	50	[41]
R series	Hitachi	0,44	LV	50/60	Air		3, 4	3	30	40	Indoor	High interruptive capacity LV applications	1200	125	[41]
BK63 series	Hitachi	0,4	LV	50/60	Air		1, 2, 3, 4	3	30	40	Indoor	Used for household and commercial applications	63	6	[41]
BTK63 series	Hitachi	0,415	LV	50/60	Air		1, 2, 3, 4	3	30	40	Indoor	Used for household and commercial applications	63	10	[41]
A series	Hitachi	0,5	LV	50/60	Air		3	3	30	40	Indoor	Application with high nominal current	6300	150	[41]
ELK04	Hitachi	170	HV	50/60	SF6		2	3	50	60	Indoor/Ou	Used in substations for HV	4000	63	[42]
BLF/PASS	Hitachi	170	HV	50/60	SF6		1, 3	3	50	60	Indoor/Ou	Used in substations for HV	3150	40	[42]

ELK-14	Hitachi	300	HV	50/60	SF6		2	3	50	60	Indoor/Ou	Industry applications	4000	63	[42]
ELK-3	Hitachi	550	EHV	50/60	SF6		2	3	50	60	Indoor/Ou	Power transmission, industry applications	6300	80	[42]
ELK-4	Hitachi	800	UHV	50/60	SF6		2	3	50	60	Indoor/Ou	Large powerplants and for large transmission rates	6300	63	[42]
ELK-5	Hitachi	1200	UHV	50/60	SF6		2	3	50	60	Indoor/Ou	Large powerplants and for large transmission rates	8000	63	[42]
EDF SK	Hitachi	72,5	MV	50/60	SF6		3	3	50	55	Outdoor	Designed for switching applications	2500	31,5	[42]
LTB D	Hitachi	170	HV	50/60	SF6		3	3	50	40	Outdoor	Designed for switching, for low frequency and for connecting applications	3150	40	[42]
LTB E	Hitachi	420	EHV	50/60	SF6		1	3	50	40	Outdoor	High altitude applications, High seismic requirement applications	4000	50	[42]
HPL B	Hitachi	1100	UHV	50/60	SF6		1, 3	3	50	40	Outdoor	Used for switching applications lower then 1100 kV	6300	80	[42]
DTB	Hitachi	800	UHV	50/60	SF6		1, 3	3	50	40	Outdoor	Used for switching applications lower then 800 kV	5000	63	[42]
DCB	Hitachi	550	EHV	50/60	SF6		1, 3	3	50	50	Outdoor	Used for switching applications lower then 550 kV	4000	63	[42]
EDI SK	Hitachi	72,5	MV	50/60	SF6		3	3	50	55	Indoor	Used for switching applications lower then 72,5 kV	2500	31,5	[42]
COMPASS	Hitachi	170	HV	50/60	SF6		3	3	50	50	Outdoor	Used for integration of renewable power to the grid	2000	40	[42]
Econiq LTA	Hitachi	145	HV	50	CO2 based gas mix		3	3	40	50	Outdoor	Line switching, Transformer switching	2700	40	[42]
GL 107X	GE	40,5	MV	50/60	SF6		1, 3	3	30	50	Outdoor	MV distribution applications lower then 40,5 kV	2000	31,5	[43]
GL 308	GE	52	MV	50/60	SF6		3	3	30	50	Outdoor	MV distribution applications lower then 52 kV	2000	31,5	[43]
GL 309	GE	72,5	MV	50/60	SF6		3	3	30	50	Outdoor	MV distribution applications lower then 72,5 kV	2000	31,5	[43]
GL 309g	GE	72,5	MV	50	g3		1, 3	3	30	50	Outdoor	SF6 free outdoor medium voltage distribution applications	3150	40	[43]
GL 310g	GE	100	MV	50	g3		1, 3	3	30	50	Outdoor	SF6 free MV applications lower then 100 kV	3150	40	[43]
GL 311g	GE	123	HV	50	g3		1, 3	3	30	50	Outdoor	SF6 free HV applications lower then 123 kV	3150	40	[43]
GL 312g	GE	145	HV	50	g3		1, 3	3	30	50	Outdoor	SF6 free HV applications lower then 145 kV	3150	40	[43]
GL 310 S	GE	100	MV	50	SF6		3	3	30	60	Outdoor	MV applications up to 100 kV	3150	40	[43]
GL 311 S	GE	123	HV	50	SF6		3	3	30	60	Outdoor	HV applications up to 123 kV	3150	40	[43]
GL 312 S	GE	145	HV	50	SF6		3	3	30	60	Outdoor	HV applications up to 145 kV	3150	40	[43]
GL 313	GE	170	HV	50/60	SF6		3	3	30	50	Outdoor	HV applications up to 170 kV	3150	40	[43]
GL 314	GE	252	HV	50/60	SF6		1, 3	3	30	38	Outdoor	HV applications up to 252 kV	4400	137	[43]
