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Alternatives to SF6 in HV Circuit Breaker Insulation

ENG4111/4112 Dissertation

SF6 is an environmentally potent and OH&S concerning substance, however it is the dominate insulation medium used in HV circuit breakers. This dissertation explores the benefits of alternative designs and technologies that seek to eliminate or reduce the use of SF6 in HV circuit breakers.

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Abstract

Sulphur hexafluoride (SF_6) is a synthetic gas extensively used in the high voltage (HV) electricity transmission and distribution industry. The unique and unrivalled properties of SF_6 gas that enable it to resist/recover from spark conduction have positioned it as the preferred HV arc interruption medium. Since its introduction in the 1960's HV circuit breakers utilising SF_6 have provided less frequent maintenance requirements and reduced installation footprints compared to their Oil/Air predecessors.

Unfortunately however, SF_6 has an extremely high global warming potential (GWP), 22,800 times that of carbon dioxide. This high global warming potential combined with a long shelf life (3000 years in atmosphere) has seen the gas identified as one of the six most potent contributors to climate change. Additionally, the decomposition by-products of SF_6 used for arc extinguishment threaten the occupational health and safety of maintenance staff.

A case study examining the use of SF_6 in the region of Central Western NSW has been undertaken as a part of this dissertation. The Central Western NSW electricity grid was found to utilise 10,216 kg of in-service SF_6 gas in its HV circuit breakers and associated apparatus. Additionally, SF_6 insulated equipment was found to contribute a growing 70% market share of switchgear applications 66 kV and above. A government prescribe annual leakage rate of 0.89% of capacity combined with handling losses suggests the case study area's SF_6 insulated equipment is responsible for 2,905 tonnes of CO_2 equivalent emissions per year.

Alternatives, eliminating or reducing the use of SF_6 insulation in HV circuit breakers and associate apparatus do exist and in some cases are fast becoming the more popular and cost effective option. Established solid-dielectric/vacuum and dry-air/vacuum circuit breakers are two such alternatives eliminating SF_6 reliance in the 66 kV and below spectrums. Other advancements include non-conventional current transformers with digital outputs that are revolutionising traditional circuit breaker installation concepts.

The 40 year dominance associated with SF_6 insulated switchgear is placing utilities in vulnerable positions. With the ongoing replacement of obsolete oil designs expected to finalise in the next decade Australian circuit breakers 66 kV and above could be near 100% SF_6 insulated by 2025. Despite a recent fall in national electricity demand, infrastructure upgrades and the diversifying renewable generation mix are supporting continual SF_6 insulated equipment growth. Environment driven regulated SF_6 price rises or application bans are of increasing concerns to network utilities.

This dissertation provides reasonable and practical recommendations of pro-active technology implementations and trials that will help alleviate reliance on SF_6. The proposals also seek to respect restricting network operating budgets recently implemented in an effort to curb rising electricity commodity prices whilst simultaneously offering environmental and OH&S beneficial alternatives.

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I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

M. Marland

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Glossary of Terms

Air-Blast (AB) Circuit Breaker: circuit breaker utilising high pressure air flow for electrical current interruption

Carbone dioxide (CO_2): naturally occurring compound, most common pollutant/greenhouse gas

Circuit Breaker: electro-mechanical device for interrupting electrical current flow

Climate Change: concept of human influenced changing global climate

Current Transformer (CT): instrument for measuring electrical currents

Dead-Tank: design style of HV circuit breakers, interruption tank at touch potential

Decomposition By-products: chemical substances formed post arc extinguishment

Dielectric: substance property to resist electrical current flow

Distribution: medium distance electrical network for supplying customers, typically 11-66kV

Dry-air: moisture free air used for electrical insulation at high pressures

Emission: Gas releases to the atmosphere

Global Warming Potential (GWP): rating assigned to a compound quantifying its radiative force on the atmosphere in comparison to 1 kg of CO_2

High Voltage (HV): general term for voltage levels above 1000 V AC, industry term for voltage levels 66 kV and above

Insulation: Substance used for dielectric purposes in electrical equipment

Live-Tank: design style of HV circuit breakers, interruption tank at operating voltage potential

Medium Voltage (MV): Industry term for voltage levels below 66 kV

Non-conventional Current Transformer (NCCT): current senor not utilising traditional magnetic windings

Occupational Health and Safety (OH&S): safety, health and well fair of people engaged in employment

Octafluorocyclobutane ($c - C_4F_8$): Fluorocarbon considered for electrical insulation

Oil Circuit Breaker: circuit breaker using oil as arc extinguishing medium, Small Oil Volume (SOV) or Bulk Oil (BO)

Re-closer: field circuit breaker for sectionalising long distribution lines

Renewable Energy: energy generated by means naturally replenishing resources

SF6 Circuit Breaker: circuit breaker utilising SF_6 gas as arc interruption medium

Solid-dielectric: solid material utilised for its ability to resist current flow

Substation: network node for electrical power distribution and transmission

Sulphur hexafluoride (SF_6): synthetic gas used for electrical insulation

Switchgear: collective term for HV electrical circuit breakers and switches

Transmission: long distance electrical network typically 132 kV and above

Vacuum Circuit Breaker: circuit breaker containing a vessel devoid of matter used for electrical current interruption

Zone-substation: network node for electrical power distribution

Chapter 1: Introduction

1.1 Setting the Scene

Sulphur hexafluoride (SF_6) is a synthetic gas that has been extensively used as an insulation medium in the electrical industry since the 1960's. The unique properties of SF_6 including its high dielectric strength and superb electrical arc extinguishing abilities have positioned it as the unrivalled substance of choice for high voltage (HV) arc interruption. Primarily used in HV circuit breakers but also transformers, its high dielectric strength offers compact designs. Additionally, its extraordinary molecular recovery post arc extinguishment offers minimal maintenance and high functionality guarantees.

Despite its unrivalled functionality, SF_6 has been labelled as the most potent greenhouse gas ever evaluated by scientists. The Kyoto Protocol in 1997 indentified the substance as one of the six most potent contributors to climate change. Alarmingly however, both production and demand for the substance has further increased since the protocol. The Australian Government Department of Climate Change and Energy Efficiency in its 2012 report indentified SF_6 emissions as having a Global Warming Potential (GWP) of 23,900. That is 1kg of SF_6 has the same global warming potential as 23,900 kg of carbon dioxide (CO_2).

Additionally decomposition of SF_6 upon the extinguishment of intense electrical arcs can give rise to toxic and Occupational Health and Safely (OH&S) concerning by-products. Minute traces of moisture in combination with SF_6 molecular decomposition during arc extinguishment can produce sulphur dioxide, hydrofluoric acid and metal fluoride compounds all which are hazardous to maintenance personnel.

High voltage circuit breakers are used in electrical supply network substations and other applications where the control and protection of HV electrical equipment is required. The oil insulated and air-blast circuit breaker predecessor to SF_6 have since become obsolete with the last of their generation install pre 1985. HV circuit breakers are largely considered to provide a 40 year in-service life span which has seen the obsolete oil and air-blast designs of the past slowly been replaced over the last 30 years. The unrivalled functionality and reasonable cost of SF_6 equipment saw limited circuit breaker technology innovations in the period 1980-2000. The industry was excusable content with the space saving and low maintenance designs SF_6 offered in a less environmentally concerned era. Currently SF_6 insulated circuit breakers hold a 70% market share of in-service units 66kV and above. By the year 2025, a close to 100% SF_6monopoly is expected in this range without change.

Global environmental awareness and concerns are increasing and the global warming potential of SF_6 has positioned itself as a highlighted substance. So much so that recently there have been calls in Europe to ban the substance in all new medium voltage (MV) switchgear applications.

Alternatives to SF_6 circuit breaker insulation as well as technologies and strategies to help reduce its usage do exist. Environmental awareness and employee OH&S concerns are prompting a revolutionary movement away from the potent substance.

1.2 This Dissertation

This dissertation seeks to deliver upon the follow five objectives.

1. Research background information on SF_6 the substance and the development of HV circuit breakers in industry to date

2. Determine the actual use of SF_6 in existing Australian electrical networks

3. Explore the materials, technologies and strategies that are seeking to, or are capable of, eliminating or reducing the use SF_6 in HV circuit breakers and associated apparatus

4. Examine the environmental, cost and life cycle implications of the continual usage of SF_6 in HV circuit breakers and the benefits or consequences of its reduction or elimination

5. Present recommendations regarding this dissertation's findings for utilities utilising SF_6 to consider in future infrastructure developments, replacement strategies and maintenance regimes.

Research into SF_6 the substance and the development of HV circuit breakers is intended to form the literature review proportion of this dissertation. Objective three has been addressed by means of a case study into the Central Western NSW electrical transmission and distribution network. The extensive results gathered analysing the region's 659 HV circuit breakers form the basis of the subsequent chapters which examine SF_6 alternatives and their benefits referred to the case study area. The concluding recommendations addressing object five seek to provide national utilities reasonable suggestions that are practical, cost effective, safe, and environmentally sensitive.

Chapter 2: What is Sulphur hexafluoride (SF_6)

This chapter seeks to provide a background on SF_6 the substance, its environmental impacts and extensive use in the HV industry. Additionally, an insight into the life cycle of SF_6 containing electrical equipment, manufacturing and costs of SF_6, related OH&S issues and applicable Australian and International standards are explored. The primary focus of this introductory chapter to provide an informative picture about SF_6 and the issues concerning its unrivalled and extensive use in HV circuit breakers worldwide.

As global awareness into our environmental responsibility increases so too do strategies and technologies intended to eliminate or reduce the reliance on such environmentally potent substances. Alternatives to SF_6 circuit breakers do exist and the need for a greater uptake and investment into the alternatives of this environmental potent and OH&S concerning substances is warranted. This point is discussed as the consolidating section of this introductory chapter and is the is presented as the overwhelming theme of this dissertation

2.1 Sulphur Hexafluoride (SF_6)

Sulphur hexafluoride is a synthetic gas extensively used in the high and medium voltage electricity industry (electrical power transmission and distribution) for its unique properties as a dielectric insulation and electrical current interruption medium. Sulphur hexafluoride gas is more commonly known by its chemical formula SF_6. SF_6 is formed by six atoms of fluorine tightly bound around a centrally positioned atom of sulphur. 'The chemical bond between fluorine and sulphur is known as one of the most stable existing atomic bonds' (Glaubitz, 2005, p. 8). The fast cooling and near total molecular recovery of SF_6 gas after being exposed to an electrical arc makes it ideal for arc quenching. Such a responsibility is burdened by the high electrical current interruption processes needed for maintaining a safe and reliable electricity supply.

Pure SF_6 is odourless, tasteless, non-toxic, non-corrosive, non-flammable and chemically inert at ambient temperature. It does not support combustion. The unique chemical properties of sulphur hexafluoride gas that enable it to resist spark conduction make it an excellent high voltage electrical insulator.

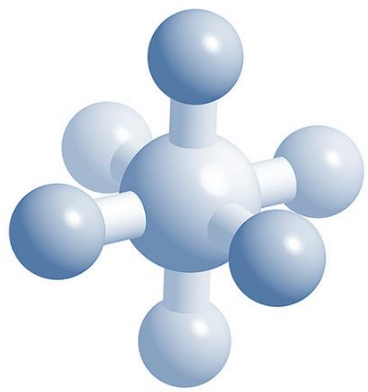


Figure 2-1 Molecular Model of Sulphur Hexafluoride

"The chemical and thermal properties of SF_6 are extremely stable. The substance's underactivity is contributed to the 'steric hindrance around the sulphur atom and the non-polarity of the octahedral molecule. Sulphur hexafluoride is obtained by an exothermal reaction of fluorine with sulphur: $S + F_2 \rightarrow SF_6$." (Eagleson, 1993)

"Sulphur hexafluoride was first synthesised in the laboratories of the Faculté de Pharmacie de Paris in 1900 by Moissan and Lebeau. Fluorine, obtained by electrolysis, was allowed to react with sulphur in a strongly exothermic reaction, giving rise to a remarkably stable gas." (Koch, 2003, p. 4)

Harnisch J et al. (2000) researched that sulphur hexafluoride is also known to occur naturally. A geological study in 2000 identified common granitic rocks and fluorite minerals from which the gas can be released extremely slowly subject to weathering processes.

For electrical equipment, SF_6 offers excellent electric insulation and switching properties. It is believed that today's high performance of high voltage (HV) switchgear cannot be reached with any other gas. Both experimentation and historical industry practice have shown that other gases under consideration for application in HV switchgear may have better insulating performance or switching performance, but not both. Most of these gases do not offer long-term stability.

Although the overwhelming majority of SF_6 gas manufactured is for the medium and high voltage electrical supply industry SF_6 is used for other industrial purposes. Non-electrical industrial applications of SF_6 include metallurgy, electronics, scientific equipment, ocular surgery, and military applications. It is used as a cover gas in the magnesium industry, for plasma etching in semiconductor manufacturing, as a reactive gas in aluminium recycling to reduce porosity. Additional uses include thermal and sound insulation in double glazed windows, atmospheric tracer studies and medical applications as well as being previously used in sports shoes.

Table 2-1 SF6 Properties at 25°C

Property	Value	Units
Physical state	Gas	
Molecular Formula	SF_6	
Colour	Colourless	
Density	6.14	$kg\ m^3$
Relative Density (gas, air =1)	5	
Relative Density (liq, water =1)	1.4	
Molecular Weight	146.05	$g\ mol^{-1}$
Thermal Conductivity	0.0136	$W\ m^{-1}K^{-1}$
Solubility in Water	7000	$ppmv$
“	41	$mg\ l^{-1}$
Melting Point	-50.8	$°C$
Boiling Point	-64 (s)	$°C$
Critical Point:		
Temperature	45.55	$°C$
Density	730	$kg\ m^3$
Pressure	3.78	MPa
Sound Velocity	136	$m\ s^{-1}$
Refractive Index	1.00783	
Formation Heat	-1221.66	$KJ\ mol^{-1}$
Specific Heat	96.6	$J\ mol^{-1}K^{-1}$
CAS Number	2551-62-4	
Vapour Pressure @ 20°C	21	Bar

Source: (Koch, 2003), (Air Liquide, 2012) see: Appendix B

2.2 Electrical Properties

Sulphur hexafluoride's preferential use as an insulating gas in the electricity industry is a result of the unique combination of its physical properties. As previously mentioned SF_6 has superb dielectric strength and arc quenching abilities which make it desirable in high and medium voltage applications.

Electrical power is transmitted and distributed over power lines more efficiently at high voltages (132-500 kV transmission 11-66 kV distribution in NSW). High voltage transmission reduces the electrical current flow required for the same resultant power transmission which in turn reduces associated power losses and required cable sizes. Transmission is typically used for connecting longer distances and distribution is used for supply to local customers. For the purpose of this dissertation, high voltage (HV) is considered as 66 kV and above, while medium voltage (MV) is taken as 11 kV to below 66 kV. These voltage level descriptions have been chosen for the occasional need to sectionalise the industry. It should be noted that the term "high voltage" in general however, can often refer to both MV and HV ranges.

2.2.1 Dielectric Strength

Electrical transmission lines and equipment are constructed in such a way the conductors carrying the electrical current are insulated from other conductive matter not at their same voltage potentials. This insulation is provided by means of either a non-conductive material or distance in air. The dielectric characteristic of an insulating substance refers to its ability oppose the flow of electrical current leakage through itself. High voltage conductors separated from other conductive matter at different voltage potentials are prone to leakage currents through the separation medium. All insulators used for the separation of high voltage conductors can be evaluated by their dielectric strength. Dielectric strength is determined by the applied voltage across a given length of a material that produces dielectric breakdown where the applied electric field frees bound electrons. SF_6's excellent dielectric strength is contributed to the electronegative character of its molecule. "Electro-negativity is the tendency of an atom or a functional group to attract electrons" (IUPAC, 1997).

"SF_6 gas has a pronounced tendency to capture free electrons forming heavy ions with low mobility making the development of electron flow very difficult." (Koch, 2003) .

SF_6 is considered to have dielectric strength about three times that of air at one atmospheric pressure for a given electrode spacing. Its dielectric strength increases with increases in pressure. At three times atmospheric pressure, the dielectric strength is similar to that of transformer oil.

Figure- Source (Mike de Swardt, 2014)

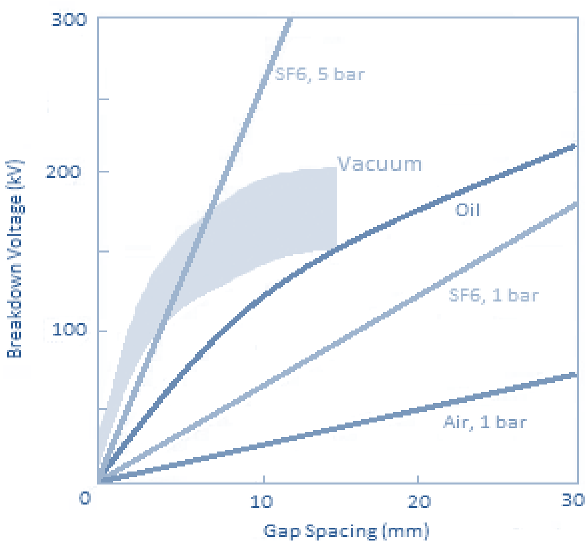


Figure 2-2 DC breakdown strength of SF_6 and other substances

2.2.2 Electrical Current Interruption

The reliable and safe transmission and distribution of electrical power also requires the ability for the electrical current flow to be switched on or off. Interrupting current flow in the event of an electrical fault or for the purposes of rearrangement and isolation of network components are essential to reliable electrical power networks. The process of interrupting HV high amplitude current flow with a HV circuit breaker is not particularly an easy one. The separation of two previously connected conductors passing electrical current between them can produce an electrical arc attempting to maintain the current flow across the separating conductors. The resultant electric arc is known as a self-sustaining electrical discharge and is capable of sustaining large electrical current flow.

“Though the most commonly observed arc discharge occurs across air at atmospheric conditions, the arc discharge is also observed at high and low pressures, in a vacuum environment, and in a variety of gases and metal vapours” (Garzon, 1997).

Dissociation refers to the “cleavage of a molecule into two or more, simpler molecules, atoms or ions” (Eagleson, 1993).

The energy required to separate the molecules is term dissociation energy and the temperature at which this reversible effect is permitted is the dissociation temperature.

Koch (2003) explains that because of SF_6’s low dissociation temperature and high dissociation energy, $SF_6$is an excellent arc quenching gas. When an electric arc cools in SF_6, it remains conductive to a relatively low temperature, thus minimising current chopping before current zero, and thereby avoiding high over voltages. In alternating current (AC), of which is the form of Australia’s national supply, current and voltage supplied alternate from a positive to negative amplitude 50 times a second (50Hz). Current flow is easiest to interrupt as it passes through zero amplitude known as “current zero”. SF_6’s arc extinquish capability is about ten times that of air.

In addition to these properties, Eagleso’s Concise encyclopedia of Chemistry (1993) acknowledges that the gases lack of toxic or corrosive effects make the compatibility of SF_6 with material used in electric construction similar to that of nitrogen, up to temperatures of about 180°C.

2.3 Environmental Impact

"SF_6, was labelled as the most potent greenhouse gas ever evaluated by the scientists of the Inter-governmental Panel on Climate Change (IPCC) in 1995" (Garzon, 1997).

In 1997, at the third conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in Kyoto colloquially now known as the Kyoto protocol, the industrialized countries of the world accepted emission reduction targets for six greenhouse gases. The international protocol is widely seen as an important step to limit global greenhouse gas emissions. Emission reductions were negotiated to such levels that were believed to avoid dangerous anthropogenic interference with the climate system.

"Carbon dioxide, methane, nitrous oxide, sulphur hexafluoride as well as groups of hydro-fluorocarbons and per-fluorocarbons were identified as the six most potent contributors to climate change, in accordance with Annex B of the Protocol. The six greenhouse gases are translated into their CO_2 equivalents to determine the reduction of emissions" (Rhiemeier, et al., 2010).

The concerning and dangerous potential of SF_6's contribution to global warming is that SF_6 has an extremely stable molecular structure. Like all the fully fluorinated family, their molecular structure ensures that the compound endures a very long life cycle, approximately 3200 years upon release to the atmosphere. A combination of this stagnant life cycle together with a proficient absorption ability of infra-red radiation has led to the substance being assigned an extremely high Global Warming Potential (GWP)

"The GWP rating is a comparative numerical value that is assigned to a compound. The value is arrived at by integrating over a time span the radiative forcing value produced by the release of 1 kg of the gas in question and then dividing the value by the value obtained with a similar procedure with CO_2 . Because CO_2 is considered the most common pollutant, it has been selected as the basis of comparison for assigning GWP values to other pollutants. The radiative forcing, according to its definition, is the change in net irradiance in watts per square meter" (Garzon, 1997).

Hence, SF_6 in particular has an extremely high global warming potential, being evaluated at 23,900 times higher than an equivalent amount of carbon dioxide over a 100-year time period. This global warming potential combined with a long shelf life enforces that even small releases of SF_6 into the atmosphere are a significant concern.

SF_6 emissions reduction may prove further problematic in future as the main usage of the identified greenhouse gas is in the ever expanding electrical power industry. "According to IEA's World Energy Outlook 2009, 19,756 TWh of electricity was consumed worldwide in 2007. World electricity demand is projected to grow at an annual rate of 2.7 % in the period 2007-2015, slowing to 2.4 % per year on average in the period 2015-2030" (Rhiemeier, et al., 2010).

In Australia however, growth has steadied over the past few years for reasons outlined in Section 6.1 of this dissertation. Despite local trends, without change in current practices the growth in worlds electricity demand and resulting infrastructure will further utilise, and hence unfortunately release, increasing amounts of SF_6 gas into the atmosphere.

2.4 Use in High Voltage Industry

Australia's electricity network consists of generation, transmission and distribution. Transmission relates to transferring power over long distances and in NSW is associated with voltage levels 132kV and above. Distribution is associated with shorter distances at voltage 66kV and below. Transmission and distribution networks consist of overhead lines or cables, in addition to other components such as switchgear and transformers. Switchgear or circuit breakers are used to protect the electrical network against overload and short circuit currents. Transformers and associated switchgear are found in high voltage substations and zone substations utilised to step up or down voltage levels for transmission from generation sites through to distribution to end customers.

Since the early 1960's, SF_6has be used by the electricity industry in power equipment facilitating HV transmission and MV distribution of electrical power. Gas insulated switch gear, transformers and cables are all common uses of SF_6 gas in the power industry. Sulphur hexafluoride has a much higher dielectric strength than air, making it possible to significantly reduce the product footprint and enable installation in constrained spaces. SF_6 insulation superseded aging oil insulated technology. Its benefits included less maintenance and more compact in designs.

A SF_6 gas insulated circuit breaker uses the superior dielectric SF_6 gas at a moderate pressure (typically 600 kPa) for phase to ground insulation and insulation across open contacts. The high voltage conductors and circuit breaker interrupter mechanisms are encapsulated in the SF_6 gas inside grounded metal enclosures. An atmospheric air installation of comparative dielectric strength would require meters of air insulation to do what SF_6 can do in centimetres. The fully sealed SF_6 circuit breaker provides the internal mechanisms protection from deterioration from exposure due to atmospheric air, moisture and contaminations, etc. As a result, SF_6 circuit breakers are considered more reliable, require less maintenance, and boast a long service life (more than 50 years).

SF_6 is used in high voltage circuit breakers at pressures from 400 to 600 kPa absolute. The pressure is chosen so that the sulphur hexafluoride will not condense into a liquid at the lowest temperatures the equipment experiences

"SF_6 has been tested to exhibit two to three times the insulating ability of air at the same pressure. SF_6 is considered about ten times better than air for interrupting arcs. The now universally used interrupting substance for high voltage circuit breakers is replacing the older mediums of oil and air. SF_6 decomposes in the high temperature of an electric arc or spark, but the decomposed gas has an unique ability to recombine back into SF_6 so well that it is rarely necessary to replenish the SF_6 within equipment" (Mcdonald, 2007).

For these reasons SF_6 has become the most dominant insulating gas of choice, particularly in the transmission voltage range where there is currently no other competitive practical alternative. For distribution equipment 33 kV and below however, vacuum interpret circuit breaker technology enjoy an equal if not preferred popularity. Vacuum technology offers similar maintenance regimes to SF_6 with reduced environmental impact. Vacuum technology also eliminates the need for SF_6 refilling equipment and stock pile costs. However, main stream vacuum technology is typically only available for applications up to 33 kV .

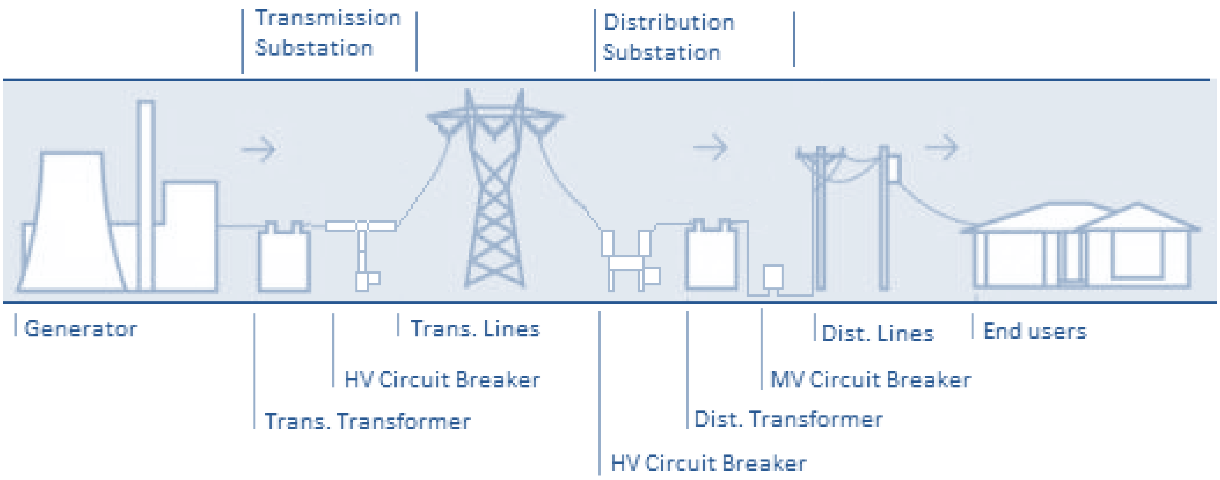


Figure 2-3 Simplistic Overview of Electrical Network

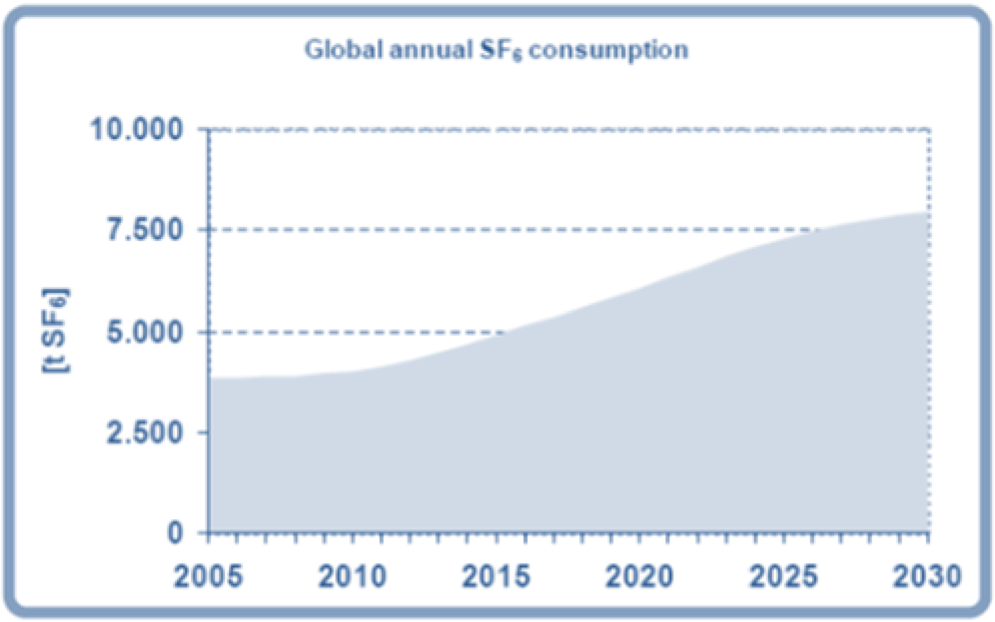


Figure 2-4 Global Annual SF6 Consumption

Source: (Deux, 2008)

2.5 Life cycle of SF6 in Electrical Equipment

2.5.1 Manufacturing of Equipment

Historically Japan and Europe are responsible for the vast majority of the world's electrical power transmission and distribution equipment. High voltage equipment containing SF_6 gas for insulation such as circuit breakers and transformers are manufactured in Japanese and European facilities. A typical facility consists of a dedicated area for large tanks (approx. 600 kg) filled with liquefied SF_6. Copper distribution pipes form a network from the tanks to the different stages of the manufacturing facility controlled by check valves. Counters, pressure gauges and SF_6 detectors monitor the SF_6 gas throughout the facility. Manufactured components are assembled and sealed pressure units are filled with SF_6 and tested to appropriate conditions. The gas is consequently reclaimed out of the equipment and replaced with nitrogen or reduced volume of SF_6 at a pressure slightly above atmospheric to eliminate moisture ingression during shipping. Once delivered and installed in the final desired location the filling medium is either replaced or topped with $SF_6$to the operational required amount and pressure.

2.5.2 In service Equipment

During the life of a SF_6 filled circuit breaker the breaker can be expected to operate thousands of times. The internal SF_6 gas could be subject to extinguishing literally thousands of arcs under normal operating conditions and possibly upwards of 100 large fault arcs. Most utility companies test the SF_6 gas for purity every four years (depending on individual company policy) and gas changes can be endorsed earlier if needed. Upon a scheduled maintenance or service due to equipment fault, the equipment's SF_6 gas is reclaimed by an appropriate gas recovery unit to allow for internal inspection. SF_6 gas identified to have purity concerns can be sent away to particular companies for recycling. After maintenance or other internal work required is completed the equipment is resealed and re-filled with either new SF_6 gas or the previous SF_6 gas if deemed suitable. Unfortunately a portion of the in-service gas will inevitably be leaked from equipment to the atmosphere due to poor sealing, cracked insulator housing or poor maintenance practices.

2.5.3 Equipment Decommissioning

Once the equipment has eventually served its purpose decommissioning is required. During decommissioning the remaining SF_6 gas is recovered. From here the gas can be disposed in accordance with local and/or international regulations. More commonly however the gas is recovered for the purpose of recycling. When returned to a SF_6 supplier, the supplying company will often clean and filter the old gas ready for re-use.

It must be noted that 100% full recovery of the SF_6 gas during any handling operation cannot be considered possible. "Typically between 2 % and 0.4% of the name plate capacity' is lost during handling activates" (Rhiemeier, et al., 2010). Filling pressure, correct equipment and efforts in staff training all contribute towards reducing handling emissions of electrical equipment containing SF_6 gas.

2.6 Manufacturing and Costs

"About 10 to 20 tonnes of SF6 are imported into Australia annually." (Australian Government Department of Sustainability, Environment, Water, populaion and Communities, 2012) NSW transmission and distribution authorities currently purchase SF_6 at a rate of $55 per kilogram

As previously mentioned historically Japan and Europe have been responsible for the manufacturing of the world's electrical transmission and distribution equipment, however, other regions are known to play minor but increasing roles. China's domestic demand in particular has seen their market share rapidly increase

Global consumption of SF_6 has been hard to establish. It is reasoned that the main SF_6 consuming regions of the electrical equipment industry are Europe, Japan and China followed by North America. Rhiemeier et al. (2010) report on global SF_6 emissions trends from electrical equipment assumes that approximately 80 % of the SF6 consumption for HV and MV electrical equipment is consumed in these regions. However, detailed data is only available for Europe, Japan, the USA and Korea. Europe, Japan and the USA's consumption of SF_6 in 2005 alone has been estimated at 1200, 600 and 300 tonnes respectively

Storage wise, the critical temperature and pressure of SF_6 is 45.55°C and 3.78 MPa respectively. SF_6 is liquefied by compression and is stored and transported as liquid in cylinders or containers in a liquid state at a pressure of about 6000 kPA. Common cylinder sizes are the "G" size bottle (56kg) and the "D" size bottle (10 kg) .

Purchased SF_6 cylinders should be stored protected from physical damage. Recommended storage of SF_6 cylinders is a cool, dry, well-ventilated area of non combustible construction, away from heavily trafficked areas and emergency exits. The temperature where cylinders are stored should not exceed 50 °C. Cylinders must be stored upright and firmly secured to prevent falling or being knocked over.

Prime Minister Gillard's Australian Government introduced a "carbon tax" to have effect from 1 July 2012. Despite the subsequent governments overturn of the tax it is worth noting that due to SF_6's high GWP, there was a significant price raise in SF_6.The tax set the price per tonne of all synthetic greenhouse gases based on the carbon price and the global warming potential (GWP) for each gas which at the time was $23 /tonne multiplied by 23,900 for SF_6.

"Cost implications of SF_6 under the carbon tax, using the initial carbon price of $23 per tonne, suggested SF_6 will translate into $550 AUD per kilo which was a ten-fold price increase. As an example, a typical live tank breaker of 72 kilovolts (kV) will have a tax burden of around $1,500. On a dead tank breaker however, which holds more gas in it, will see a more significant rise and on a full GIS 145 kV system, you would expect to see a tax exposure of around $55,000 per bay" (ABB Australia, 2012).

The Gillard Australian government did confirmed that recycling SF6 would not be considered as manufacturing and therefore will not incur a carbon tax.

2.7 Occupational Health & Safety with SF_6

"SF_6 is extremely proficient at extinguishing electrical arcs and is completely non-toxic in its pure state . When SF_6 gas is subject to high temperatures however, like those present in an electrical arc, the SF_6 molecules will break down into sulphur and fluorine ions. An electric arc can exceed temperatures of 10 000 degrees Kelvin. Upon cooling, (below 1000 °K) the gas molecules will recombine almost totally and only a small fraction will react with other substances such as air, moisture and vaporised metal." (Garzon, 1997)

These "other" gaseous and solid breakdown products upon reaction with incinerated SF_6 have proven to produce toxic properties. They can also have strong, distinctive odours and pose health and safety risks when coming into contact with the skin or eyes. On top of these by-product hazards are the hazards associated with the heavier than air gas itself as well as storage of the gas in high pressure vessels.

2.7.1 By-Product Hazards

Transgrid is the NSW state government owned electrical transmission authority. Transgrid's (2009) Management of SF_6 policy advises that - One of the breakdown products is thionyl fluoride, which is a gas with chemical formula: SOF_2. SOF_2 has a smell similar to hydrogen sulphide (rotten egg gas). With time, SOF_2 also decomposes in the presence of moisture to form sulphur dioxide (a gas, chemical formula: SO_2) and hydrogen fluoride (chemical formula: HF). Hydrogen fluoride, which is also known as hydrofluoric acid, is normally a gas at ambient temperatures. It is corrosive and will chemically burn, irritate the eyes, respiratory tract and mucous membranes (nose, mouth, throat, stomach etc). If it comes into contact with the skin, it can cause burns and deep tissue damage. Hydrogen fluoride is highly soluble in water, so care should be taken to prevent direct contact with any liquids present in electrical equipment after failure. The white powdery SF_6 breakdown product which is commonly referred to as "SF_6 decomposition products" is a complex mixture of compounds. It may contain metal fluorides which can act in a similar way to hydrogen fluoride, creating a dangerous acid in the presence of moisture. Therefore, care must be taken when handling or working near possible SF_6decomposition products in particular when working with gas that has been subject to moderate or heavy arc extinguishing.

2.7.2 Heavier than Air Hazards

SF_6 is five times heavier than air and as a result will accumulate in low lying indoor areas where there is no mechanism for the gas to dissipate. SF_6 does not support life and there for can cause asphyxiation in situations where large quantities of SF_6 can dilute the oxygen content of the air. The maximum permissible concentration of SF_6 gas in a workroom is 200 ppmv. If the concentration exceeds this level, personnel should leave the area and forced ventilation should be used to remove the SF_6 gas. Although SF_6 is odourless, its contaminant gases are not, therefore if workers detect a rotten egg smell then they should leave the area as quickly as possible and utilise forced ventilation to evacuate the area.

2.7.3 Pressure Hazards

The failure of pressure vessels containing SF_6 gas at high pressure (commonly 600 kPa) is another hazard associated with SF_6 equipment. Cuts, falls and dangerous impacts can result from vessel failure or explosion. SF_6 insulated switchgear is not designed to withstand external impact when under full pressure and therefore ladders and similar items should not be used up against equipment under full pressure. Sudden pressure release caused by failed fittings or hoses could also create a risk of injury through violent movement of parts.

Another hazard associated with SF_6 is when the gas is released from a high pressure container to be used at a lower pressure, rapid temperature drop can occur at the reducing valve. This can occur when filling equipment from cylinders and could result in freeze burns to nearby personnel.

Table 2-2 Origins of SF6 Impurities

SF_6 Situation and Use	Source of Impurities	Possible Impurities
During Handling in Service	Leaks and incomplete evacuation Desorption	Air, Oil, H_2O
Installation Function	Partial discharge: Corona and Sparking	$HF, SO_2, SOF_2, SOF_4, SO_2F_2$
Switching Equipment	Switching arc erosion Mechanical erosion	$H_2O, HF, SO_2, SOF_2, SOF_4, SO_2F_2,$ $CuF_2, SF_4, WO_3, CF_4, AIF_3$ Metal dusts, particles
Internal Arc	Melting and decomposition of materials	Air $H_2O, HF, SO_2, SOF_2, SOF_4, SO_2F_2$ $SF_4, CF_4,$ Metal dust particles $AIF_3, FeF_3, WO_3, CuF_2$

Source: (Transgrid, 2009)

2.8 Gas Quality

With SF_6 impurities having a considerable effect on both the functionality of the gas as an insulating medium and on occupational health and safety or maintenance personnel, monitoring of gas quality is of high importance. The gas quality of an SF_6 filled circuit breaker can be measured using field test instruments such as dew point and SF_6 content analysers.

The dew point measurement, also known as relative humidity, provides the moisture content of the gas sample. Dew point is expressed in degrees Celsius and moisture content in parts per million by volume (ppmv). In addition, devices that compare the speed of sound or thermal conductivity of SF_6 with that of pure SF_6 are used to determine the SF_6 content.

2.8.1 Gas Quality Limits for In-Service Equipment

The maximum allowable contamination levels in gas contained in in-service equipment is shown in the following table3

Table 2-3 Gas Quality Limits for In-Service Equipment

Impurity	Specification
Non-Reactive Gases (Combined Value)	3000 ppmv
SF4, WF6 (Combined Value)	100 ppmv
SOF2, SO2, HF (Combined Value)	2000 ppmv
H2O	470 pmmv (Dew Point -28°C at 100 kPa)

Source: (Transgrid, 2009)

2.9 Applicable Standards

2.9.1 Australian Standards

AS 2791: 1996 - High-voltage switchgear and control gear: Use and handling of sulphur hexafluoride (SF_6) in high-voltage switchgear and control gear. (Reproduction of IEC 1634:1995).

AS 62271.100-2008 High-voltage switchgear and control gear: Part 100: High-voltage alternating current circuit breakers (Reproduction of IEC 62271-100, Ed. 1.2 (2006) MOD).

2.9.2 International Standards

IEC 60694-2002, Common Specifications for High-Voltage Switchgear and Controlgear Standards

IEC 62271-100-2003, High-Voltage Switchgear and Controlgear—Part 100: High-Voltage Alternating-Current Circuit-Breakers

IEC 61634 report: High-voltage switchgear and controlgear - Use and handling of sulphur hexafluoride (SF6) in high-voltage switchgear and controlgear

IEEE Guide to Specifications for Gas-Insulated, Electric Power Substation Equipment, IEEE Std. C37.123-1996

IEEE Guide for Sulphur Hexafluoride (SF6) Gas Handling for High-Voltage (over 1000 Vac) Equipment IEEE Std C37.122.3™-2011

IEEE Std 1247TM-1998, IEEE Standard for Interrupter Switches for Alternating Current Rated Above 1000 Volts.

2.10 The Need to find a Replacement

Sulphur hexafluoride, as far as the electrical power industry in concerned, seems too good to be true. It's extremely fast post arc quenching recovery, space saving dielectric design capability, resistance to spark conduction, and zero toxic effects in its pure state make it an electrical power engineer's dream insulation medium with next to no substitute. However, like asbestos was thought the inimitable substance of its time, the global warming potential and occupational health and safety risks associated with SF_6 warrant research into replacement mediums.

Ruben Garzon, almost 16 years ago in his 1997 book High Voltage Circuit Breakers Design and Applications notes that:
"Presently the concentration of SF_6has been reported as being only about 3.2 parts per trillion by volume. This concentration is relatively low, but it has been observed that it is increasing at a rate of about 8 % per year. This means that if the concentration continues to increase at this rate, in less than 30 years the concentration could be about 50 pptv. More realistically, assuming a worst case scenario, the concentration of 50 pptv is expected to be reached by the year 2100. A more optimistic estimate is 30 pptv. At these concentrations the expected global wanning attributable to SF_6has been calculated as 0.02 and 0.014°C for the most pessimistic and the most optimistic scenarios respectively. Additional data indicates that the expected global warming due to SF_6, through the year 2010 is about 0.004 In comparison with an increase of 300 parts per million by volume (ppmv), of CO_2 , the expected change in the global temperature is 0 .8 °C." (Garzon, 1997)

Even though these contributions to global warming could be perceived as minor they are none the less human inflicted contributions. The International Energy Agency's World Energy Outlook predicts global electricity demand (and most likely SF_6 resulting infrastructure) to grow at an annual rate of 2.4 % in the period 2015-2030. The most likely proportional growth in SF_6 electrical equipment could be magnified by the continual replacement of obsolete air and oil circuit breakers by SF_6 designs. Undoubtedly, SF_6 technology has a potent and ever increasing foothold in today's electrical industry. With no foreseeable alternative in the high end transmission voltage scope, combined with best practice gas handling techniques releasing between 2 and 0.4% of equipment nameplate capacity atop of annual leakage estimates (typically 1% of capacity) continual SF_6 emissions are a daily reality.

Alternative technologies and SF_6 minimising strategies do exist. The tendency towards vacuum interrupters and solid-dielectric designs in the sub 33 kV medium voltage range is offering some positive outlooks. In an industry driven by proven reliability to maintain commodity supply to already high price conscious customers, few innovations have been explored or accepted from the 1980's up until the now. Our more recently environmentally concerned and educated global community has seen calls in Europe for the banning of SF_6 in MV switchgear applications. With an SF_6 circuit breaker monopoly in HV applications fast approaching the time for innovation is now.

Chapter 3: HV Circuit Breaker Trends and Innovation

The previous chapter outlines the properties of SF_6 and its unrivalled application in the electrical power industry as an insulation medium. However it is also apparent that SF_6 is an extremely potent environmental substance attributed with concerning OH&S risks.

Any innovative approach eliminating or reducing SF_6 use in high voltage circuit breakers for the future requires a detailed understanding of HV circuit breaker technology and practices to date. High voltage circuit breakers have evolved a long way since their introduction in the early 1900s. From separation in air to oil immersed contacts through to vacuum interrupters and SF_6 technology, knowledge of the evolution of circuit breaker designs is fundamental to future developments.

Today a large mix of circuit breakers are common in any given substation site. High voltage circuit breakers typically experience an up to 40 year life cycle, meaning a substation could contain a mixture of brand new through to 40 year old equipment. Four decades ago many now obsolete technologies were considered state of the art.

High voltage circuit breakers come in many different shapes and sizes and can be classified by voltage, application, location, physical design or current breaking technique. This chapter seeks to explore these design classifications and evolutions, the relevance of which is highly important to understanding any eventual SF_6 eliminating or reducing designs and strategies. Additionally this chapter provides a brief history of high voltage circuit breakers, their application and current maintenance activities involved with different types.

3.1 High Voltage Circuit Breakers

AS 62271. 100-2008, High-Voltage Switchgear and Control Gear, Part 100: High-Voltage Alternating Current Circuit Breakers, defines circuit breakers as:

"A mechanical device capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specific time and breaking currents under specified abnormal circuit conditions such as those of short circuit." (Standards Australia, 2008)

High voltage circuit breakers reside in high voltage substations and are used for the protection and control of electrical current flow though substation equipment such as transformers, feeders, busbars and reactive plant. HV substations accommodate the transformation of large transmission voltages used for connecting long distances down to lower level distribution voltages that supply local customers. A substation will typically comprise of multiple incoming and outgoing feeders, transformers and associated plant. Circuit breakers provide a means to turn on or off the electrical current flow through HV apparatus and will automatically operate (cut off supply) in the event of electrical fault detection.

A circuit breaker must be able to close onto and maintain full load current for long periods of time and then also be able to automatically disconnect that current irrespective of the inductive or capacitive nature of the load current. A circuit breakers primary purpose however is to interrupt and disconnect fault currents from damaging the system. The open circuit breaker gap across its contacts requires an ability to withstand rated system voltage. Circuit breakers are also required to carry short circuit fault currents for small periods of time, most commonly until another circuit breaker nearer to the fault location opens to clear the fault. In the event of closing a circuit breaker onto a fault it must have the ability to immediately re-open to clear the fault. The ability to withstand the effects or arcing at the contact surfaces and withstand the electromagnetic and thermal conditions which arise as a result of fault conditions is a major design consideration of circuit breaker engineers.

Circuit breakers are one of the few electro-mechanical devices in a substation which may remain in a quiescent state for long periods of time (even years) and then are required sometimes unexpectedly, to operate in less than 20 milliseconds. They must be designed to operate satisfactorily after long idle periods of service with great reliability. They are also called upon to operate at their maximum capacity very late in their life since generally their initial installation coincides with lower system fault levels.

There was a considerable change in the design of circuit breakers in the 1970's. The theory of operation has now evolved an in many cases the power utilities committed themselves to a 30 or 40 year life with an outdated design.

The high voltage circuit breakers now offered by the majority of manufacturers are generally spring operated SF_6 with very similar operating principles. These have now evolved to the point where they are extremely reliable, compact and require minimum maintenance.

3.2 History

Historically the need to reduce power transmission losses has driven the need to develop higher voltage equipment and infrastructure. Electrical transmission power loss is directly related to the amount of electrical current being transmitted. At higher transmission voltages, less current is required to flow to produce the same resultant electrical power and thus higher voltage transmission systems are desirable. High voltage circuit breakers needed to protect and control the flow of electrical current along network transmission and distribution lines have there for also had to evolve alongside the growing electrical power systems.

“It was in Tamworth NSW that Australia and the southern hemisphere seen the first town street lights illuminated by means of electricity on the 9th of November 1888” (Wilkenfeld & Spearritt, 2004).

Throughout the next two decades the capital cities and many other towns illuminated their streets by mean of electricity and in 1905 Sydney council (the latter of the capital cities to embrace electricity) had 519 customers.