GL 314X	GE	300	HV	50	SF6		1, 3	3	30	40	Outdoor	HV applications up to 300 kV	4000	173	[43]
GL 315	GE	362	EHV	50/60	SF6		3	3	30	38	Outdoor	HV applications up to 362 kV	4000	137	[43]
GL 315X	GE	362	EHV	50	SF6		3	3	30	40	Outdoor	HV applications up to 362 kV and 50 Hz only systems	5500	173	[43]
GL 316	GE	420	EHV	50/60	SF6		1	3	30	38	Outdoor	HV applications up to 420 kV	4000	137	[43]
GL 316X	GE	420	EHV	50	SF6		1	3	30	40	Outdoor	HV applications up to 420 kV and 50 Hz only systems	5500	173	[43]
GL 317	GE	550	EHV	50/60	SF6		1	3	30	38	Outdoor	HV applications up to 550 kV	4000	137	[43]
GL 317X	GE	550	EHV	50	SF6		1	3	30	40	Outdoor	HV applications up to 550 kV and 50 Hz only systems	5500	173	[43]
GL 318	GE	800	UHV	50/60	SF6		1	3	30	38	Outdoor	HV applications up to 800 kV	4000	137	[43]
GL 318X	GE	800	UHV	50	SF6		1	3	30	40	Outdoor	Outdoor high voltage applications up to 800 kV and 50 Hz only systems	5500	173	[43]
DT1	GE	362	EHV	50/60	SF6		3	3	30	33	Outdoor	Is qualified for controlled switching	5000	63	[43]

DT2	GE	550	EHV	50/60	SF6		3	3	30	42	Outdoor	HV applications up to 550 kV	5000	60	[43]
FKG2S	GE	24	MV	50/60	SF6		3	3	30	50	Indoor/Ou	Generator Circuit Breaker for powerplants from 50 to 150 MW	6800	63	[43]
FKG2M	GE	24	MV	50/60	SF6		3	3	30	50	Indoor/Ou	Generator Circuit Breaker for powerplants from 100 to 200 MW	8400	80	[43]
FKG1N	GE	27	MV	50/60	SF6		3	3	30	75	Indoor/Ou	Generator Circuit Breaker for powerplants from 200 to 300 MW	10800	120	[43]
FKG1F	GE	27	MV	50/60	SF6		3	3	30	75	Indoor/Ou	Generator Circuit Breaker for powerplants from 300 to 450 MW	13500	120	[43]
FKGA2	GE	27	MV	50/60	SF6		3	3	30	75	Indoor/Ou	Generator Circuit Breaker for powerplants from 200 to 450 MW	14100	100	[43]
FKG1X	GE	32,4	MV	50/60	SF6		3	3	30	75	Indoor/Ou	Generator Circuit Breaker for powerplants from 450 to 600 MW	17000	160	[43]
FKG1XV	GE	32,4	MV	50/60	SF6		3	3	30	75	Indoor/Ou	Generator Circuit Breaker for powerplants from 750 to 900 MW	24000	160	[43]
FKG1XP	GE	32,4	MV	50/60	SF6		3	3	30	75	Indoor/Ou	Generator Circuit Breaker for powerplants from 600 to 750 MW	21000	160	[43]
FKG1XW	GE	32,4	MV	50/60	SF6		3	3	30	75	Indoor/Ou	Generator Circuit Breaker for powerplants from 900 to 1000 MW	24000	160	[43]
FKGA8	GE	33	MV	50/60	SF6		3	3	30	75	Indoor/Ou	Generator Circuit Breaker for powerplants from 700 to 1500 MW	30000	210	[43]
SBS Minimum Oil CB	BBC Brown	12	MV	50	Oil	2	3	1	no data	100	Outdoor	Used in high for on-load circuit breaking voltage installations as power circuit breaker	1600	43	[44]
T type	Fuji Electric	12	MV	50/60	Oil	5	3	1	no data	100	Outdoor	Used in power distribution systems	2000	36	[45]
SM AirSeT	Schneider	24	MV	50/60	Clean Air, vacuum		3	3	40	50	Indoor	Switchgear for secondary distribution systems	1250	25	[46]
GM AirSeT	Schneider	24	MV	50/60	Clean Air, vacuum		3	3	40	50	Indoor	Switchgear for primary distribution systems	1250	25	[46]
RM AirSeT	Schneider	24	MV	50/60	Clean Air		3	3	40	50	Indoor	Switchgear for secondary distribution applications	630	20	[46]
Xpert UX	Eaton	24	MV	50/60	Air, vacuum		1	3	40	50	Indoor	For power distribution and motor control in primary distribution	4000	50	[47]
Xpert FMX	Eaton	24	MV	50/60	vacuum		1	1	40	50	Indoor	Designed for secondary distribution systems	2000	25	[47]
N2 Blue	SGC	17,5	MV	50/60	N2 gas		1	1	40	50	Indoor	Designed for most switching applications	2500	25	[48]
DF2	SGC	24	MV	50/60	Air		1	1	40	50	Indoor	Designed for most switching applications	1250	25	[48]