Australia, heavily influenced by a its European settling culture today reliably delivers country wide house hold supply at the European nominal 230 V $\pm 10\%$ (phase-to-ground). The nations four wire 415 V (phase-to-phase) low voltage distribution network is feed via distribution transformers from a three wire medium voltage distribution network 11kV up to 66kV in New South Wales. Transmission voltages in NSW are restricted to 132 kV, 330 kV and 500 kV with a one off 220 kV line that runs from Darlington Point to Broken Hill in the far western region of the state. The transmission network links the states generation supply to the distribution networks.

“To achieve current interruption some of the early circuit breaker designs simply relied on stretching the arc across a pair of contacts in air, later arc chute structures, including some with magnetic blow-out coils were incorporated, while other devices used a liquid medium, including water but more generally oil, as the interrupting medium.” (Garzon, 1997)

In Australia for system voltages up to 33kV, minimum oil circuit breakers were common use for indoor applications up until to the late seventies. Outside applications utilised a mixture of air-blast (AB), bulk oil (BO) and small oil volume (SOV) designs until the advent of vacuum (VAC) and sulphur hexafluoride (SF6) in the late seventies early eighties. Today SF_6 circuit breakers are the overwhelming majority in applications 66 kV and above with the exception of some well maintained small oil volume circuit breakers that are currently serving out the remaining years of their service life. These aging SOV installations will eventually be replaced with most likely a SF_6 incorporated design. Below 66 kV sees vacuum and SF_6 designs in all new installations and are slowly but surely replacing the few remaining high maintenance prone oil circuit breakers still in service.

“Much of the development of interrupter designs in both SF_6 and vacuum took place in the seventies and eighties. It is fair to say that there have been few innovations in interrupter design in the last few years although design improvements in other parts of the equipment have led to more simple spring and other type mechanisms, to improvements in automation, in safety features and in reduced costs.” (Harris, 1996)

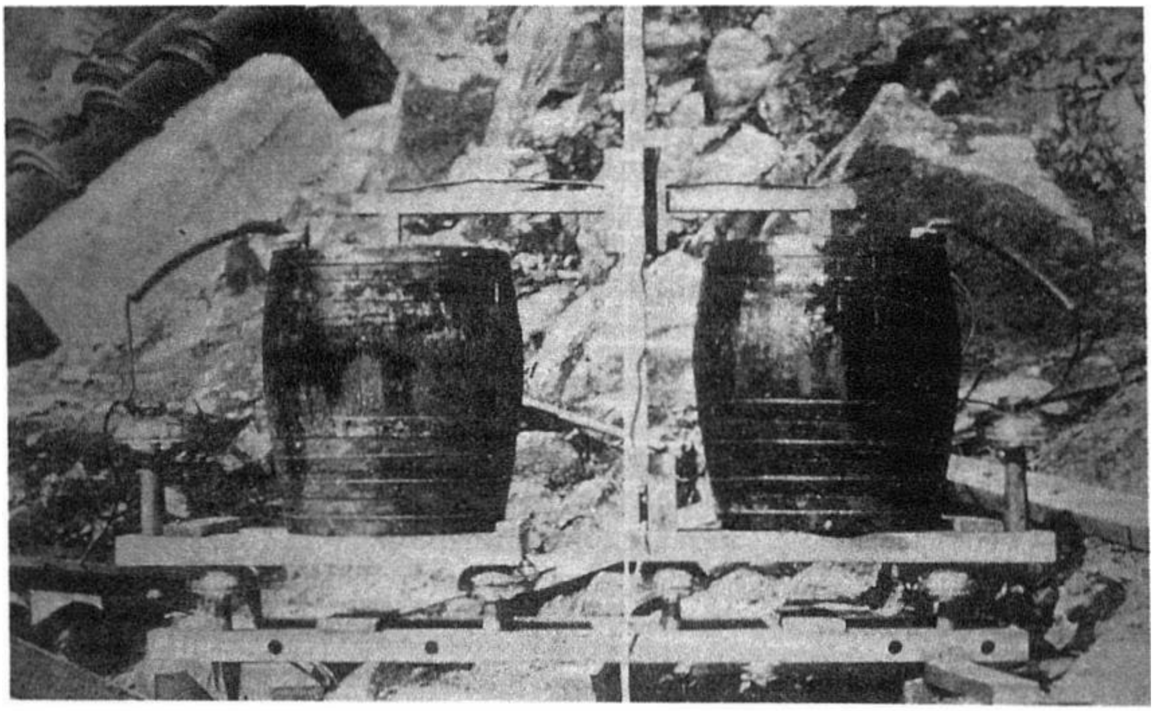
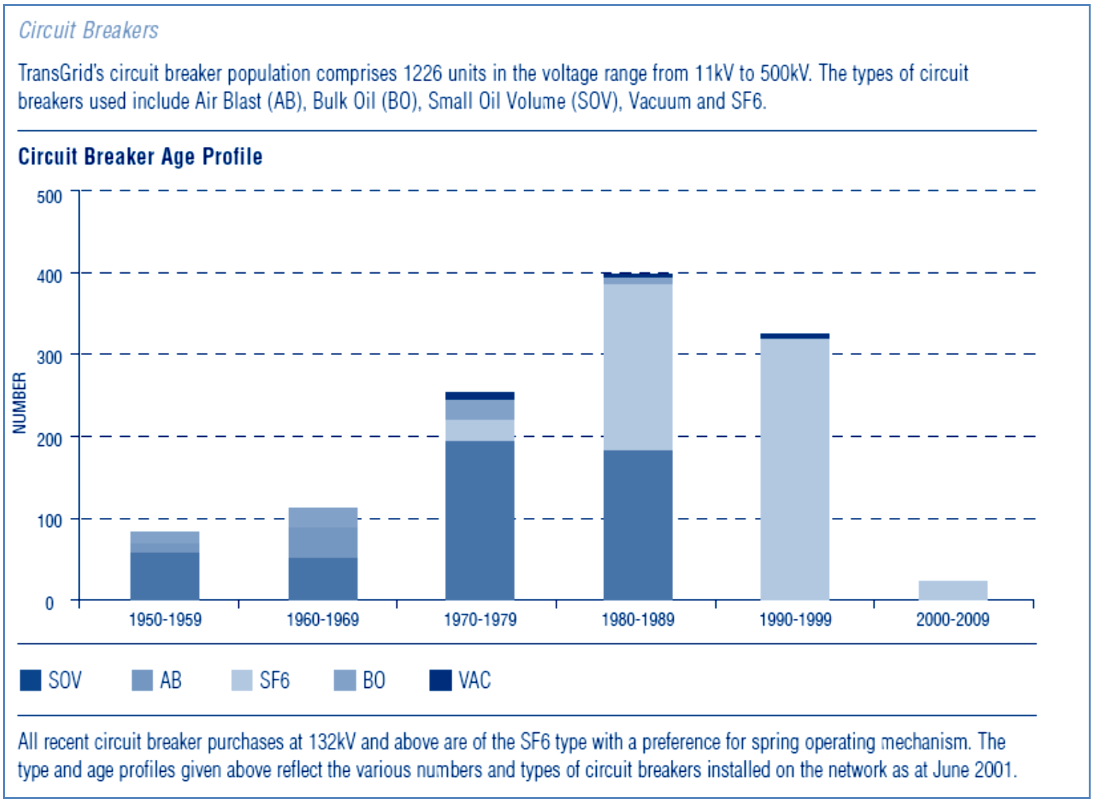


Figure 3-1 Oil Circuit Breaker Built in 1901

Below is an excerpt from Transgrid's 'Network Management Plan 2001-2006' which gives an overview of the range of circuit breakers they had in-service and their installation periods.



Circuit Breakers

TransGrid's circuit breaker population comprises 1226 units in the voltage range from 11kV to 500kV. The types of circuit breakers used include Air Blast (AB), Bulk Oil (BO), Small Oil Volume (SOV), Vacuum and SF6.

Circuit Breaker Age Profile

All recent circuit breaker purchases at 132kV and above are of the SF6 type with a preference for spring operating mechanism. The type and age profiles given above reflect the various numbers and types of circuit breakers installed on the network as at June 2001.

Figure 3-2 Excerpt from Transgrid Network Management Plan 2001-6: Circuit Breaker Age Profile

3.3 Circuit Breaker Designs and Classifications

High voltage circuit breakers can be grouped by many different criteria. Common criteria adopted to group circuit breakers are often the installations' intended voltage application e.g. 11 kV, the installations' specific network application e.g. transformer or line circuit breaker, the installations' location e.g. indoor or outdoor, and also the circuit breakers' specific design characteristics. An important circuit breaker classification is also the method and medium used for electrical current interruption and the variations of these are outlined specifically in the next section 3.4 Current Breaking Techniques.

3.3.1 Voltage Classification

High voltage is defined by Australian standards as a voltage level exceeding 1000 V ac or 1500 V dc. Circuit breakers designed to have an in service rating of above 1000 V ac or 1500 V dc are therefore considered as high voltage circuit breakers. High voltage circuit breakers can be further categorised into two groups by voltage level, namely that of "distribution" (66 kV and below in NSW) and "transmission" (132 kV and above). It should be noted that "distribution" level equipment is sometimes referred to as "medium voltage" equipment even though MV typically refers to equipment less than 66 kV. The classification of high voltage equipment in Australia is outlined in Australian Standard: AS 62271 in coordination with ANSI C37.06 and the International Electro-technical Commission (IEC) 56

3.3.2 Application Classification

The network specific applications of a circuit breakers within a given high voltage electrical network is an important classification. High voltage circuit breakers protecting and/or controlling the flow of electrical current in equipment such as transmission/distribution lines, transformers, generators and reactive plant may be similar (or in fact be the exact same) in appearance but will have vastly different settings and operational objectives. Many of these differences will be more prevalent in the relay or control settings operating the circuit breaker and may be considered within the scope of secondary systems. However, some variations for example point-on-wave operation used by reactive plant circuit breakers are at times achieved by slightly different mechanical linkages in an otherwise undistinguishable ordinary line circuit breaker. It is therefore common in industry to identify high voltage circuit breakers by their application on occasion e.g. transformer breaker, capacitor breaker, etc.

3.3.3 Location Classification

High voltage circuit breakers can be utilised in either indoor or outdoor electrical substations and switching yards. In rural or other settings where space is in surplice it is common for the electrical transmission and distribution substation equipment to be securely fenced off in open air, outdoor compounds. In other urban or settings where space (or extreme weather) is sometimes an issue electrical substations are located indoors. The primary difference between an indoor and outdoor circuit breaker is generally the structural packaging or enclosure housing. Indoor circuit breakers generally utilise the same internal chambers and operating mechanisms as outdoor circuit breakers but are instead housed in cabinets located inside a building or sometimes within a metal clad enclosure that itself is located outside. Indoor circuit breakers also have slightly different high voltage conductor arrangements to their outdoor counterparts, often allowing for the use of insulated high voltage cables as opposed to spaced bare conductors used in outdoor yards. High voltage circuit breakers cabinets located inside a substation building are often situated side by side, connected by a common bus to further reduce the infrastructure footprint.

3.3.4 Physical Design Classification

Physically there are two main design categories of high voltage circuit breakers that hold the most significance, that being “dead-tank” or “live-tank”.

A dead-tank high voltage circuit breaker is one in which the vessel (or tank) containing the electrical current breaking mechanism (or interrupter) and insulating medium is at ground voltage potential considered “dead” in terms of voltage hazard potential. This design allows for the tank to be safely contactable during operating conditions and located within reach of maintenance staff. Usually however, maintenance is still conducted under de-energised conditions. An advantage of dead-tanks is that ladders and or elevated work platforms are not usually needed during maintenance outages. The high voltage conductors are held at safe distances away from the grounded voltage metal tank by means of tall insulation bushings. The bushings allow for the high voltage conductors to feed down through them and into the tank, at all times remaining insulated from the metal tank enclosure wall. The design offers a structurally stable, four leg, horizontal tank design with high seismic withstand capability. The dead-tank design’s main advantage however is that it allows for the inclusion of multiple low voltage, bushing type, current transformers on both sides of the interrupter. This configuration is highly advantageous to protection and metering secondary systems as well as eliminating a common protection short coming known as blind spots inherit in other current transformer/circuit breaker arrangements.

The high voltage circuit breaker live-tank configuration consists of the vessel or tank housing the interrupter kept at what could be considered “live” or system operating voltage levels (i.e. the same voltage level as that of the high voltage conductors feeding into the circuit breaker). The high voltage conductors feed in and out of the interrupter housing tank which is supported at a safe distance from the ground support structure by tall high voltage withstanding bushings. This design allows for a smaller installation footprint to that of the dead-tank, however, the tall, top heavy, two or single legged structure is often seen as having reduced stability and also requires ladders or elevated work platforms for maintenance staff. External current transformers on additional adjacent structures are also required for current detection.

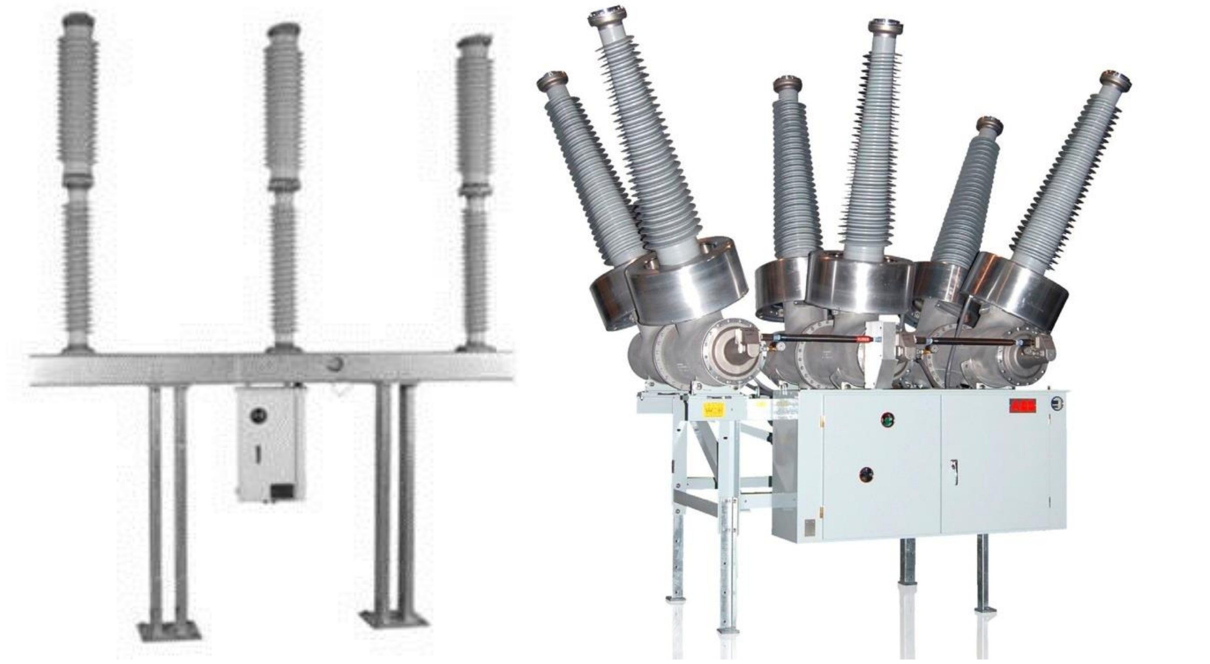


Figure 3-3 Live Tank (left) & Dead Tank (right) Circuit Breakers

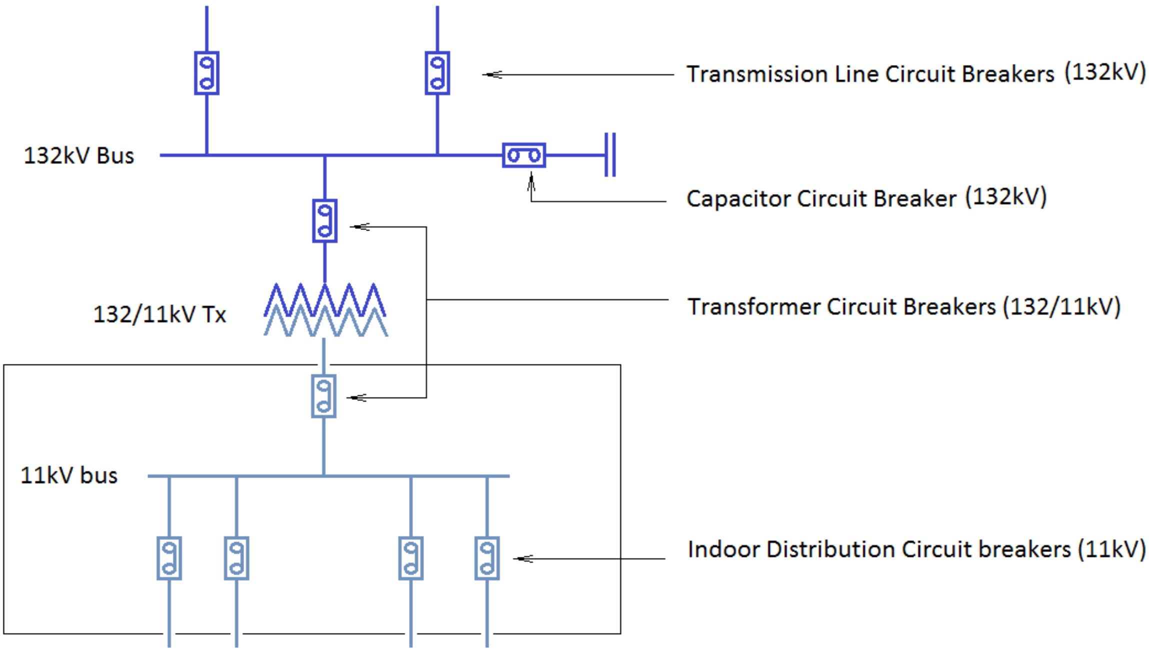


Figure 3-4 Single Line Diagram Demonstrating the Different Classifications of HV Circuit Breakers

3.4 Current Breaking Techniques

High voltage circuit breakers have evolved at a steady pace alongside the evolving electrical power industry. The electrical current interruption technique together with the insulation medium and the coordination of these two design aspects has been a major overall design parameter of high voltage circuit breakers over time. Initially air and oil served the industry as the interruption and insulation mediums of choice. Remarkable these two initially chosen mediums served the industry so well and reliably that many oil and some air type installations still exist in service today. The appearance of vacuum and SF_6 technologies in the late 1950's and overwhelming industry acceptance of these from the late 1970's onwards has slowly but surely rendered air and oil obsolete. Vacuum and SF_6 technologies offer less maintenance requirements, smaller installation footprints and superior dielectric recovery and arc quenching abilities.

In the closed position high voltage distribution and transmission network circuit breakers allow alternating electrical current to flow through their contacts and have no voltage drop. The ideal operation of a circuit breaker is that when its contacts open apart the electrical current completely stops flowing and the voltage drop across the produced contact gap is equal to the system voltage. However, at the moment the circuit breaker contacts begin to move apart the electrons in insulating material between the contacts begin to migrate towards the positive (anode) contact. This migration rapidly ionises a conductive path between the two contacts. The conductive path is formed supported by the increasing voltage drop between the separating contacts and accommodates an electric arc. The resultant electric arc is known as a self-sustaining electrical discharge and is capable of sustaining large electrical current flow. The arc will form on both opening and closing of a circuit breaker, although the arc that requires interruption and control is the opening arc.

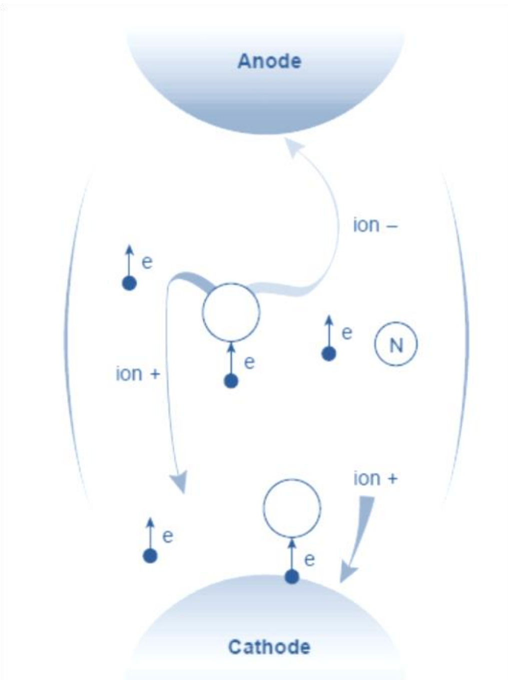


Figure 3-5 Electric arc in a gaseous medium

3.4.1 Air & Air Blast (AB) Circuit Breakers

One of the earliest methods for making or breaking current was a plain knife switch in air, perhaps best envisioned to that of the switch that turned Edison ear power systems on. This simply device was limited in terms of capacity where early experimentation revealed high voltages could re-spark across the open air gap and high currents would maintain the arc across the open air gap. More sophisticated interpretations of the knife switch are still used in industry today however, manually operated air break switches (ABS) are still commonly used for electrical current interruption at lightly loaded rural substations or feeders. ABS's are also still the isolation mechanism of choice for no-load breaking visual isolation in most high voltage switch yards. It is known now that interrupting the resulting self sustaining electrical arc in air is directly related to the natural deionisation process in the air surrounding the arc. Cooling the arc increases the deionisation which in turn increases the arc resistance. Increased arc resistance limits the arc sustaining electrical current flow and increases the success rate of arc interruption.

In an air circuit breaker, increasing the resistance of the arc in effect increases the arc voltage. Thus, to effectively increase the arc voltage any of the following means can be used

1. Increase the length of arc and hence the voltage drop across the arc gap
2. Split the arc into a number of short arcs connected in series, resulting a number of small voltage drops that can sum to greater than that of one large arc's voltage drop or even greater than that of the system voltage enabling quick arc extinguishing.
3. Constricting the arc, by constraining it between very narrow channels. This in effect reduces the cross section of the arc column and thus increases the arc voltage.

Methods two and three are commonly achieved by the development of the arc chute, a box like component device that contains a number of either metallic or insulated plates. Drawing the arc into these segmented chambers aids the cooling process of the arc. The arc can be drawn into the arc chutes via the assistance of an arc attracting magnetic field produced by a coil known as a magnetic blow-out coil.

Another successful electrical current interruption technique utilising air was that of the Air Blast (AB) circuit breaker. Especially popular from the 1940's-1970's, until the introduction of SF_6 it was the transmission voltage class circuit breaker of choice and the only design available for successful interruption above 330 kV. More generally the Gas-Blast circuit breaker could actually use a range of gases other than air to successfully extinguish the arc, including; nitrogen, carbon-dioxide and sulphur hexafluoride. There have been a couple of different designs of air blast circuit breakers exploring a range of air blast directions, nozzle and contact configuration types.

Garzon (1997) advised that in all of the designs of air blast circuit breakers the interrupting process is initiated by establishing the arc between two receding contacts and by, simultaneously with the initiation of the arc, opening a pneumatic valve which produces a blast of high pressure air that sweeps the arc column subjecting it to the intense cooling effects of the air flow.

The number of different systems (mechanical, electro-mechanical, pneumatic, electrical) that needed to be timed perfectly for operation resulted in extensive maintenance costs. Operation of the circuit breaker is also extremely loud and often deemed inappropriate in residential settings.

3.4.2 Oil Circuit Breakers

Oil insulated circuit breakers are still quite common in the electrical power distribution and transmission industry in Australia. Despite being considered obsolete to that of newer $\mathrm{SF_6}$ designs in terms of maintenance requirements and dielectric strength degradation speed, well maintained oil circuit breakers can still be seen in service. The sheer number of oil circuit breakers previously in service in Australia combined with infrastructure up-grade budget pressures by private and government utilities have resulted in a small number staying in service where deemed appropriate.

Insulating oil at medium voltage applications is actually superior to that of air or $\mathrm{SF_6}$ at atmospheric conditions for a given contact gap given that it is pure and non-degraded. Unfortunately however, by nature of its sheer purpose of being the arc extinguishing medium, carbonization and hence degradation of the oil takes place every time the oil comes into contact with an electrical arc. Small carbon deposits resulting from in service electrical arc contact carbonization as well as water quantities from general ingress, poor sealing or maintenance techniques can quickly degrade the insulating oil's dielectric strength. Oil insulated circuit breakers require regular oil monitoring and oil changing maintenance tasks.

The basic oil insulated circuit breaker consist of a pair (one phase) or three pairs (three phases of opening contacts used for electrical current interruption totally submerged in oil within a sealed vessel. The insulating oil acts as both the arc extinguishing medium and as an insulation medium between the energised high voltage contacts and conductive metal vessel housing. During the opening operation of the current carrying contacts submerged in the oil it is the resultant hydrogen obtained by the cracking of the oil molecules exposed to the electrical arc that serve as the arc extinction medium.

Oil is a good extinguishing agent due to its thermal properties and its deionization time constant which is better than air, especially at high pressures. On separation of the immersed contacts, the resultant arc causes the oil to break down "releasing hydrogen (≈70%), ethylene (≈20%) methane (≈10%) gas and free carbon" (Theoleyre, 1999). This gas forms a bubble which, because of the inertia of the oil's mass, is subjected during breaking to a dynamic pressure which can reach 5000 to 10,000 kPa. When the alternating current passes to zero, the gas expands and blows on the arc which is extinguished.

Bulk Oil (BO) volume and minimum oil or Small Oil Volume (SOV) circuit breakers are the two categories that oil insulated circuit breakers fall under.

In bulk oil circuit breaker designs all phase contacts are located within the same vessel and oil, sometimes in conjunction with submerged insulating barriers such as Bakelite or compressed paper boards. Arc resultant gas bubbles need to be restricted from forming conductive paths between phases and the vessel wall, resulting in large tank designs. As all three phases utilise the same oil, they require more regular oil monitoring and oil changing. Bulk oil circuit breakers are most commonly dead-tank style circuit breakers.

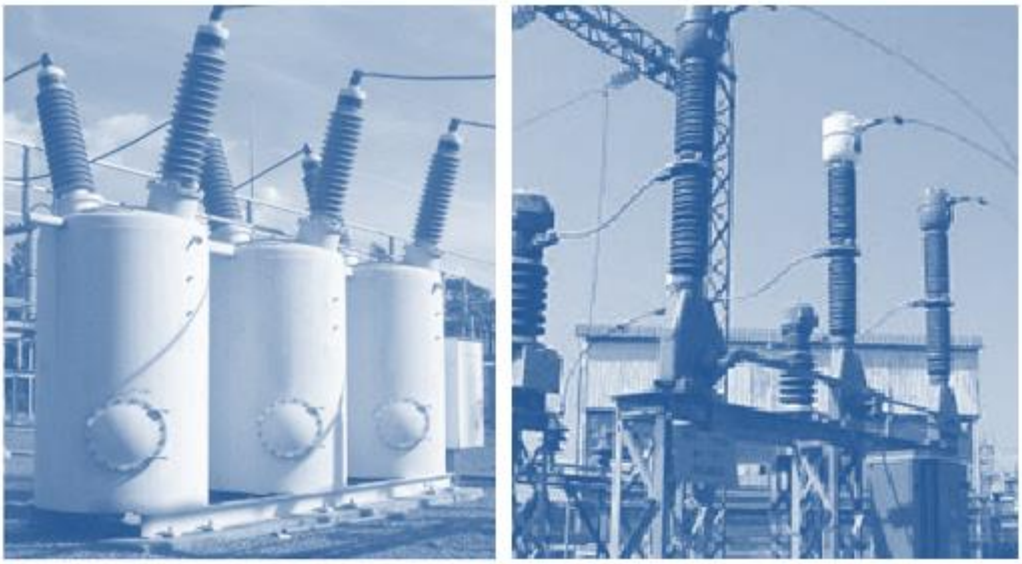


Figure 3-6 Bulk Oil (BO) Circuit Breaker (left) and Small Volume Oil (SOV) Circuit Breaker (right)

Small Oil Volume (SOV) circuit breakers utilise separate single phase insulating braking chambers to confine the arc and resultant gas bubbles. The gas pressure increases as the arc passes through a successive set of chambers. To help control pressure build up and venting as well as oil circulation, baffle interrupter chambers were developed which permit the lateral venting of the pressure generated inside of the chamber. The three pole design for a three phase circuit breaker most commonly utilise three separate live tanks with a common mechanically linked operating mechanism. Small Oil Volume circuit breakers only use oil in the live tank interruption chambers and use a soild dielectric such as porcelain in the phase-to-ground support structure.

3.4.3 Vacuum (VAC) Circuit Breakers

Vacuum interrupters (VI) use the exceptional dielectric characteristics and diffusion capabilities of a vacuum as the interruption medium. Utilising vacuums and their dielectric properties isn't a completely new science with knowledge of vacuum bulbs and x-ray tubes known throughout the 1900's. However, technical difficulties in vacuum interrupter manufacturing held up the introduction of vacuum interrupters on the industrial scene until the 1960's. These difficulties included degassing the internal contact materials that would otherwise degrade the vacuum once in service and competent welding/brazing technology to attach the vacuum's ceramic envelope to its metallic ends.

Figure 3-7 11kV Vacuum Circuit Breaker

In theory a vacuum is an ideal high dielectric medium. A vacuum does permit, in the presence of electrical fields, or electro-magnetic fields, the passage of electrons (Beta particles), protons, neutrons, quarks, alpha particles (helium nucleus) etc. Astrophysics has enormous examples of this, and valve technology uses this for its fundamental operation. However, in reality a vacuum does see a dielectric strength limitation and this limitation is more a function of contact or electrode shape and contact opening distance which quickly reduces effectiveness at voltages above 33 kV. For this reason vacuum interrupter technology is mainly exclusive to medium voltage applications however some higher voltage VIs are beginning to emerge.

The design of a vacuum interrupter stems from intense analysis of the electrical arc produced upon opening contacts previously conducting unhindered electrical current within a vacuum. The arcing column is made up of metal vapour and electrons coming from the contact electrodes which are vastly different from the other interruption mediums. AC electrical current cycles from a peak amount to zero to a negative peak amount every 20 milliseconds in Australia's fifty hertz supply. Between current zeros an arc has been studied to be in two states depending on current intensity. "Namely - diffused (<2 kA) and concentrated (>10 kA)" (Theoleyre, 1999). The longer the existence of the arc in its diffuse mode the easier it is to interrupt the flow of electrical current. Re-establishment of the arc is supported through current zeros by high residual temperatures of the contact material. High temperatures enable an arc anode to easily appear where a previous cathode was. When the energy provided by the arc is no longer sufficient to maintain a high enough temperature at the foot of the arc the arc ceases to re-establish.

A vacuum interrupter therefore seeks to minimize the heating of the contacts by maximizing the time during which the arc remains in the diffused mode during the half current cycle. This objective can be accomplished by designing the contacts in such way that advantage can be taken of the interaction that exists between the current flowing through the arc and the magnetic field produced by the current flowing through the contacts or through a coil that may be assembled as an integral part of the interrupter. This interaction of the magnetic field can be designed in such a way that it acts in a radial or axial direction with respect to the arc.

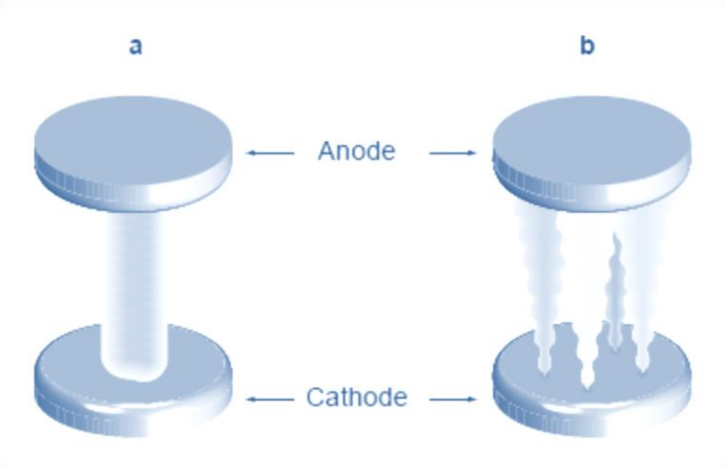


Figure 3-8 Concentrated arcing (a) and diffused arcing (b) *source: Cahier Technique no.193*

"The radial magnetic field design establishes a field created by the current circulating in the complex shaped electrodes designed for this purpose. The current flowing through the arc obeys electromagnetic laws and therefore experiences a force moving it from the centre to the outside of spiral shaped electrode contact, uniformly distributing concentrated arcing heat and aiding arc diffusion." (Theoleyre, 1999)

"The axial magnetic field design requires the ions to take a circular trajectory which stabilizes the diffuse arc and delays the appearance of the concentrated state. The appearance of the arc footing spot is avoided, erosion is limited and this enables fairly high breaking capacities to be reached." (Theoleyre, 1999)

The vacuum interrupter is typically constructed with a ceramic insulating envelope, sealed at both ends with stainless steel caps. At one end of the internal envelop sits a fixed contact and the other allows for a moving contact attached most commonly by means of a seamless metallic bellows. The vacuum is achieved within the interrupter during manufacturing by means of an afterwards sealed evacuation pipe or by specially design ovens that braze and evacuate the chamber simultaneously.

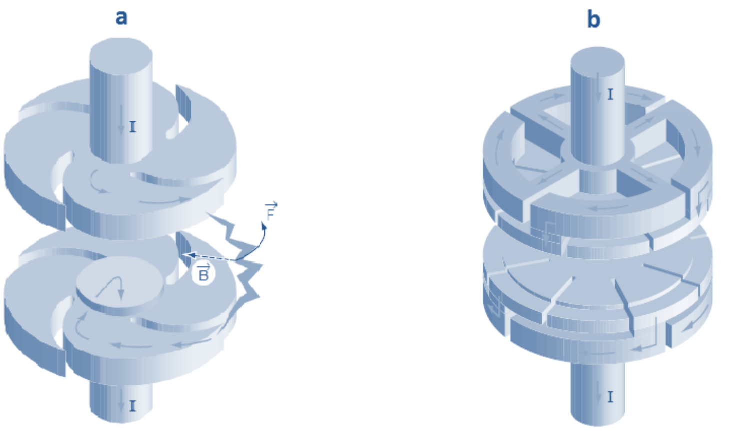


Figure 3-9 Radial contacts (a) and axial contacts (b) *source: Cahier Technique no.193*

3.4.4 SF6 Circuit Breakers

Due to the non-comparative superior dielectric strength recovery and arc quenching properties of SF_6 gas, SF_6 gas high voltage circuit breakers have all but dominated the circuit breaker market in a relatively short time. Vacuum interrupters are expanding their share of the medium voltage industry but no alternative currently exists in the high voltage transmission scope where SF_6 far supersedes its air blast and oil predecessors. SF_6 circuit breakers offer less maintenance and smaller installation footprints atop their already superior dielectric recovery and arc quenching capabilities.

The extremely chemically stable gas is non-flammable, non-corrosive, colourless, odourless, chemically inert and has high enthalpy (high dissipation of heat). The synthetic gas is the almost perfect arc extinguishing dielectric medium.

"During the arcing phase, in which the temperature can reach between 15,000 °K and 20,000 °K, the SF_6 breaks down. This decomposition is virtually reversible: when the current is reduced the temperature is reduced and the ions and electrons can reform to make the SF6 molecule." (Theoleyre, 1999)

Of the molecules that do not recombine to form SF_6 post arc there are some reactive decomposition by-products formed because of the interaction of sulphur and fluorine ions with trace amounts of moisture, air, and other contaminants. The harmful effects of these by products are introduced in section 1.7 (Occupational Health and Safety with SF_6) of this publication.

The arc that forms within a SF_6 circuit breaker can be described as a SF_6 plasma cylinder at an extremely hot temperature surrounded by a cooler gaseous sheath. SF_6 reaches its peak thermal conductivity at around 2,000 °K as opposed to air at 6,000 °K. This difference enables SF_6 to cool much more effectively than air at lower temperatures and is therefore a more proficient manager of recover voltages faster. This faster time constant is appreciated in comparison to air when large transient effects prevalent in transmission voltage levels are expected.

SF_6 circuit breakers within the higher end of the distribution voltage range are most commonly dead-tank designs. In the transmission voltage spectrum, 132 kV installations are common in both dead and live tank designs with the latter typically being older designs that did not incorporate bushing current transformers. From 132 kV upwards to the 500 kV system in NSW, designs are exclusively live-tank. Many in the Extra High Voltage (EHV) range (500 kV) incorporate multiple breaking chambers, grading capacitors and shunt resistors to aid current interruption. Pictured right is an EHV SF_6 circuit breaker utilising dual interruption chambers and grading capacitors

Figure 3-10 EHV SF6 Circuit Breaker

SF_6 circuit breakers utilise one of two different internal interruption methods to extinguish the arc, namely the puffer method or self blast method.

The SF_6 puffer circuit breaker uses an internal puffer piston action to compress the gas and raise its pressure to aid cooling. The gas is forced through a Teflon nozzle during the opening stoke, however the heavy arc blocks the flow of the gas until the current decreases towards zero. This blocking effect may increase the pressure within the cylinder to a pressure well in excess of the maximum no load pressure. A high energy mechanism is therefore required to ensure the contact movement velocity is maintained. As the arc approaches current zero the arc reduces in diameter allowing maximum gas flow past the arc when it is most needed. If the recovery voltage is too great the arc may re-strike but will subsequently be attempted to be extinguished with high success at the next current zero.

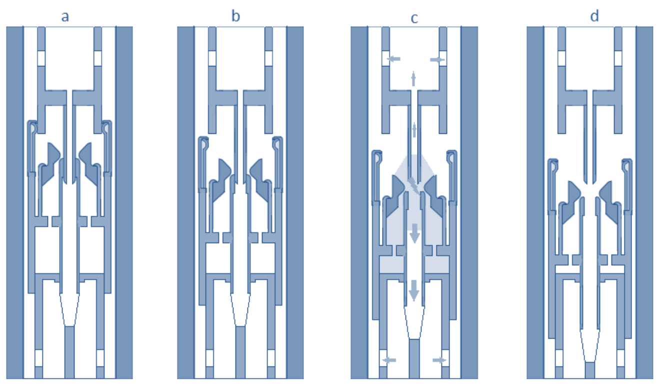


Figure 3-11 Puffer SF6 circuit breaker opening sequence

The SF_6 self blast circuit breaker utilises a valve between expansion and compression gas volumes formed upon an opening operation. When interrupting low currents the valve opens under the effect of the overpressure generated in the compression volume and the arc is extinguished similar to that in a puffer system. In the case of high currents interruption, the arc energy produces a high overpressure in the expansion volume, which leads to the closure of the valve. In this second high current case a self blast circuit breaker uses the pressure increase created by the arc to compress the gas which extinguishes the arc at current zero. It is possible to reduce the mechanism energy requirement by 70% in a self blast circuit breaker. A self blast circuit breaker directs hot gas from the arc into a heating volume adjacent to the nozzle. The hot gas mixes with cold gas in this constant volume resulting in warm high pressure gas which returns to the arc zone at current zero. The gas between the open contacts is cooled and interruption is achieved. Self blast pictured below (a) closed, (b) interrupting low current, (c) interrupting high current, and (d) open.

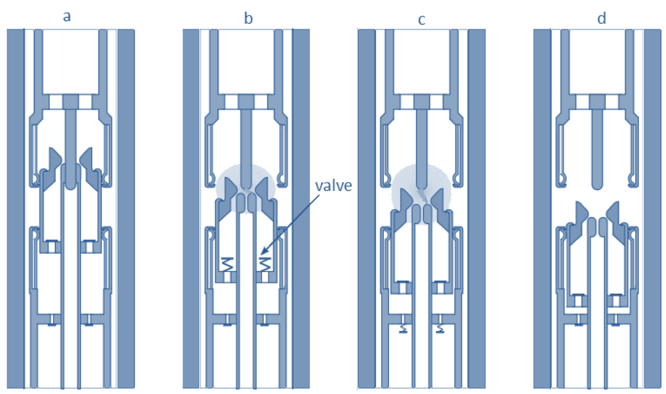


Figure 3-12 Self blast SF6 circuit breaker

3.5 Maintenance

Transgrid, the NSW state transmission authority employs the follow maintenance intervals and corresponding maintenance checks to their high voltage circuit breaker inventory. (see Appendix C)

Table 3-1 Transgrid Circuit Breaker Periodical Maintenance Checks

Maintenance Checks Required	Interrupter Type								
	CBs other than SF6		SF6 Types in normal application			SF6 Types Reactive Plant		Vacuum Types	
	Minor	Major	Detailed Inspection	Minor	Major	Minor	Major	Minor	Major
Timing measurement	X	X		X	X	X	X	X	X
Insulation resistance across breaks and to earth	X	X							
Alarm, interlocks and indication	X	X	X	X	X	X	X	X	X
Energy source measurements (mechanical tolerance and accumulator pressures)	X	X		X	X	X	X	X	X
Lubrication without dismantling	X	X		X	X	X	X	X	X
Air or hydraulic oil consumption on trip and close	X	X	X	X	X	X	X		
SF6 gas density checks and pressure switch settings			X	X	X	X	X		X
Close and trip checks:									
• Operation checks (includes CO checks)	X	X	X	X	X	X	X	X	X
• Point on Wave operation checks						X	X	X	X
Operating Mechanism Cut-in, cut-outs	X	X	X	X	X	X	X	X	X
Replace Hydraulic Oil	X	X		X	X	X	X		
For Small Oil-Non Pressurised CB units change the oil	X	X							
For Small Oil Pressurised CB units change the oil		X							
Bushing DDF (where DDF point fitted)	X	X							
Contact resistance measurements	X	X			X	X	X		
Dynamic Contact Resistance measurements					X	X	X		
Interrupter Inspection		X			X		X		
Condition Monitoring Device data download			X	X	X	X	X		

Table 3-2 Transgrid Circuit Breaker Maintenance Intervals

Circuit Breaker Service Intervals (All Voltages)				
CB Interrupter Type	Operational Checks	Detailed Inspection	Minor Service	Major Service
SF6	Annual	4 yrs	8 yrs	2,500 ops
SF6 on reactive plant	Annual	N/A	4 yrs	12 yrs or 800 ops
SF6 capacitor >=80MVAr	Annual	N/A	2yrs	12 yrs or 800 ops
Small Oil	Annual	N/A	4 yrs	12 yrs, 800 ops
Vacuum	Annual	N/A	4 yrs	12 yrs or 800 ops
Bulk Oil	Annual	N/A	4 yrs	12 yrs or 800 ops

Soure: Table 2-1 & 2-2 (Transgrid, 2012)

Chapter 4: Case Study - The Central Western NSW

Building upon the foundation knowledge of SF_6 and high voltage circuit breakers presented in Chapters Two and There, Chapter Four undertakes a regional case study to analyse actual data concerning SF_6 circuit breaker usage. Obtaining some meaningful figures concerning SF_6 circuit breaker usage in Australian regions is an important first step to any future elimination or reduction strategies of the environmentally potent substance.

The case study seeks to determine the current, real life market share of SF_6 circuit breakers as well as the mass (kg) of SF_6 gas currently in service. Data is intended to be obtained across the entire transmission and distribution voltage spectrum. Additionally, this chapter provides a brief analysis of the discovered trends in specific voltage range applications as well as preferred design types and ages of equipment.

The case study focuses on the Central Western Region of NSW. The region presents a fair mixture of generation, transmission and distribution and supports a 11-500 kV network. The region is predominately rural but also supports some moderate urban centres as well as large coal and gold mines.

Accurate data detailing the number of circuit breakers and their amount of in-service SF_6 in kilograms will enable the calculation of annual CO_2 equivalent leakage and handing activities emissions. The primary purpose of the case study is to gain a realistic perspective as well as obtain tangible working numbers of the power industry's SF_6 use. The data obtained will form the basis of subsequent chapters seeking to evaluate possible elimination or reduction strategies and their associated benefits.

4.1 Central Western NSW

To analyse the usage of SF_6 gas in high voltage circuit breakers in Australia, a bounded Australian geographical region was chosen in which to investigate and record relevant data. The chosen case study region was based on that of Central Western New South Wales, Australia. For the purposes of this research project the region of Central West NSW was deemed appropriate as it enables a convenient proximity for data collection as well as presenting a reasonable sample of the larger Australian electrical network and technology mix.

The chosen case study region of approximately sixty-eight thousand square kilometres is a primarily rural area located right in the heart of the state of New South Wales. The region lies inland, directly west of Sydney and the Blue Mountains. With a regional population of 237,064 its major urban centres are Bathurst, Dubbo, Orange and Lithgow

Historically, when the rural regions of NSW were first developing their electrical supply networks the state's electrical infrastructure outside of Sydney was made up of numerous isolated smaller networks managed by local council governments. These small, often diesel generated, load centred, NSW municipal networks were not connected on a state wide scale until the formation of Electricity Commission in 1950. The eventual transmission network of initially 132 kV and later 330 and 500 kV, connected the new larger base load generators to the previously existing local government networks. Once connected the locally managed networks were eventually amalgamated into larger state controlled authorities. The local government aligned, connected networks characteristic of NSW's overall electrical network enables convenient segmented analysis.

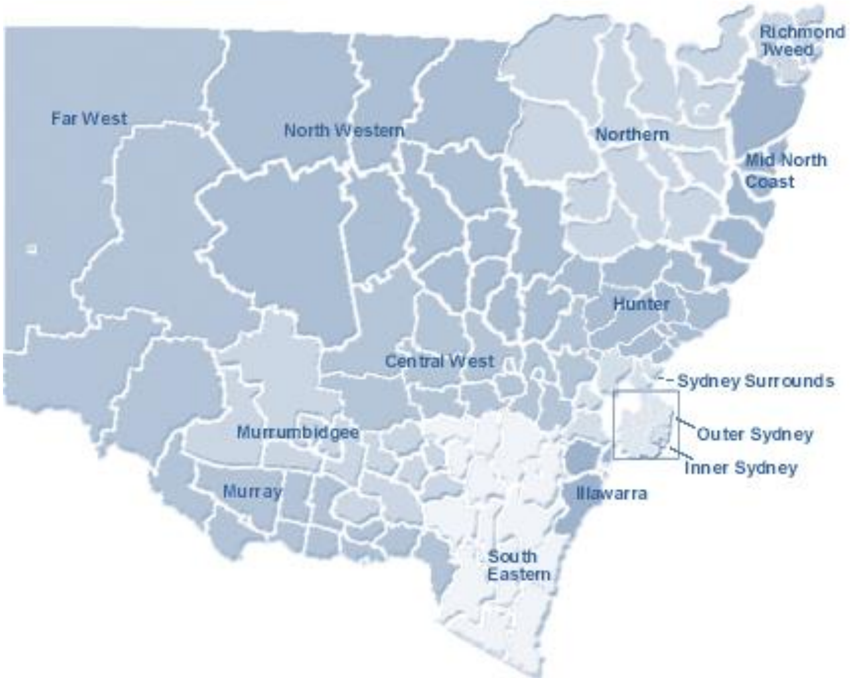


Figure 4-1 NSW Regional Local Government Divisions

The Central West Electrical Transmission Network connects many of the Central Western Local Government regions. The case study region chosen for evaluation is primarily based on the transmission network and therefore differs slightly from the state's allocated combined Central West NSW Local Government region pictured below.

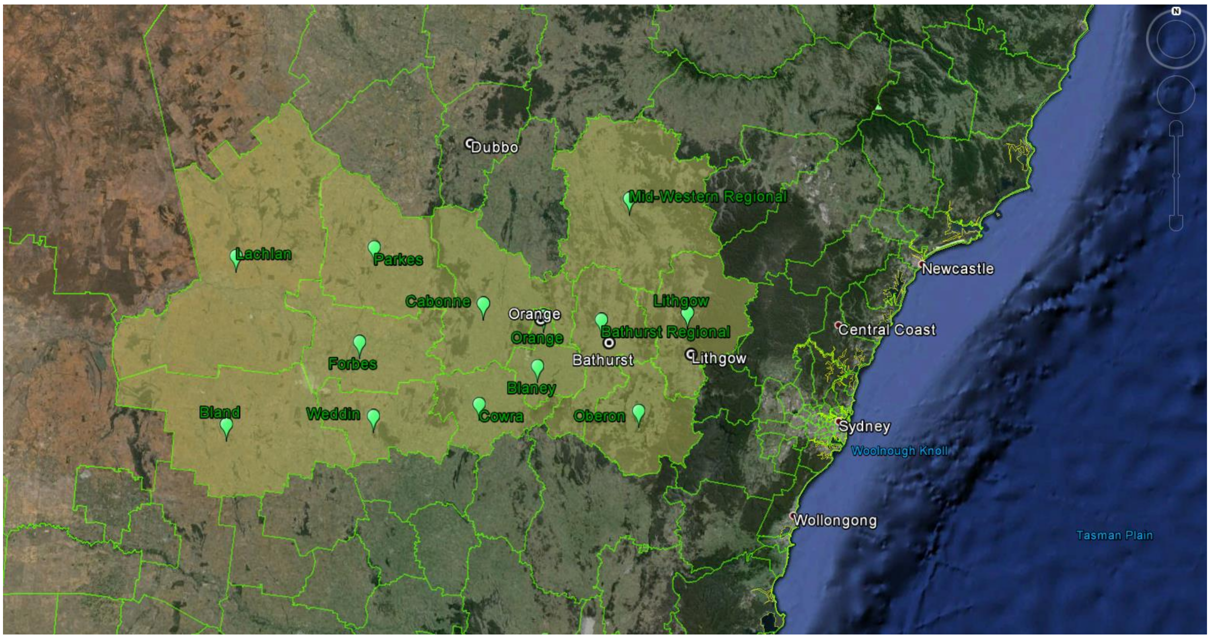


Figure 4-2 Central West NSW Region - Local Council Boundaries (NSW Government Region)

The subsequent case study area includes additional Local Government regions key to the Central West Electrical Network. The regions of Dubbo and Wellington are therefore included in this scope and the region of Bland is excluded as Bland it is connected and supplied solely from the southern Murrumbidgee region.

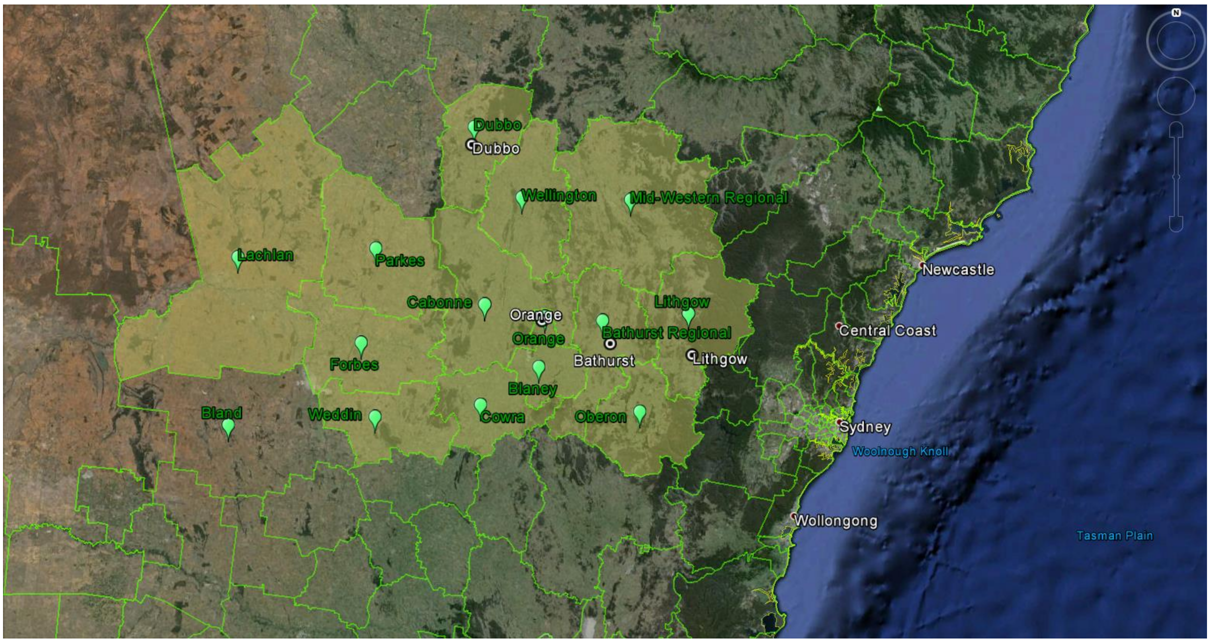


Figure 4-3 Central West NSW Region - Local Council Boundaries (For Project Purposes)

4.2 The Central Western NSW Electrical Power Network

A Single Line Diagram of the Central West Electrical region of which the case study region is mostly based on can be seen on the following page.

The diagram depicts the dual 500 kV line (purple) that runs from Bayswater to Bannaby down the western side of the Blue Mountains. These lines connect the major coal fired power stations near Muswellbrook (Bayswater 2640 MW, Liddell 2000 MW) to those near Lithgow (Mt Piper 1400 MW, Wallerwang 1000 MW). It also runs down to the southern portion of the state (Yass, Goulburn, Canberra). The line was intended to eventually form a ring with NSW's other dual 500kV line that runs down the eastern side of the Blue Mountains from Newcastle through Sydney.

From the two 500 kV Substations located in the Central West region (Wollar and Mt Piper), 330 kV lines (blue) from each run out west to the town of Wellington near Dubbo. An additional dual 330 kV line connects Mt Piper Substation to Wallerwang Substation and also runs across the Blue Mountatins to help feed the western portion Sydney. The 132 kV network (red) connects the major centres of the Central West (Bathurst, Dubbo, Orange etc) to each other and also back to the 330 kV Substations. From there the 66 kV (Brown) feeders supply the old Local Government Networks with some 66 kV interconnections between regions allowing for outage back-feeding and further redundancy.

The following feeders and substations (Pink) and their associated HV Circuit Breakers have not been included in the evaluation scope for the subsequent reasons:
The 132 kV "940" and "941" feeders to Katoomba and Lawson out of Wallerwang 132 kV substation have been excluded as they lie outside the Central West region (considered more Blue Mountains or Outer Sydney) and are also both maintained by Endeavour Energy of which access to their sites was unavailable.
The 66 kV "852" feeder out of Beryl 132 kV Substation to Dunedoo and Coonabaraban was also excluded as these sites are geographically substantially north of the chosen region and site visits/data collection proved beyond time constraints.

The case study does include however, the circuit breaker equipment associated with the high voltage lines that connect the Central West back to the rest of the NSW grid. The reliability of the Central West network requires alternate supplies, as does the rest of the state require the Central West's infrastructure to aid its reliability. These lines are the 500 kV "5A3,4,6,7", the 330 kV "76 and 77" lines to Sydney and the 66 kV "891"line to Young.

Consequently the case study region is largely based on the Central West Transmission Network where possible. The final region takes in the Local Government areas of Bathurst Regional, Blayney, Cabonne, Cowra, Dubbo, Forbes, Lachlan, Lithgow, Mid-Western Regional, Oberon, Orange, Parkes, Weddin and Wellington. It has 14 Transmission Substations and 41 Distribution Substations.

The major load centres for the Central West include Cadia Mine, North Parkes Mine, Dubbo, Orange and Bathurst.

The region presents an adequate mix of high voltage circuit breakers across all voltages levels present in NSW (500-11 kV).

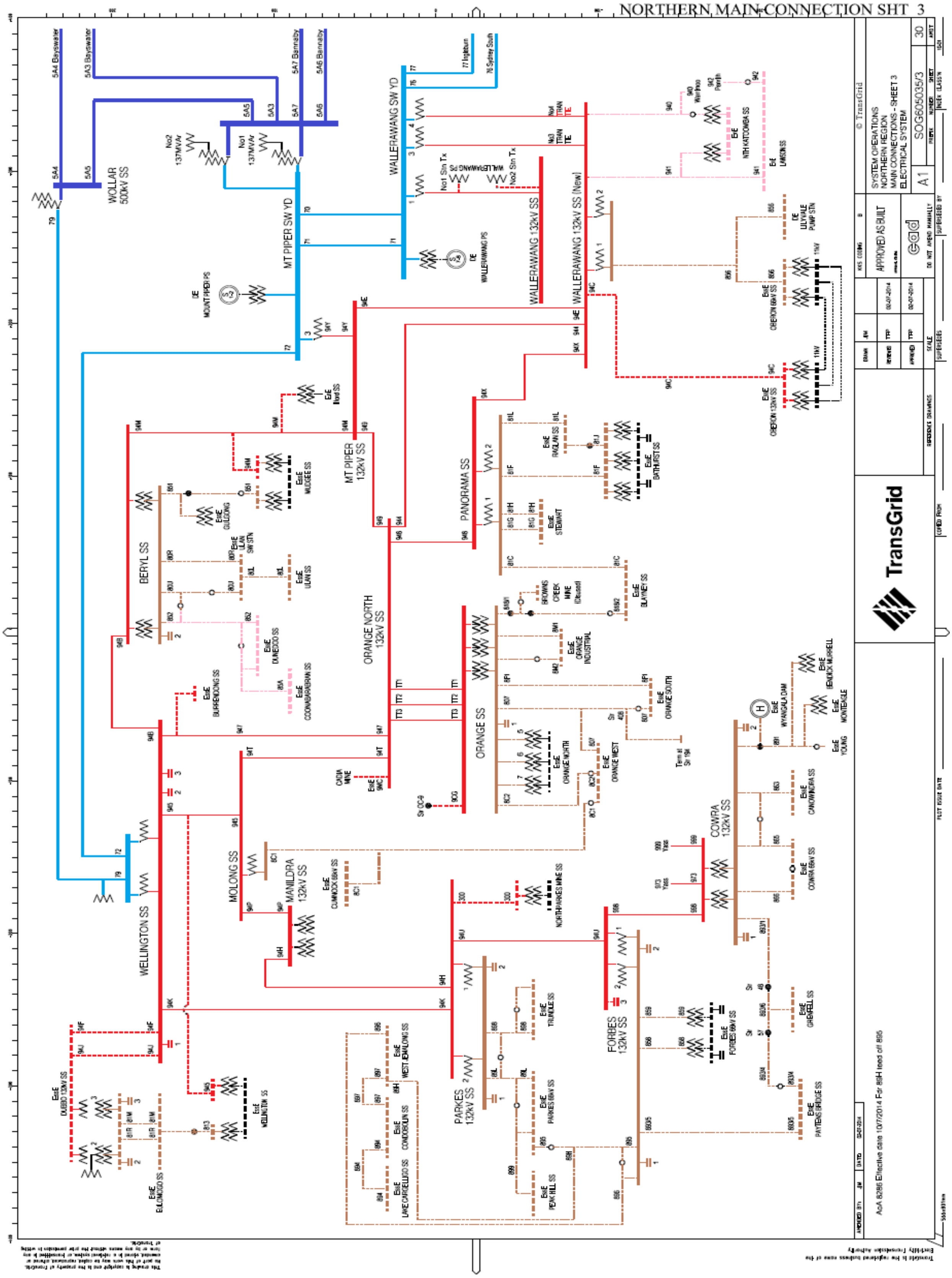


Figure: 4-4 Central West NSW Region – Electrical Grid Single Line Diagram

500kV 330kV 132kV 66kV Excluded

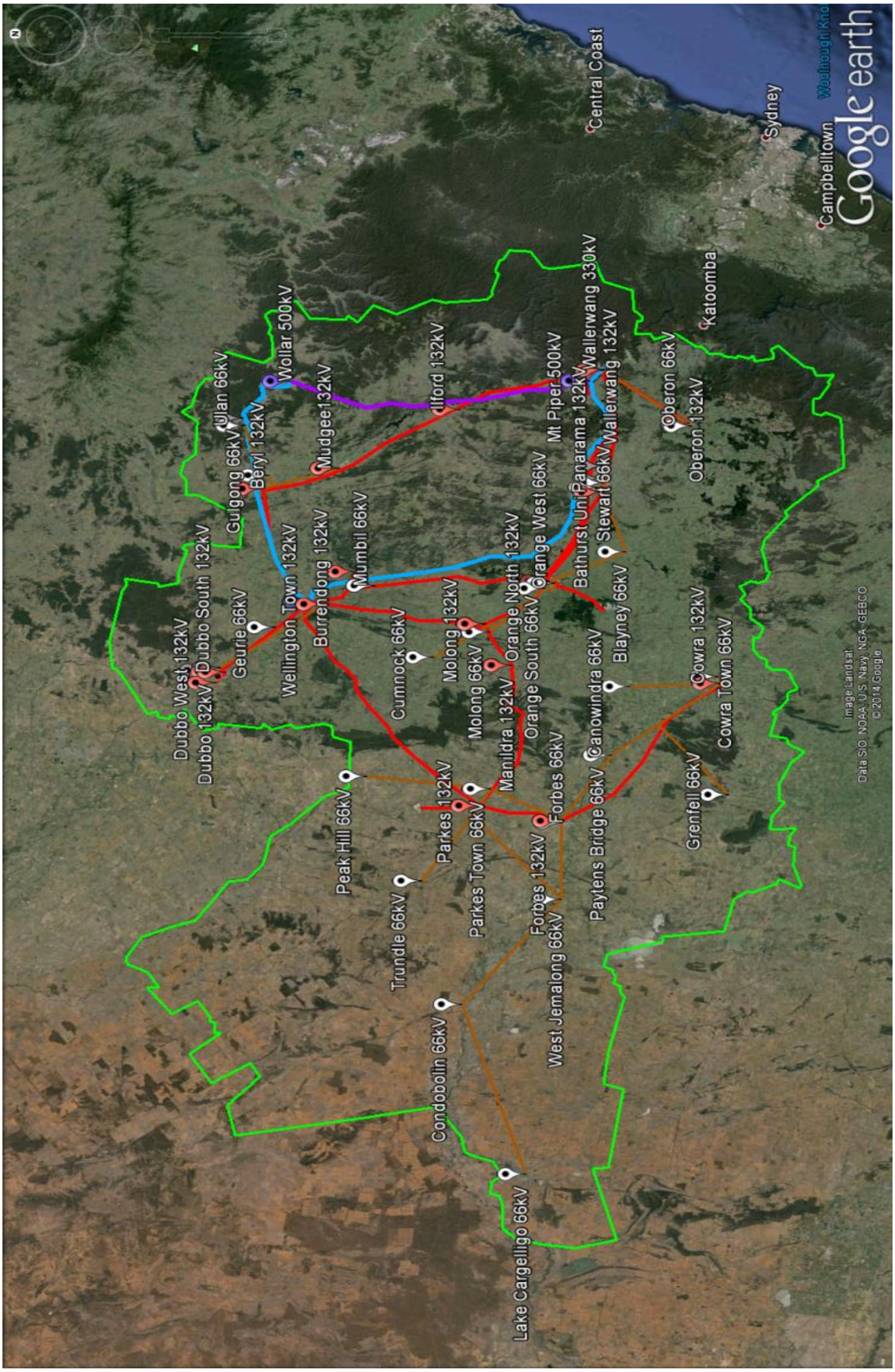


Figure 4-5 Central West NSW Region –Electrical Grid Google Earth Representation

Table 4-1 Sub-Regional Break Down of Case Study Area

Sub-Region	Area (km^2)	Population	Dwellings	Major Towns	Substations	Generation (MW)
Bathurst Regional	3830	38432	15852	Bathurst	1 Transmission 4 Distribution	
Blayney	1520	6991	3020	Blayney Carcoar Milthorpe	2 Distribution	9.9 MW (wind)
Cabonne	6080	12815	5586	Cargo Cudal Manildra Molong	2 transmission 3 Distribution	1 MW (landfill)
Cowra	2780	12141	5840	Cowra Woodstock	1 Transmission 1 Distribution	22.5 MW (hydro)
Dubbo	3410	38747	16054	Dubbo	6 Distribution	
Forbes	4750	9217	4174	Forbes	1 Transmission 3 Distribution	
Lachlan	15060	6509	3223	Condobolin	2 Distribution	
Lithgow	4530	20050	9420	Lithgow Portland Wallerwang	4 Transmission	2400 MW 1400 MW* (black coal)
Mid-Western Regional	8750	22391	10899	Gulgong Kandos Mudgee	2 transmission 6 Distribution	
Oberon	3660	5027	2597	Oberon	2 Distribution	1.32 MW (wind)
Orange	280	38002	16048	Orange	2 Transmission 4 Distribution	
Parkes	5970	14612	6564	Parkes Peak Hill Tullamore Trundle	1 Transmission 3 Distribution	
Weddin	3410	3647	1832	Grenfell	1 Distribution	
Wellington	4120	8483	3770	Wellington Geurie	1 Transmission 4 Distribution	14.5 MW (hydro)
Total	68150	237064	104879		14 Transmission 41 Distribution	2449.2 MW 1449.2 MW*

*Note: **Wallerawang:** EnergyAustralia advises that Wallerawang C unit 7 (500 MW black coal) has been removed from service in January 2014. Unit 8 (500 MW) will remain available until the end of March 2014, and will then be placed on a three-month recall should market conditions change. (AEMO: Australian Energy Market Operator, 2014) reducing regional generation by 1000 MW

Source (Google Maps: NEM Power Stations and Generation Sources, 2014) (NSW Government, 2014)

4.3 Data Collection Aim

The aim of the case study data collection is to collect relevant information on high voltage circuit breakers in the case study region to obtain an overall insight into SF_6 gas utilisation in this field.

SF_6 insulated high voltage circuit breaker equipment has been utilized in NSW since its introduction in the 70's. A range of HV circuit breaker designs, models and insulation types are available in the transmission and distribution industries. An exact market share as well as an insight into technology trends would be vital information for analysis of any eventual SF_6 equipment replacement or reduction.

The case study region data collection phase seeks to obtain information concerning the exact number of in-service HV circuit breakers servicing the case study area's distribution and transmission requirements. The exact proportion of HV circuit breakers utilising SF_6 for insulation or current breaking purposes is the most desirable objective second to the mass in kilograms of in-service SF_6 gas. Subsequent relevant data concerning the possible trend towards replacing old non-SF_6 insulated equipment with newer SF_6 models and the growth of new infrastructure utilising SF_6 equipment is also intended to be sort. Additionally, information on HV circuit breaker design types (e.g. Dead-Tank or Live-Tank) and their respective SF_6 gas mass amounts and market share trends is desirable.

High voltage circuit breaker data can be sort from the equipment's specific name-plate details.

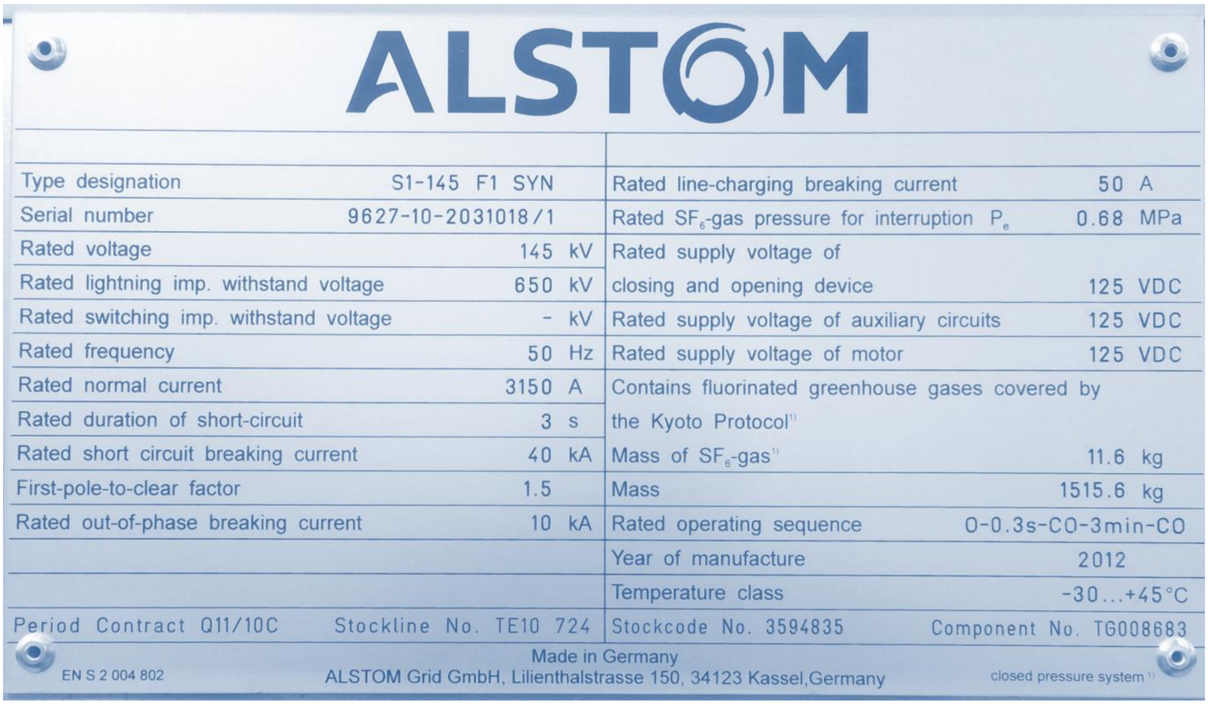


Figure 4-6 Example HV Circuit Breaker Name-plate

4.4 Data Collection Methodology

The process of collecting data regarding the quantities of SF_6 gas in in-service HV circuit breaker equipment in Central West NSW began with investigating the number and location of all transmission and distribution substations within the boundaries of the chosen region.

Access to the 14 transmission and 41 distribution sites was achievable by means of personal or colleague employment with the relevant utility infrastructure owners, namely Transgrid (NSW Transmission) and Essential Energy (Non-metro NSW Distribution).

Note: Employee site access would not necessarily be considered crucial to the investigation as similar results could have been compiled with mere site location knowledge, Google Earth, circuit breaker types/name-plate information, internet research and staff/company public relation officer interviews. All of the Central West substations are viewable to the general public through mesh security fences and its concealed 11 kV indoor equipment was most commonly not of SF_6 types. Employee site access did however allow for a more accurate and comprehensive data collection.

Site visits were conducted over the two month period of June and July in 2014 in accordance with Transgrid and Essential Energy substation entry safety rules by existing trained/inducted staff. Where site visits were not feasible employee local knowledge and utility data base information was sort by means of interview/discussion.

Upon site visits, the substation's name, address, global positioning coordinates and voltage levels were recorded. All individual HV and MV circuit breakers were then investigated and their attributes recorded taking into consideration the voltage level, manufacturer, model, type and insulation medium. If the insulation medium was that of SF_6 gas the mass of the contained gas in kilograms was recorded. The relevant circuit breaker attribute information can be sourced from the circuit breaker name-plate. All high voltage equipment has an individualised name-plate attached to it in a readable location. The name-plate contains vital information relevant to that piece of equipment including manufacturer, model number, mass, manufacture date, service voltage and other individualised information.

In some transmission substations it was noted that a proportion of HV live-tank circuit breakers utilised SF_6 filled associated post current transformers (CTs) and therefore the mass of SF_6 gas in these associated CTs was recorded as well. Equipment installation dates were desirable but exact dates proved difficult to obtain in all circumstances. An installation window of whether or not the equipment had been installed within the last five years was considered obtainable to gain an approximate trend in new equipment and aging equipment replacements. Installation information was located from onsite log books, utility data bases, and onsite employee interviews.

The Recorded information was then tabulated in a large Excel spread sheet to allow for convenient data analysis and query. The site global positioning coordinates were used to map the case study substations sites on Google Earth. The 55 Google Earth sites were then connected by their respective transmission and distribution lines for presentation purposes.

4.5 Results

A simplified representation of the obtained data collection results from the case study area is presented below.

4.5.1 Transmission Sites Results

Table 4-2 Transmission Sites Circuit Breaker Data

Site	Circuit Breaker						No. CB's
	Make	Model	Type	kV	SF_6 (kg)	Inst 5yrs	
Wollar 500kV Barigan Rd, Wollar	Siemens	3AP2F1-2	SF6 Live Tank	500	64.4		3
Mt Piper 500kV Boulder Rd, Portland	Siemens	3AP3F1-2	SF6 Live Tank	500	96.7		10
	Sprecher	HGF215/2B	SF6 Live Tank	330	33		7
	Siemens	3AP2F1	SF6 Live Tank	330	64.4		2
	Siemens	3AQ2	SF6 Live Tank	330	24		6
	ASEA	HLR 145 250E	Small Oil Vol	132	0		1
Wallerawang 330kV Heel St, Wallerwang	Areva	GL 315	SF6 Live Tank	330	40.4		7
	Areva	GL 315	SF6 Live Tank	330	40.4	Yes	2
	M & G	FA2	SF6 Live Tank	330	40		3
	Siemens	3 AS 2	SF6 Live Tank	330	43		2
Wellington 330kV Goolma Rd, Wellington	Siemens	3 AS 2	SF6 Live Tank	330	43		5
	Areva	GL315	SF6 Live Tank	330	40.4		2
	Siemens	3AP1DT	SF6 Dead Tank	132	26.7	Yes	1
	ABB	LTB145D1	SF6 Live Tank	132	5		4
	ASEA	HLR 145 250E	Small Oil Vol	132	0		8
	Alstom	S1 145 F1	SF6 Live Tank	132	11.6		1
Wallerawang 132kV Heel St, Wallerwang	Areva	DT1 145F1	SF6 Dead Tank	132	34	Yes	13
	Areva	DT1 72.5F1	SF6 Dead Tank	66	13	Yes	11
Mt piper 132kV Boulder Rd, Portland	ASEA	HLR 145 250E	Small Oil Vol	132	0		6
	ASEA	HLR 84 2501B	Small Oil Vol	66	0		7
Beryl 132kV Beryl Rd, Beryl	Areva	GL 312	SF6 Live Tank	132	9.9		2
	Siemens	3AP1FG	SF6 Live Tank	132	9.8		2
	Areva	GL 309	SF6 Live Tank	66	7.4		3
	ASEA	HLC 72.5	Small Oil Vol	66	0		1
	Siemens	3AP1FG	SF6 Live Tank	66	4.5		2
	Siemens	3AP1DT	SF6 Dead Tank	66	13.7	Yes	3
Orange 132kV William St, Orange	ASEA	HLD 145	Small Oil Vol	132	0		1
	Siemens	3AP1FG	SF6 Live Tank	132	9.8		2
	Siemens	3AP1DT	SF6 Dead Tank	132	26.7		4
	ABB	LTB145D1	SF6 Live Tank	132	5		1
	Siemens	3AP1DT	SF6 Dead Tank	66	13.7		3
	Delle	HPGE 9/12E	Small Oil Vol	66	0		12
Orange North 132kV McLachlan St, Orange	Areva	DT1 145F1	SF6 Dead Tank	132	34	Yes	13
Panarama 132kV Mid-Western Hwy, Bathurst	ASEA	HLR 145 250E	Small Oil Vol	132	0		4
	ASEA	HLC 72.5	Small Oil Vol	66	0		8
	Alstom	GL 390 F1	SF6 Live Tank	66	6		2
Cowra 132kV Bulkhead Rd, Cowra	Siemens	3AP1DT	SF6 Dead Tank	132	26.7		2
	Siemens	3AP1FG	SF6 Live Tank	132	9.8		2
	Alstom	S1 145 F1	SF6 Live Tank	132	9		2
	Siemens	3AP1DT	SF6 Dead Tank	66	13.7		1
	ABB	EDFSK1-1	SF6 Live Tank	66	2.5		7
	Alstom	GL 390 F1	SF6 Live Tank	66	6		2
Forbes 132kV Newell Hwy, Forbes	Alstom	S1 145 F1-3	SF6 Live Tank	132	12		2
	Areva	S1 145 F1-3	SF6 Live Tank	132	12		1
	ASEA	HLR 145 250E	Small Oil Vol	132	0		2
	Alstom	S1 72.5 F1	SF6 Live Tank	66	3		3
	Siemens	3AP1FG	SF6 Live Tank	66	4.4		2
	GEC	FXT-9	SF6 Live Tank	66	3.5		2
	ABB	SK 1-1	SF6 Live Tank	66	2.5		1
	Delle	HPGE 9/12E	Small Oil Vol	66	0		2

Site	Circuit Breaker						No. CB's
	Make	Model	Type	kV	SF_6 (kg)	Inst 5yrs	
Parkes 132kV Pat Meredith Dr, Parkes	Siemens	3AP1DT	SF6 Dead Tank	132	26.7	Yes	2
	Sprecher	HGF 312	SF6 Live Tank	132	6		4
	GEC	FXT-9	SF6 Live Tank	66	3.5		4
	Siemens	3AP1DT	SF6 Dead Tank	66	13.7	Yes	3
	Areva	GL 390 F1	SF6 Live Tank	66	6		1
Molong 132kV Delight St, Molong	Alstom	S1 145 F1	SF6 Live Tank	132	9		4
	Alstom	S1 72.5 F1	SF6 Live Tank	66	3		3
	Reyrolle	LMVP	Vacuum	11	0		6
Manildra 132kV Old Orange Rd, Manildra	Alstom	S1 145 F1	SF6 Live Tank	132	9		3
	Siemens	3AP1DT	SF6 Dead Tank	132	26.7		1
	Reyrolle	LMVP	Vacuum	11	0		9

4.5.2 Distribution Sites Results

Table 4-3 Distribution Sites Circuit Breaker Data

Site	Circuit Breaker						No. CB's
	Make	Model	Type	kV	SF_6 (kg)	Inst 5yrs	
Bathurst 66kV Russell St, Bathurst	Alstom	unknown	SF6 Dead Tank	66	13	Yes	10
	Email	J18	Bulk Oil	11	0		9
Bathurst Uni 11kV	Holec	unknown	Vacuum	11	0		1
Blayney 66kV Marshall Lane, Blaney	Reyrolle	LMVP	Vacuum	11	0		10
	Siemens	3AP1DT	SF6 Dead Tank	66	13.7		6
Burrendong Dam 66kV	unknown	unknown	unknown	66	0		1
Canowidra 66kV Eugowra Rd, Canowindra	Hawk Sid	Horizon	SF6/Vac	11	2.6		2
	Sprecher	FXT-9	SF6 Live Tank	66	3.5		1
Condobolin 66kV Maitland St, Condobolin	Hawk Sid	Horizon	SF6/Vac	22	2.6		9
	AEI	LGIC/44	Bulk Oil	22	0		1
	Siemens	3AP1DT	SF6 Dead Tank	66	13.7		5
Cowra 66kV Wyangla Rd, Cowra	M & G	Evolis 17P1	Vacuum	11	0		14
	Siemens	3AP1DT	SF6 Dead Tank	66	13.7	Yes	2
Cumnock 66kV Baldry Rd, Baldry	Kyle	KFME	Oil Re-closer	11	0		4
	Siemens	3AP1FG	SF6 Live Tank	66	4.5	Yes	1
Dubbo 132kV Wheelers Lane, Dubbo	Delle	HPGE 9/12E	Small Oil Vol	66	0		1
	Siemens	3AP1DT	SF6 Dead Tank	66	13.7		7
	Sprecher	FXT-9	SF6 Live Tank	66	3.5		2
	Alstom	S1 72.5 F1	SF6 Live Tank	66	3		1
	Siemens	3AP1FG	SF6 Live Tank	66	4.5		1
	ABB	EDF SK1-1	SF6 Live Tank	66	2.5		1
	Oerlikon	TOF 60.6	Small Oil Vol	66	0		1
	ASEA	HLR 145 2502B	Small Oil Vol	132	0		1
	Siemens	3AP1DT	SF6 Dead Tank	132	26.7		5
	Alstom	DT1 145 F1	SF6 Dead Tank	132	34		1
	Sprecher	HGF 112-1	SF6 Live Tank	132	4		1
Dubbo South 132kV Boundary Rd, Dubbo	Siemens	3AH5204-2	Vacuum	11	0		10
	Areva	DT1 145 F1	SF6 Dead Tank	132	34	Yes	4
Dubbo West 132kV West St, West Dubbo	Reyrolle	LMVP	Vacuum	11	0		9
	Siemens	3AP1DT	SF6 Dead Tank	132	26.7		4
Eulomogo 66kV Sheraton Rd, Dubbo	M & G	Evolis 17P1	Vaccum	11	0		10
	ASEA	HLR 72.5	Small Oil Vol	66	0		4
Forbes 66kV Patterson St, Forbes	M & G	Evolis 17P1	Vaccum	11	0		14
Geurie 11kV Mitchell Hwy, Geurie	Nu-Lec	N15	SF6/Vac	11	1.8		1
	Nu-Lec	U15	Vacuum	11	0		3
Grenfell 66kV Cowra rd, Grenfell	Kyle	KFME	Oil Re-closer	11	0		4
	Sprecher	FXT-9	SF6 Live Tank	66	3.5		1
Gulgong 66kV Fisher St, Gulgong	M & G	DM1-A	SF6 Live Tank	22	2		3
Ilford 132kV Ilford Hall Rd, Ilford	ASEA	HLR 145 2502B	Small Oil Vol	132	0		1
	Siemens	3AP1DT	SF6 Dead Tank	66	13.7		1
	Areva	unknown	SF6 Dead Tank	66	15		1

Site	Circuit Breaker						No. CB’s
	Make	Model	Type	kV	SF_6 (kg)	Inst 5yrs	
	Schnider	unkown	SF6 Dead Tank	66	2.9		1
Lake Cargellico 66kV Lake Rd, Lake Cargelligo	Nu-Lec	N24	SF6/Vac	22	1.8		2
Mandurma 66kV Felltimber Rd, Mandurama	Nu-Lec	N24	SF6/Vac	11	1.8		3
	Reyrolle	66 OSM	Small Oil Vol	66	0		1
Molong 66kV South St, Molong	Galileo	OCE60	Small Oil Vol	66	0		3
	W’house	unknown	Bulk Oil	11	0		2
Moolarben 66kV Ulan Rd, Ulan	Siemens	3AP1DT	SF6 Dead Tank	66	13.7	Yes	1
Mudgee 132kV Mortimer St, Mudgee	Hawk Sid	Horizon	Vacuum	22	2.6		10
	GEC	GL 107	SF6	22	2.5		1
	Delle	HPGE 9/12E	Small Oil Vol	66	0		1
	Siemens	3AQ1FG	SF6 Live Tank	66	4.4	Yes	1
Mumbil 11kV Neirea Rd, Mumbil	Kyle	KFME	Oil Re-closer	11	0		3
Oberon 132kV Lowes Mount Rd, Oberon	ABB	SACE HA1/ZC	SF6	11	1		12
	ABB	LTB145D1	SF6 Live Tank	132	5		3
Oberon 66kV O’Connell Rd, Oberone	M & G	Evolis 17P1	Vacuum	11	0		10
	ASEA	HLC 72.5	Small Oil Vol	66	0		1
	Siemens	3AP1DT	SF6 Dead Tank	66	13.7		1
Orange Industrial 66kV Cleargate Rd, Orange	BBC	HBS 12.06.25C	SF6	11	1		11
	EIB	HPFA 409G	Small Oil Vol	66	0		4
Orange North 66kV March St, Orange	Reyrolle	LMVP	Vacuum	11	0		14
Orange South 66kV Lords Place, Orange	Reyrolle	LMVP	Vacuum	11	0		17
	Siemens	3AQ1FG	SF6 Live Tank	66	4.4	Yes	3
	Siemens	3AP1DT	SF6 Dead Tank	66	13.7	Yes	3
Orange West 66kV Glendale Cres, Orange	GEC	SBV2	Vacuum	11	0		11
	Siemens	3AP1DT	SF6 Dead Tank	66	13.7		1
	EIB	HPFA 409G	Small Oil Vol	66	0		3
Parkes Town 66kV Brolgan Rd, Parkes	Siemens	3AH5204-2	Vacuum	11	0		15
	Siemens	3AP1DT	SF6 Dead Tank	66	13.7		4
	Sprecher	FXT-9	SF6 Live Tank	66	3.5		1
Paytens Bridge 66kV Paytens Bridge	AEI	JB821	Oil	11	0		3
	Delle	HPGE 9/12E	Small Oil Vol	66	0		1
Peak Hill 66kV Whitten Park Rd, Peak Hill	Nu-Lec	N15S	SF6/Vac	11	1.8		4
	Siemens	3AP1DT	SF6 Dead Tank	66	13.7	Yes	1
Phillip St (Dubbo) 66kV Phillip St, Dubbo	Reyrolle	LMVP	Vacuum	11	0		13
Raglan 66kV Adrienne St, Raglan	Siemens	3AF0143-4	Vacuum	11	0		8
	Areva	GL 107	SF6 Live Tank	11	2.5		3
	M & G	Evolis 17P1	Vacuum	11	0		3
	Hawk Sid		Vaccum	11	2.6		1
	ASEA	HLC 72.5	Small Oil Vol	66	0		4
Stewart 66kV Mitchell highway, Bathurst	GEC	SBV2	Vacuum	11	0		11
	ASEA	HLC 72.5	Small Oil Vol	66	0		5
Trundle 66kV Back Trundle Rd, Trundle	Hawk Sid	Horizon	Vacuum	22	2.6		4
	Nu-Lec	N15S	SF6/Vac	11	1.8		3
	Siemens	3AP1DT	SF6 Dead Tank	66	13.7		1
Ulan 66kV Ulan Rd, Ulan	Nu-Lec	N24	SF6/Vac	22	1.8		3
Ulan Switch 66kV Ulan Rd, Ulan	Siemens	3AQ1FG	SF6 Live Tank	66	4.4		1
	ASEA	HLC 72.5	Small Oil Vol	66	0		6
Wellington Town 132kV Pierce St, Wellington	M & G	Evolis 17P1	Vacuum	11	0		9
	ASEA	HLC 72.5	Small Oil Vol	66	0		3
	EIB	HGF 312	SF6 Live Tank	132	4		1
West Jemalong 66kV Condobolin Rd, West Jemalong	Reyrolle	LMVP	Vacuum	11	0		7
	Siemens	3AP1DT	SF6 Dead Tank	66	13.7	Yes	2
	Siemens	3AQ1FG	SF6 Live Tank	66	4.4		4
Yarrendale 66kV Yarrendale Rd, Yarrendale	ASEA	HLC 72.5	Small Oil Vol	66	0		1
	Siemens	3AP1DT	SF6 Dead Tank	66	13.7	Yes	1
	Reyrolle	LMVP	Vacuum	11	0		10

4.5.3 Results Graphics

Circuit Breakers Less than 66kV

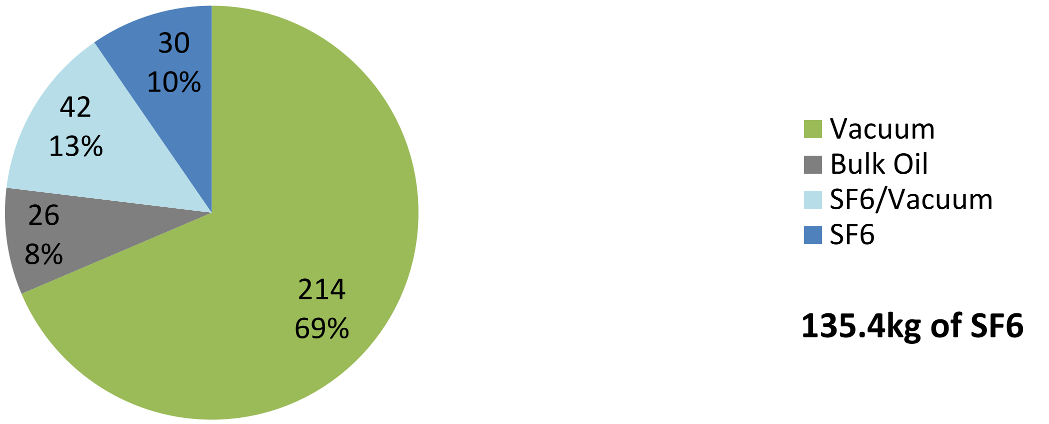


Figure 4-7 Pie Chart of Case Study Results - Circuit Breaker Types (less than 66kV)

The below 66 kV range was made up of the 11 and 22 kV distribution circuit breakers. In this range, the **312** circuit breakers, the majority utilised vacuum interrupters. A moderately low number of SF_6 breakers were recorded. The 42 SF_6/vacuum models only use SF_6 gas for phase to ground insulation, utilising vacuum interrupters for current breaking.

Circuit Breakers 66kV

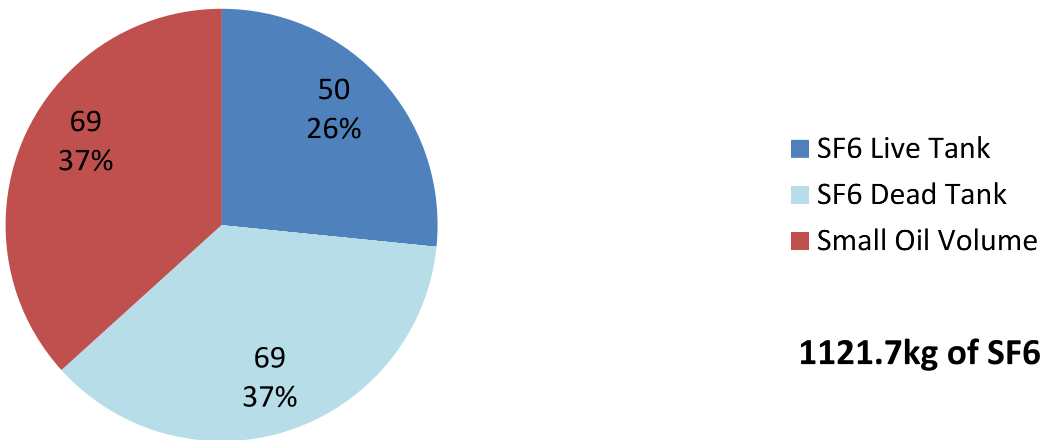


Figure 4-8 Pie Chart of Case Study Results - Circuit Breaker Types (66kV)

Above 66 kV the choice of circuit breaker was limited to either SF_6 dead/live-tank or Small Oil Volume (SOV) Designs. The **188** Circuit breakers saw a nearly equal share of the three types.

Circuit Breakers 132kV

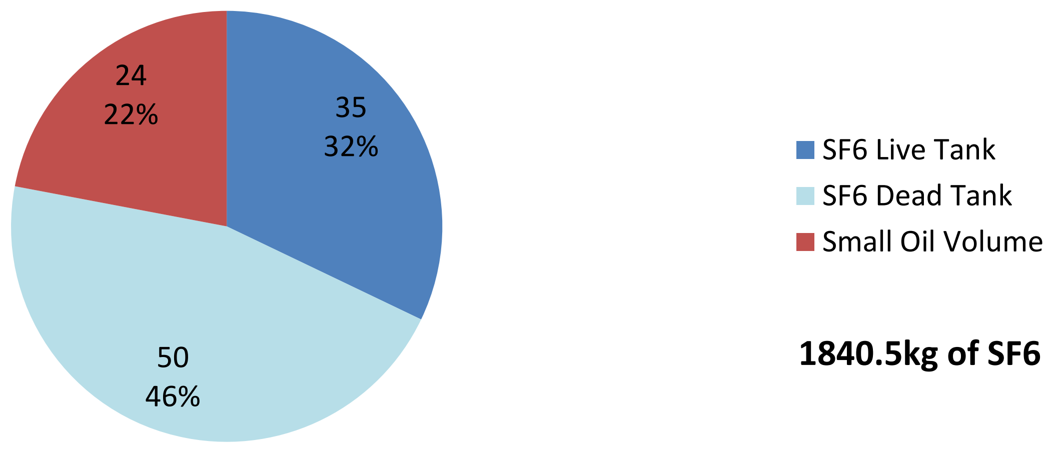


Figure 4-9 Pie Chart of Case Study Results - Circuit Breaker Types (132kV)

The **109** 132 kV circuit breakers displayed a surprisingly large market share of the popular SF_6 dead-tank design type. This number was contributed by two fairly recently constructed 132 kV substations in the case study area that utilised only dead-tank designs.

Circuit Breakers 330kV and Above

Figure 4-10 Pie Chart of Case Study Results - Circuit Breaker Types (330kV and Above)

The **49**, 330 kV and above circuit breakers were all SF_6 live-tank models. In this range few other designs can functionally compete.

4.6 Age of Oil Circuit Breakers/Growth of SF_6 Circuit Breakers

The case study reveals two main types of high voltage circuit breakers in use: Small Oil Volume (SOV) and SF_6. The NSW state transmission authority Transgrid, suggests in its Network Management Plan 2011-2016 (see Appendix D) that:

"Small Oil Volume circuit breakers are now considered to be obsolete technology and this type of circuit breaker is no longer generally available. Maintenance costs for this type of circuit breaker are higher than SF6 units, and a substantial level of maintenance knowledge and effort are required to ensure continued reliability of the circuit breakers. Support for these circuit breakers from manufacturers is limited as this type is no longer supplied." (Transgrid, 2011)

Transgrid indicates that an expected economic life of a HV circuit breaker is up to 40 years or shorter taking into consideration reliability and supportability. Transgrid and the distribution authority Essential Energy conduct economic evaluations on circuit breaker replacements on a case by case basis. Occasionally entire model replacements are recommended where trending data indicates future type faults are a high possibility.

Aging circuit breaker replacement is not limited to obsolete Small Oil Volume types but can also encompass early SF_6 designs (1975-1987). These designs have also proven to be prone to type faults (e.g. corrosion, gas leaks) and refurbishment programs have been largely proven unsuccessful.

Transgrid as an entire company employs 1483 high voltage circuit breakers in its NSW transmission infrastructure, ranging from 11-500 kV. The company stopped purchasing Small Oil Volume type circuit breakers in the late 80's and has a diminishing number of the aging technology still in service. The overwhelming majority of obsolete Small Oil Volume circuit breakers are replaced with new SF_6 models in the 33 kV and above voltage ranges.

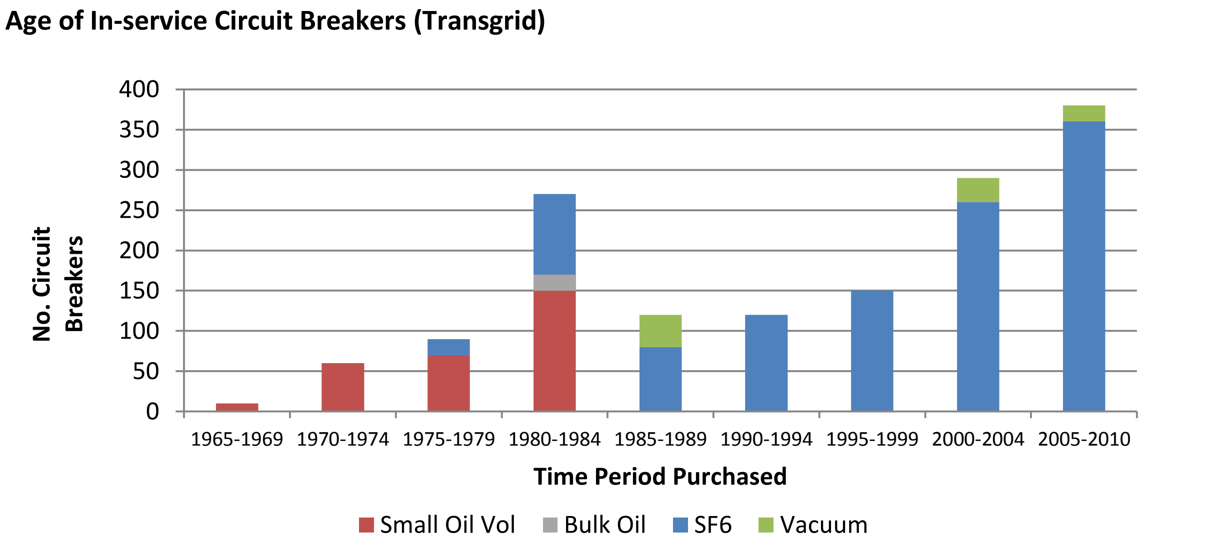


Figure 4-11 Bar Graph of Types of Circuit Breakers Purchased 1965-2010 (Transgrid)

Table 4-4 Circuit Replacements from 2011 Onwards

Make	Model	Type	kV	Install Date Range	Project Time Frame	No. in Case Study Area (Transgrid)	No. in Case Study Area (total)
Brown Boveri	ELF	SF6	66	1981-86	2013	0	0
Delle	HPGE	Small Oil Vol	66	1973-75	2018	14	17
ASEA	HLD	Small Oil Vol	132	1968-81	2020	1	1
M & G	FA1	SF6	132	1980-86	2013	0	0
ASEA	HKEY	Small Oil Vol	132	1957-60	2011	0	0
ASEA	HLR	Small Oil Vol	132	1972-84	2014	21	23
Sprecher	HPF	Small Oil Vol	330	1976-81	2015	0	0
M & G	FA2	SF6	330	1980-84	2019	3	3
M & G	FA4	SF6	500	1982-83	2017	0	0
ASEA	HLR	Small Oil Vol	66	1983	as req.	16	20
Magrini		Bulk Oil	11	unknown	2016	0	0
Siemens	3AS2	SF6	330	1982-84	as req.	7	7
Siemens	3QS2	SF6	330	1991-93	as req.	6	6
Total:						**68**	**77**

Source: (Transgrid, 2011)

Transgird's 2011-2016 Network Management Plan identifies 13 HV circuit breaker models it plans on replacing in the next five years. Six of these models are Small Oil Volume types in the 66 kV and above voltage range which will more than likely need to be replaced with SF_6 models.

If Essential Energy follows a similar replacement strategy as Transgird it is plausible that a total of 61 new SF_6 type HV circuit breakers could be installed in the case study area in the next five years.

An analysis of the new equipment installed across the case study area in the previous five years presents that of a coincidental 61 newly installed circuit breakers (66-132 kV) all of which were SF_6 type.

Of these 61 new installations in the 66-132 kV range the majority were of dead-tank type construction. Dead-tank SF_6 circuit breakers contain significantly more SF_6 gas then their live-tank counterparts. The average 66 kV SF_6 dead-tank contains 13 kg of SF_6 gas compared to the average SF_6 live-tank that contains about 4 kg. The 132 kV SF_6 circuit breaker range sees about a 27 kg to 10 kg difference in the dead-tank and live-tank designs respectively.

The 66 kV SF_6 circuit breaker range saw 95% of new installations within the last 5 years to be dead-tank type construction with the Siemens 3AP1DT being the most popular. The 132 kV range saw a 100% market share of newly installed SF_6 dead-tanks with the Areva DT1 145F1 the most popular in this range. The dead-tank type construction is often stipulated in the model number with the letters "DT"

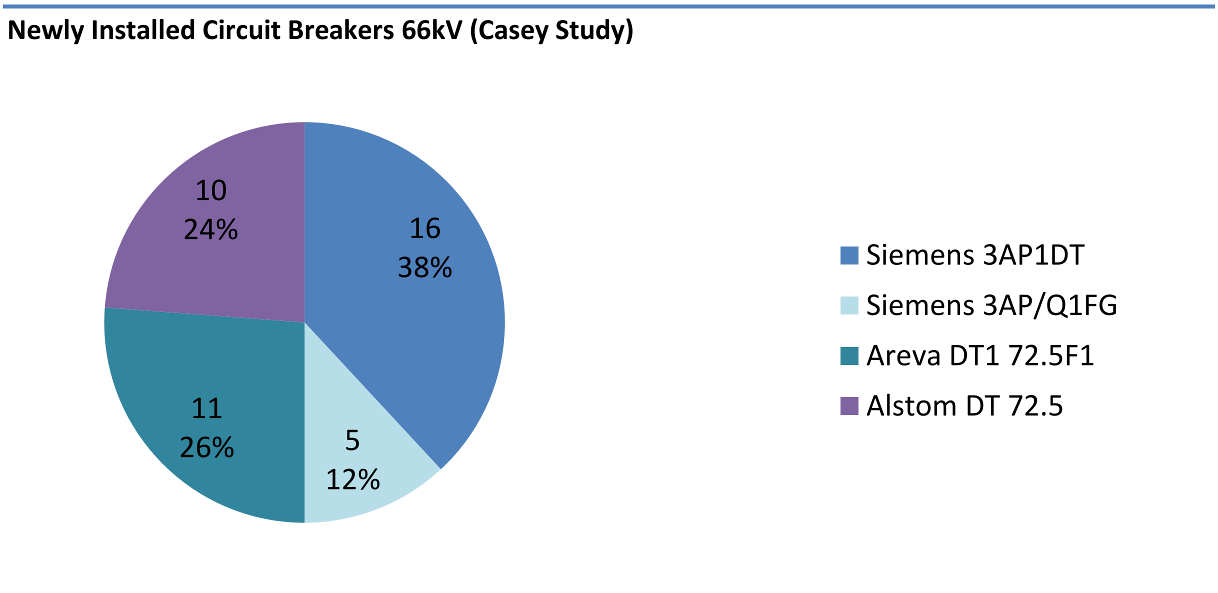


Figure 4-12 Pie Chart of Case Study Results – Newly Installed Circuit Breaker Types (66kV)

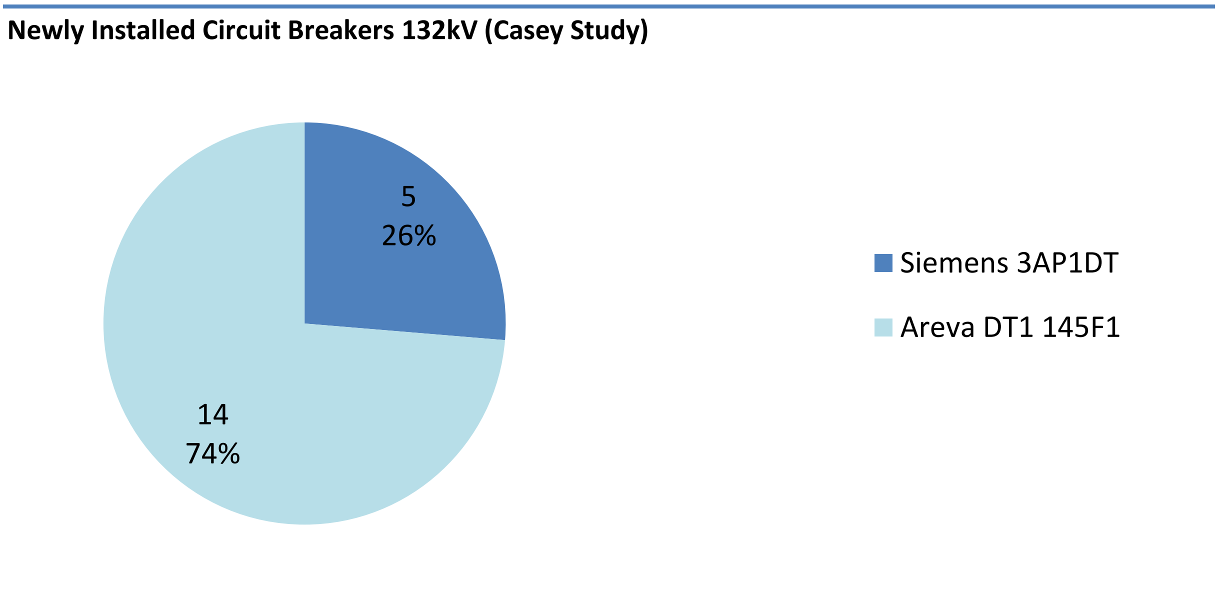
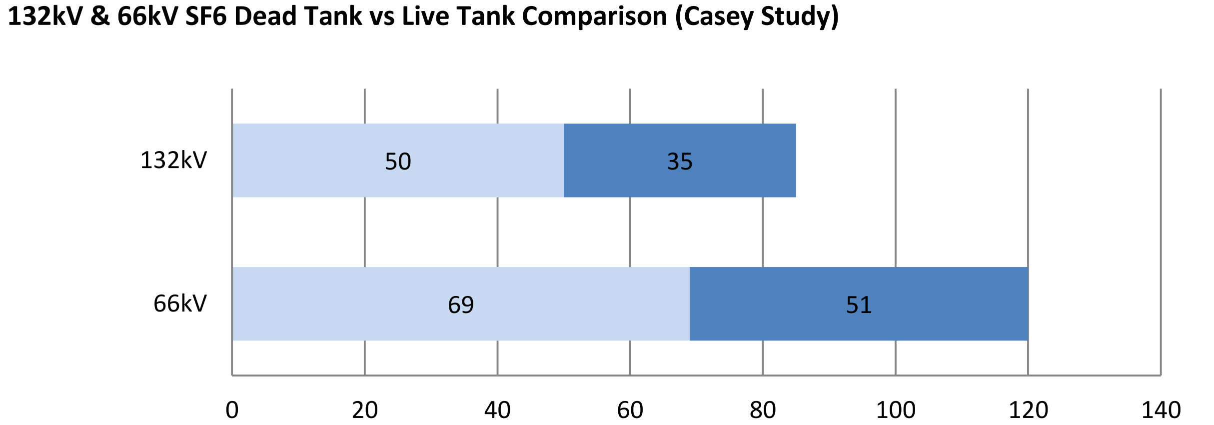


Figure 4-13 Pie Chart of Case Study Results – Newly Installed Circuit Breaker Types (132kV)

4.7 Dead-Tank vs Live-Tank

From the case study results it is apparent that dead-tank type circuit breaker construction is the preferred design type of new SF_6circuit breaker installations in the 66-132 kV range. Of the 205 in-service SF_6 66-132 kV circuit breakers in the case study region 119 (58%) were dead-tanks. Dead-tank designs in NSW have been installed from 2001 onwards. Many manufactures including Siemens, Alstom, Areva and Mitsubishi offer competitive dead-tank designs. Dead-tank designs require roughly three times the SF_6 gas needed for insulation purposes then their live tank counterparts. This last decade's movement towards dead-tank designs is seeing a growing shift in their installations and consequently a growing amount of in service SF_6 gas.



	66kV	132kV
SF6 Dead Tank	69	50
SF6 Live Tank	51	35

Figure 4-14 Bar Chart 132kV and 66kV SF6 Dead Tank and Live Tank Comparisons

Dead-tank designs are seen as preferable as they allow for the interrupter tank to be located at ground voltage potential considered "dead" in terms of the voltage hazard potential. The design type allows for the tank to be safely contactable during operating conditions.

The dead-tank design's main advantage is that it allows for the inclusion of multiple low voltage, bushing type, current transformers on both sides of the interrupter. Current transformers are vital for conveying a useable, reduced ratio, representation of the primary operating current. The reduced secondary current is supplied to protection and metering relays which monitor and operate the circuit breaker in the event of a high current fault. This reduced representative current supplied to the relays allows for smaller secondary cable sizes and reduced relay component insulation. The dead-tank's all in one compact design is seen as superior to the live-tank design which utilises separate high voltage "post" current transformers on adjacent structures giving the live-tank infrastructure an unwanted overall larger installation footprint.

4.8 SF6 Metering Current Transformers

Although live-tank SF_6 circuit breaker designs exhibit lower amounts of required SF_6 gas insulation, this is not always the case given the overall infrastructure needed for circuit breaker operation. When considering a circuit breaker's current transformer (CT) requirements, additional SF_6 may not have been accounted for.

As mentioned previously, a high voltage circuit breaker requires extremely accurate CTs to convey smaller representative currents to protection relays. The protection relays utilise the secondary representative currents to determine whether the circuit breaker needs to operate in the event of large fault currents. Live-tank circuit breaker designs minimise the overall required amount of non-solid insulation medium (oil or SF_6) by housing only the interruption vessel (or tank) atop solid-dielectric post insulators. Unlike the dead-tank design the required CTs are not housed within the same unit. Being that the interruption tank is held at the "live" operating high voltage level, further insulation and a cumbersome design would be required to accommodate "built in" CTs.

As such, the CTs required for live-tank circuit breakers are housed inside or on top of separate, specific high voltage, "post CTs". These post CTs live separately on directly adjacent structures in series with the circuit breaker.

Traditional HV CTs most commonly consisted of a "hairpin" primary conductor that loops down though multiple toroidal current transformers all submerged in insulating oil. The submerged current transformers are housed in a tank at ground potential whilst the hairpin extends up though the post porcelain housing to the high voltage conductors. As the transformer oil is rarely subject to arcing the oil does not suffer the same high maintenance regimes associated with carbonising circuit breaker oil, however it does still require periodic monitoring. For this reason oil post CTs have been regarded as adequate for their purpose however rising maintenance and condition monitoring cost have seen an onset of new designs.

Live-tank post CTs are a more modern design where the primary conductor and current transformers are housed in a tank held at the live operating voltage atop a post insulator. The secondary wiring is insulated and taken to ground. This design often utilises SF_6 as the tank filled insulation medium. The shorter primary conductor of this arrangement gives better rigidity and high short circuit current withstanding capability.

In the case study area 46 live-tank circuit breakers were observed to have SF_6 insulated adjacent post CTs utilising a total of 4239 kg of SF_6. Three CTs per circuit breaker gave a total of 138 SF_6 insulated CTs. Disregarding the 500 kV range where 100% of circuit breakers are SF_6 live-tanks with SF_6 post CTs, the post CT equipment category adds a further 2304.6kg of in service SF_6 to the case study area.

33% of 330 kV circuit breakers in the case study area (all live-tanks in this range) utilised SF_6 insulated post CT's. In the 132 kV range 25.53% of live-tanks used SF_6 insulated post CT's and 5.66% of 66 kV live-tanks.

Table 4-5 Case Study Area SF6 Current Transformer Results

Site	Circuit Breaker			No. CB's	CT	Total SF_6
	Make	Model	kV		SF_6(kg) per CT	(kg)
Forbes 132kV	Areva	S1 145 F1-3	132	1	13.5	40.5
Molong 132kV	Alstom	S1 72.5 F1	66	3	6.4	57.6
Molong 132kV	Alstom	S1 145 F1	132	4	6.6	79.2
Orange 132kV	Siemens	3AP1FG	132	2	13.5	81
Mt Piper 500kV	Siemens	3AP2F1	330	2	25.7	154.2
Wallerawang 330kV	Areva	GL 315	330	2	25.7	154.2
Wallerawang 330kV	Siemens	3 AS 2	330	2	25.7	154.2
Wellington 330kV	Areva	GL315	330	2	25.7	154.2
Wellington 330kV	ABB	LTB145D1	132	5	13.5	202.5
Wallerawang 330kV	M & G	FA2	330	3	36	324
Wollar 500kV	Siemens	3AP2F1-2	500	3	49.6	446.4
Wallerawang 330kV	Areva	GL 315	330	7	43	903
Mt Piper 500kV	Siemens	3AP3F1-2	500	10	49.6	1488
Total				**46**		**4239**

Figure 4-15 Live-tank Circuit Breakers with adjacent SF6 Post CTs (left) and Oil Post CTs (right)

4.9 Re-closers

Another important consideration in the case study area's SF_6 quantities is that of Line Re-closers. A Line Re-closer is a pole mounted circuit breaker that resides outside the substation along MV distributions lines (mainly 11-22 kV) to sectionalise the line in the event of a fault. In particular on long sections of radial lines, the use of multiple Re-closers enables a minimum amount of supply loss to customers. When a fault occurs on a radial line the closest Re-closer upstream of the fault will operate. The operation of the Re-closer cuts supply to the downstream faulted section of line whilst ensuring supply is unaffected upstream. A Re-closer earns its name from its ability to re-close automatically after a small time delay post fault operation. This time delay often lets any previous fault instigators, such as a fallen tree branch, clear and supply is restored open re-closing. A Re-closer can often be set to operate or "trip" and then close multiple times in an effort to allow the fault a chance to clear. Mainly rural feeders utilise Re-closers due to their long distance nature where it would be inconvenient to lose supply to the whole line when the fault could be sectioned off only at the extreme end.

Evaluation of every feeder in the 11-22 kV range in the case study area would be a large evaluation. For the purpose of this research project ten rural feeders were chosen at random and the types of Re-closers utilised recorded.

Table 4-6 Feeder Re-closer Numbers: Case Study Sample

Re-closer Make	Feeders										Insulation Medium
	1	2	3	4	5	6	7	8	9	10	
Noja	1	1	1	1	4	2	2	2	1	2	Solid-dielectric
Reyrolle	1			1	1				1	1	Oil
Lexington	4					2		3		1	Oil
Nu-Lec N	3	6	4	4		3	3	4	3	2	SF6/Vacuum
Nu-Lec U		2	3	2	2	2	3		3		Solid-dielectric
Nu-Lec W					1						Solid-dielectric
Nu-Lec Duo		2	3		3		1	1	2	3	Solid-dielectric
Kyle		1	1	1		2	1	1	1	1	Oil

One popular type of Re-closer is the Nu-Lec N Series. The N Series utilises vacuum interrupters within a SF_6 filled tank (SF_6 for phase to ground insulation purposes). The N Series can handle up to 38 kV operating voltages and has relatively high fault current interrupting capabilities. Its self-sustaining control system runs off small batteries re-charged from the HV conductors via a small power transformer which makes it convenient for outlying rural substations also.

Of the 312, 11-22 kV circuit breakers in substations in the case study area a conservative approximation of 20% could be assumed as supplying rural feeders. From the sampled data it could be hypothesised that each rural feeder has an average of 3.2 N Series Nu-Lec Re-closers. The 61 likely rural feeders could accommodate 195 N series Re-closers given the sampled data trends. Each N Series Nu-Lec contains 1.8 kg of SF_6 gas, equating to approximately 350 kg of additional SF_6 in the case study area.

4.10 Environmental Effects and Cost

From data collected it can be deduced that transmission and distribution substations in the case study area employ a total of 9866kg of in-service SF_6 gas for circuit breaker and associated current transformer purposes in 11-500 kV equipment range. With an additional estimated 350 kg for distribution line Re-closers the case study could quite possibly contain excess of 10,216 kg of SF_6 gas in its electrical infrastructure network. The over 10 tonnes of stored SF_6 has a global warming potential of 23,900 times that of carbon dioxide.

Of the contained 10 tonne potential, minimal environmental impact is caused unless the gas is released to the atmosphere. The two main causes of SF_6 gas loss from HV circuit breaker equipment are vessel/seal leaks and losses during handling activities such as routine maintenances.

The Australian Government Department of Climate Change and Energy Efficiency in its National Greenhouse Accounts Factors report of July 2012 present an annual SF_6 gas leakage rate of gas insulated switchgear and circuit breaker applications as 0.89% of capacity (see Appendix E). This figure is based on the National Greenhouse and Energy Reporting (Measurement) Determination 2008 (Section 4. 102)

Using the example calculations in the report as basis to determine the CO_2 equivalent, the case study area leakage emissions (E_l) are calculated by:

$$E = \frac{Q \times GWP}{1000} \times L \tag{4.1}$$

Where:
E = Emissions (tonnes CO_2)
Q = Quantity (kg)
GWP = substance global warming potential rating
L = Annual leakage rate (decimal %) i.e. 10% = 0.1

$$E_l = \frac{10216 \times 23900}{1000} \times 0.0089 = 2173 \; tonnes \; CO_2$$

Maintenance wise “Typically between 2 % and 0.4% of the name plate capacity’ is lost during handling activates” (Rhiemeier, et al., 2010). At minimum a detailed inspection of a SF_6 filled circuit breaker is required every 4 years (in reality SF_6 alarms or circuit breaker service faults could cause for more regular handling activities). A detailed inspection requires SF_6 density and pressure checks which require SF_6 handling activities. Taking an average handling loss as 1.2% of capacity every four years (or 0.3% annually) the handling emissions of the case study area can be calculated as:

Annual handling emissions (E_h) of case study equipment can similarly be calculated as:

$$E_h = \frac{10216 \times 23900}{1000} \times 0.003 = 732.5\ tonnes\ CO_2$$

The total annual case study SF_6 emissions can be calculated as:

$$E_{total} = E_l + E_h \tag{4.2}$$

Total annual case study SF_6 emissions = 2905.5 tonnes CO_2 equivalent

Using the above leakage and handling loss rates and the annual cost of SF_6 replacement at a rate of \$55 per kilogram, the annual cost of SF_6 replacement in the case study area can also be determined, and has been calculated as:

$$C = \big((Q \times L_l) + (Q \times L_h)\big) \times c \tag{4.2}$$

Where:

C = Annual cost of SF_6 (\$)
Q = Quanty (kg)
L_l = Annual leakage rate, leakage (decimal %)
L_h = Annual leakage rate, handling (decimal %)
c = substance cost per kilogram (\$/kg)

$$\big((10216 \times 0.0089) + (10216 \times 0.003)\big) \times 55 = \$6686.37$$

This equates to \$267,454 over the 40 year life cycles of typical circuit breakers.
Alternatively, if carbon pricing for CO_2 was returned to \$23/tonne, this would equate to 10 times the value: \$2,674,548

Note: leakage = 90.92kg SF_6, handling loss = 30.65kg SF_6

4.11 Case Study Data Summary

Table 4-7 Case Study Data Summary

Population:		237,064	
Area:	(km^2)	68,150	
Dwellings:		104,879	
Generation:	(MW)	2449.2	(1449.2 Wallerawang closed)
Substations:	**No.**	**Mass of SF6 (kg)**	
Distribution:	41	1281.4	
Transmission:	14	8584.6	
total:	55	9866.0	
Circuit Breakers	**No.**	**Mass of SF6 (kg)**	
11 kV	279	58.1	
22 kV	33	77.3	
66 kV	189	1121.7	
132 kV	109	1840.5	
330 kV	36	1369.2	
500 kV	13	1160.2	
total:	659	5627.0	
Current Transformers	**No.**	**Mass of SF6 (kg)**	
66 kV	9	57.6	
132 kV	36	403.2	
330 kV	54	1843.8	
500 kV	39	1934.4	
total:	138	4239.0	
Re-closers*	**No.**	**Mass of SF6 (kg)**	
	195	350	
New CBs (<5yrs)	**No.**	**Mass of SF6 (kg)**	
66 kV	42	514.3	
132 kV	19	1180.9	
total:	61	1695.2	
CB Replacement (5yrs)	**No.**	**Mass of SF6 (kg)**	
66 kV	37	0	
132 kV	24	0	
330 kV	16	565	
total:	77	565	
Annual Emissions	**%**	**Mass of SF6 (kg)**	**CO_2 Equivalent (tonne)**
Leakage	0.89	90.26	2173.0
Handling Activities	0.30	30.65	732.5
Total:	1.29	120.91	2905.5

*calculations based on reasonable assumptions.

Chapter 5: SF6 Replacement & Reduction: Materials, Technologies & Strategies

Chapter Five of this dissertation explores materials, technologies and strategies to replace or reduce SF_6 and its associated emissions in high voltage circuit breaker applications. Due to the environmental and OH&S concerning attributes of SF_6, replacement and reduction strategies are seeing further development and utilisation. With the major use of SF_6 being for insulation in HV circuit breakers and their associate apparatus, innovations providing either replacement or reduction in this field are highly welcomed.

Chapter Three explained that after the overwhelming industry acceptance of SF_6 insulated circuit breaker technology in 1970's and 80's there was few innovations in circuit breaker and interrupter designs. The industry experienced a relatively stagnate innovative period leading into the new millennium, excusably content with the highly reliable, low maintenance, space saving and affordable designs offered by SF_6.

It wasn't until the global community became more concerned with climate change in the early 2000's that an awareness of SF_6 and its global warming potential sparked a re-consideration of the medium. By this time, 30 plus years of continued investment in SF_6 circuit breakers had refined the design to such proficiency and market affordability that alternatives would have to be extraordinary to compete. Energy is one of the most scrutinised and essential commodities. Energy providing utilities suffer extreme public and consequently government pressure to ensure that their service is of the highest possible reliability at affordable prices. Hence the industry as a majority is quite conservative when it comes to new technology that seeks to replace its already reliable service at "acceptable" prices.

Despite this conservative nature, recent public environmental awareness pressure has seen a re-evaluation of some previously overlooked technologies prior to the SF_6 revolution as well as the introduction of some new ideas. This Chapter examines more closely these technologies and also strategies that seek to reduce or eliminate SF_6 in HV circuit breakers and associated apparatus. The concepts presented are a mixture of some already industry accepted practices gaining popularity to some that are in theoretical stages. However all boast competitiveness to SF_6, with some even suggesting benefits (beyond environmental) above what SF_6 designs currently offer.

The seven replacement/reduction concepts are:

1. solid-dielectric circuit breakers
2. dry air/vacuum circuit breakers
3. Live-tank circuit breakers with Oil current transformers
4. Live-tank circuit breakers with non-conventional current transformers (NCCT)
5. Octafluorocyclobutante
6. Leakage monitoring - specialist camera equipment
7. Government regulations.

5.1 Continual Development of the Vacuum Interrupter (VI)

The first two SF_6 alternatives presented in this chapter have relied heavily upon the development of the vacuum interrupter (VI) over the past half century. Being that the vacuum interrupter is one of the most promising alternatives; its developments are therefore worthy of a brief consideration.

5.1.1 Vacuum Interrupter Limitations

Vacuum Circuit Breakers came into use in the 1960's. In theory a vacuum is an ideal dielectric medium - no substance should result in any conducting electrons. However, in reality a vacuum does see a dielectric strength limitation and this limitation is more a function of contact or electrode shape, as well as the contact material used and contact opening distance. The required contact distance to maintain dielectric strength for a vacuum interrupter increases quite quickly for voltages above 30 kV. For this reason VI technology has previously been exclusive to medium voltage applications (typically 11-33 kV).

The main hindrance to the VI development has been the technical difficulties involved in its construction. These included such areas as the degassing of the contact and the lack of the proper welding or soldering technologies needed to effectively and reliability attach the external ceramic envelopes to the metallic ends of the interrupters. Both of these technical difficulties have been improved dramatically over the last 30 years. Degassing the contacts is an especially important requirement as the release of any gases trapped within the contact metals can significantly degrade the vacuum. It is essential that the materials used for the contacts and the surfaces in contact with the vacuum be very pure and gas-free.

Although the small insulation gap required rapidly increases for voltages above 30 kV, the simplicity of the mechanisms means the vacuum bulb can generally be very compact. It is actually the breaking capacity, which is proportional to contact diameter, which is the defining property of the vacuum internal envelope volume. Externally however, it is the dielectric strength of the external enclosure material that defines the overall device size. The external dielectric strength is limited by the insulation capacity the surrounding air or medium. A requirement for compensation for adverse ambient conditions such as soiling of the ceramic surface or extreme condensation is needed and typically takes the form of an insulating gas or mould.

Up until the last 20 years, VI designs had been limited to sub 33 kV voltages applications. This limitation was mainly to maintain the functional sizes required for integration into tank type circuit breakers. Initially high voltage vacuum designs utilised combinations of glass containers and spiral electrodes insulated externally with SF_6 gas. Although there were no discharge products, and relatively small amounts of SF_6 gas were used, it had previously not been possible to completely eliminate the use of SF_6 gas for external insulations for high voltages.

5.1.2 Vacuum Interrupter Development

To maintain the maximum vacuum bulb seal, mobile inserting parts are avoided in VI designs. Contacts are consequently placed simply end to end.

Contact materials are sort to have a low resistance to reduce the tendency to weld which can occur after closing under short-circuit conditions. Low contact to contact resistance is a desired property maintained by means of high contact pressure, requiring contacts to attribute high mechanical strength also. In the early 1980's cooper Chromium (CuCr) based electrode materials came into use exhibiting superior current interruption and voltage withstand performance.

Contact shapes and designs have also been experimented with. Designs seek to take advantage of either axial or radial magnetic field interactions with the arc to maintain its defused state and aid interruption. Explanations of developed contact shape designs have been previously outline in section 3.4.3

Upon developing the superior current breaking, axial magnetic field electrode structures in the 1990's, a combination of glass containers and the new axial field electrodes came into use. In 2001 developments in ceramic bulb construction that had previously been unique to sub 33 kV deigns extended to 66 kV. Ceramic VI chambers exhibit greater production ability and higher baking temperatures which result in cleaner vacuum interiors. Furthermore, detailed electric and magnetic field analysis's and measurement technologies carried out and developed prior to 2001 optimised the modern electrode structure. This electrode optimisation combined with a more capable ceramic bulb construction paved the way to high capacity, higher voltage withstand vacuum interrupters.

The modern vacuum interrupter's external dielectric strength is still however limited somewhat by the insulation capacity of the surroundings, although mediums other than SF_6 gas can be used. A major advantage of the VI over other interruption mediums is that the internal dielectric requires no checking whatsoever throughout the service life of the interrupter. Functional designs are now available that utilise vacuum interrupters and eliminate the use of SF_6 external insulating gas in the 11-66 kV range. Solid-dielectric and dry compressed air are two such dielectric SF_6 gas elimination mediums.

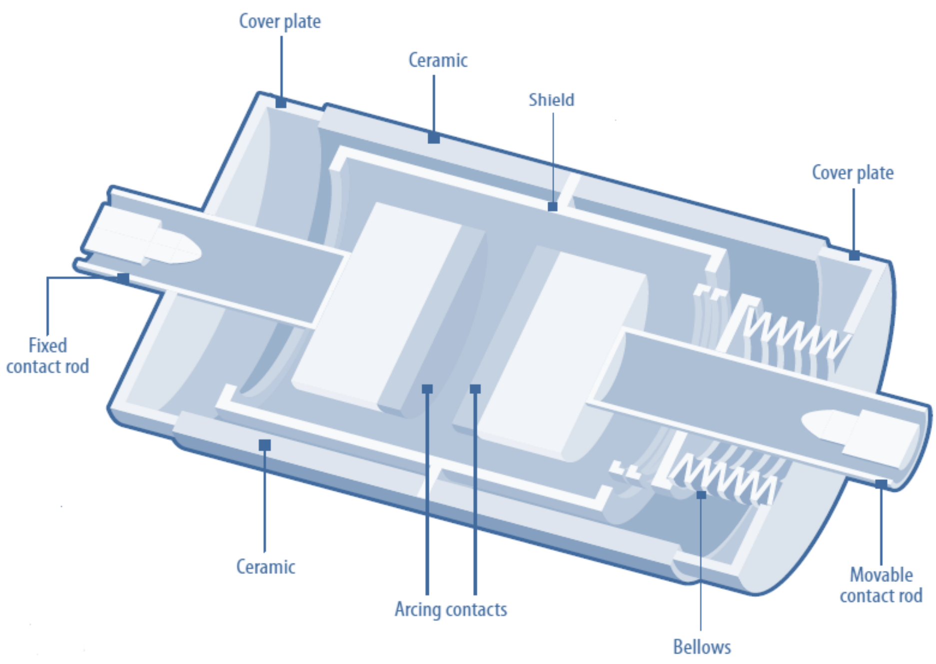


Figure 5-1 Vacuum Interrupter Layout
Source: (Dr. Drews, 2013)

5.2 Vacuum Interrupters Embedded in Solid-dielectric

5.2.1 Solid-dielectric Designs

"One method of increasing the external dielectric strength of the vacuum interrupters is to embed the chamber in a solid material (e. g. silicone or epoxy resin moulding compound). In such cases, the vacuum interrupter is additionally well protected against external mechanical influences such as impacts." (Fenski, et al., 2007)

Like most high voltage circuit breakers a Solid-dielectric/vacuum circuit breaker is a three pole device consisting of three interruption chambers (vacuum interrupters) actuated by a linked mechanical or magnetic operating mechanism. Poles can either be manufactured in column or embedded form. In each case each pole of the solid-dielectric design consists of a VI, bolted to its terminal connections embedded inside an insulating tube or casting of epoxy resin.

In the embedded casting technique the VI can be encapsulated within the resign with the smallest number of bolted connections. This technique eliminates maintenance and facilitates compact and robust designs.

"The main advantages of embedded poles are high dielectric strength without additional external compensation in air. The design also sees high usability in an extremely wide range of climatic conditions and good protection of the vacuum interrupter from dust, mechanical impacts and moisture. Furthermore, the greatly reduced number of individual parts required allows significantly increased production reliability to be achieved with shortened production times." (Fenski, et al., 2007)

Solid-dielectric embedded pole designs are available and established on the Australian market for all indoor and outdoor applications up to 40 kV with short circuit breaking capacity of 50 kA

Alternate epoxy resin systems are available for outdoor applications to withstand even the most adverse environmental conditions. The hydrophobic cycloaliphatic epoxy resin (HCEP) now commonly used boasts high ultra violet resistance, high impact strength and is unaffected in temperatures as low as minus 60 degrees Celsius.

This solid-dielectric, highly compact, robust and maintenance free design is fast becoming the dominating technology of choice in medium voltage circuit breakers. The run until fail design has an extremely low in-service environmental impact and eliminates oil and SF_6 handling activities inherent to the alternatives.

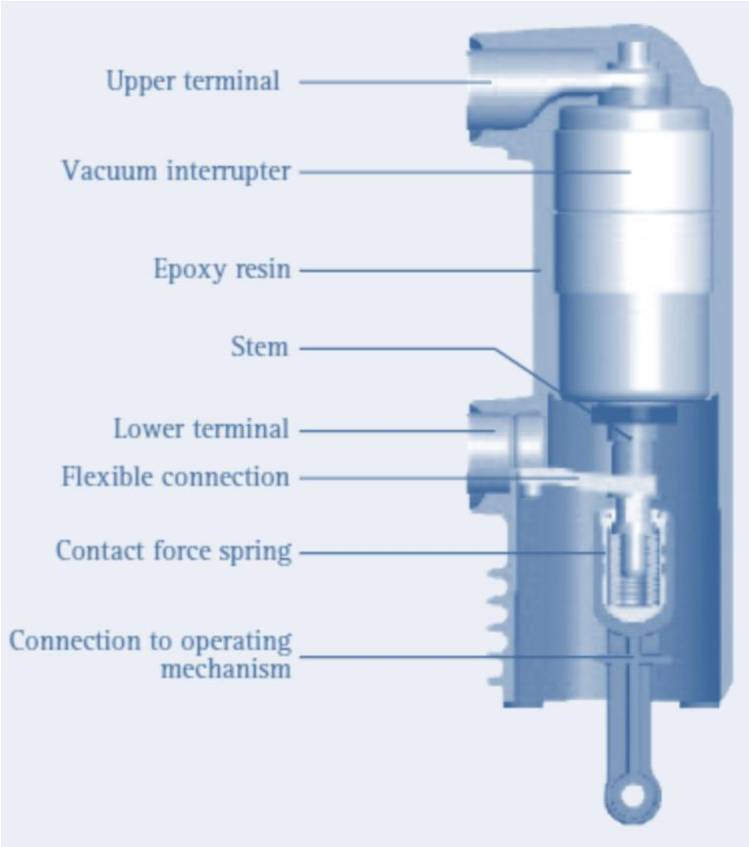


Figure 5-2 Vacuum Interrupter Embedded in Solid-dielectric

Source: (Fenski, et al., 2007)

5.2.2 Implication of Solid-dielectric Designs on Case Study Area

The strong movement towards solid-dielectric vacuum technology in the case study area's circuit breaker range below 66 kV can be already seen. Results show 69% of circuit breakers in substations in this range where found to be vacuum interrupter type designs using solid-dielectric or in some cases simply the ambient air as the external dielectric medium. Also, 47% of Re-closers were found to be solid-dielectric vacuum types.

However, 23% of circuit breakers less than 66 kV in case study area substations are still utilising SF_6 gas, attributing to 28.8 tonnes of annual CO_2 emissions in leakage alone. It should be noted that more than half of the SF_6 containing circuit breakers in this range were using vacuum interrupters for current breaking combined with SF_6 gas for external dielectric purposes only. Furthermore, 30% of Re-closers were also using SF_6 for external dielectric purposes, with an estimated 350 kg of SF_6 in this field attributing a further 74.4 tonnes of unnecessary annual CO_2 emissions. Thus, a total of 98 substation circuit breakers (includes 26 oil type) and possibly 340 oil or SF_6/vacuum relcosers could be beneficially replaced with a solid-dielectric vacuum design.

The routine maintenance of a vacuum circuit breaker compared to an SF_6/vacuum circuit breaker is typically the same (both based on vacuum type) with a minor service ever 4 years, major every 12 years or 800 operations. However, the SF_6/vacuum design is more prevalent to non-routine call out activities such as SF_6 leakage alarms. SF_6 filled circuit breakers also require additional SF_6 handling equipment such as evacuation/filling pumps and storage cylinders for more involved maintenance activities, which increases maintenance costs and logistics.

Additionally 8% of substation circuit breakers and 22% of field Re-closers, all in the sub 40kV range were still utilising oil as the insulation medium and would be soon due for replacement. A sensible replacement for these aging models would be the respective indoor or outdoor solid-dielectric vacuum replacements rather than SF_6 designs.

Many indoor high voltage board type circuit breaker design companies produce a replacement modular vacuum design that can be utilised in the same compartment as the previous rack-able oil circuit breaker. Other replacements include entire module exact matching swap designs with the only difference being the internal circuit breaker now utilises vacuum interrupters encased in solid-dielectric resin. Newer indoor designs offer comparative or even slightly smaller installation footprints.

Outdoors, solid-dielectric Re-closers are smaller and weigh less than their SF_6 counterparts. A Nu-Lec U Series solid-dielectric model weighs 146 kg and is significantly smaller than the N Series 327 kg SF_6 model. This same installation footprint reduction can been seen in rural substations also which use Re-closers mounted on steel structures within the yard as a convenient self sufficient circuit breaker replacement. In the case study area substations, 16 of the 72 SF_6 insulated circuit breakers below 66 kV where N Series Nu-Lec Re-closers, utilised as substations permanent circuit breakers.

Furthermore, and maybe most importantly, the continued investment in solid-dielectric/ vacuum circuit breakers over the last decade has reduced their price to that lower then SF_6models. With comparative maintenance regimes and installations sizes, zero emissions and cheaper purchasing costs the solid-dielectric design is unsurprisingly gaining dominance in the market.

Table 5-1 Vacuum /Solid-dielectric Implications Summary

Item	SF6 CB	Vacuum/Solid-dielectric CB
Case study Substation units effected	72	-
Case study Re-closer units effected	195	-
$\mathbf{SF_6}$ (kg) total	485.4	0
Annual Leakage emissions $\mathbf{SF_6}$ (kg)	4.32	0
Annual Leakage emissions $\mathbf{CO_2}$ equiv (tonnes)	103.2	0
Typical unit cost ($)	20,000*	18,000*
Maintenance requirements	Comparative	Comparative
Installation size	Comparative	Comparative

*Prices based on 22kV Re-closer models

5.3 Vacuum Interrupters Encased in Dry Air

5.3.1 Compressed Dry Air Designs

For 66 kV circuit breaker applications, a high voltage withstand vacuum interrupter has been developed. The development was made possible by the optimisation of the electric field with axial field electrodes and encapsulation of the interrupter within composite insulation. An environmentally friendly insulation type gaining popularity is that of high pressure dry air.

Figure 5-3 Sumotomo Dry-Air/Vacuum 66kV CB

Conventional vacuum circuit breakers in the 66 kV range utilise SF_6 gas filled tank enclosures to externally insulate the internal vacuum interrupter. Dry air insulated vacuum interrupter designs seek to replace the SF_6 gas with the compressed dry air medium within a similar installation footprint/design size. It was additionally theorised as a possible retro fitting direct replacement option.

The dielectric strength of dry air is about one third that of SF_6 gas. Early designs accommodating the additional gas and larger container sizes required for a similar dielectric response resulted in actual equipment being unsatisfactorily large. To reduce equipment sizes down to that similar to existing SF_6 designs some additional dielectric strategies were undertaken. These strategies involved increasing the pressure of the sealed dry air to a higher value than that of sealed SF_6 and also adopting dielectric moulded coverings for the internal high voltage conductors. These dielectric design adjustments meant that the overall circuit breaker could be made to a similar size to that of existing SF_6 designs.

One consequence of utilising the insulation medium at higher pressures than existing designs is that: “the container and bellows of the vacuum interrupter must withstand excessive stress” (Matsui, et al., 2006). This consequence has been overcome by means of an alternatively designed VI structure in which the bellows it not adversely effected by external pressure increase.

There are currently both dead-tank and live-tank 66 kV dry-air/vacuum circuit breakers available on the market. The Japanese company Sumotomo produces a 66 kV dead-tank circuit breaker with integrated low voltage bushing type current transformers similar to that of the Siemens 3APDT1 SF_6 design. Alternatively, Alstom now produces a 66 kV dry-air/vacuum VL109 live-tank as a direct replacement for its SF_6 type GL309.

One design altercation that Alstom noted in its development of the GL309 replacement was that of the lower required stoke of the vacuum interrupter. The modified mechanical energy balance meant optimising the mechanical chain/spring operating mechanism to make it possible to keep their established FK-type operating system.

"An environmental life-cycle analysis has shown that the vacuum technology-based VL109 compared to its SF_6 equivalent, has a climate change impact 24 percent lower but with a higher electrical and mechanical lifetime and reliability." (Dr. Drews, 2013)

5.3.2 Implications of Dry Air Designs on Case Study Area

With both live-tank and dead-tank dry-air/vacuum designs now available in the 66 kV circuit breaker range, it is possible that 100% of case study circuit breakers in this range could be eventually replaced with this technology. The available technology enables zero in-service equipment SF_6 emissions. However, with only limited companies offering dry-air designs, awaiting a greater market spread may be warranted in any across the board replacement strategies to avoid type fault consequences.

Rising SF_6 amounts associated with ongoing replacement of obsolete oil insulated 66 kV circuit breakers could be also be reduced with dry-air/vacuum alternatives. Currently the 119 SF_6 filled, in-service, dead and live-tank 66 kV circuit breakers within the case study area attribute 238.5 tonnes of annual CO_2 equivalent emissions in leakage. Annual SF_6 emissions and handling activities could be greatly reduced with a phased replacement of aging oil and SF_6 filled 66 kV circuit breakers

Maintenance wise, Transgrid's current regime suggests that a vacuum circuit breaker requires a minor maintenance every four years as opposed to a SF_6 model only requiring a detailed inspection in the same time frame. However, a minor maintenance for a vacuum circuit breaker requires the same number of activities as a detailed inspection for a SF_6 circuit breaker and would approximate the same personnel labour hours cost.

One of the great design philosophies of circuit breaker manufactures is to deign equipment similar to, or smaller than, that of existing equipment installation footprints. This is especially important in substation design where phase clearances and equipment spacing is of fundamental concern. There has been no exception to this philosophy in the development of SF_6 free equipment with very few designs making the market that can not directly compete with existing equipment installation sizes. Thus, making any possible future replacement options as straight forward an activity as possible.

Additionally, investigations into equipment pricing have shown that currently the leading Japanese manufactured 66 kV dry-air/vacuum dead-tank is $36,000 cheaper than the leading European manufactured SF_6model. Arguably national economic factors and company "quality assurance" marketing could reflect in the price difference, however, both designs advertise similar functionality.

Table 5-2 Vacuum/Dry Air Implications Summary

Item	SF6 CB	Vacuum/Dry Air CB
Case study Substation units effected	119	-
$\mathbf{SF_6}$ (kg) total	1121.7	0
Annual Leakage emissions $\mathbf{SF_6}$ (kg)	9.98	0
Annual Leakage emissions $\mathbf{CO_2}$ equiv (tonnes)	238.6	0
Typical unit cost ($)	105,000*	69,000*
Maintenance requirements	Comparative	Comparative
Installation size	Comparative	Comparative

*Prices based on Siemens 3APDT1 (SF_6) and Sumotomo DT VCB (vac/dry-air)

5.4 Current Transformers

Live-tank circuit breakers utilise one third of the insulation gas required in dead-tank designs, but require external current transformers. Additional SF_6 usage reductions can be made by utilising live-tank circuit breakers with non-SF_6 adjacent current transformers.

5.4.1 Oil Current Transformers

Oil filled current transformers may seem dated but they may still present some relevance considering the environmental potency of the SF_6 alternatives. Mineral oil-based transformer oil used in CTs can be made from either naphtha or paraffin. The production of more commonly used naphtha , requires extraction from crude oil and further refining processes. Being as naphtha is just one of many refinery products, its share exhibits a moderate production energy requirement; 1.6 MJ (0.44 kWh) per kilogram of transformer oil produced (Lippiatt, 2007). Based on these figures each tonne of transformer oil refined in a NSW would produce 387.2 kg of CO_2 emissions. Interestingly, 1.8 kg of in service SF_6 exhibit a similar amount of CO_2 equivalent emissions annually.

To recap from section 4.8, traditional oil insulated CTs most commonly consist of a “hairpin” primary conductor that loops down though multiple toroidal, paper insulated current transformers all submerged in insulating oil. The submerged current transformers are house in a tank at ground potential whilst the hairpin extends up though the post porcelain housing to the high voltage conductors.

The concerning transformer oil additive Polychlorinated biphenyls (PCBs) were banned in 1975 (Australian Governement Department of Environment, 2014). Monitored transformer oil can achieve a 30 year plus life span. Unlike a power transformer the secondary windings of a CT expects minimal current flow and intense heating of the oil is uncommon. The oil is also rarely subject to electrical arcing and so carbonising is also uncommon. Moisture content within the oil is the main concern which can adversely affect the winding’s paper insulation properties. One of the benefits of the aged technology is that experience in oil testing can predict oil degradation rates and CT failures.

As SF_6 is environmentally potent to the atmosphere, oil can also be a pollutant the ground and water ways. Substations have accommodated oil equipment for the majority of their existence and are equipped with bunds and oil spill kits however this pollutant property should be noted.

5.4.2 Implications of Oil Current Transformers on Case Study Area

It was found that 138 SF_6 CTs account for 4239 kg of SF_6 gas in the case study area and contribute for more than 900 tonnes of equivalent annual CO_2 emissions in leakage. A substantial SF_6 reduction could be made with the uptake of an alternate current transformer medium. Oil filled current transformers do require more regular maintenance and monitoring than SF_6, however these savings could be outweighed in the future if harsh SF_6 emissions fees and regulations are imposed.

“Environmental regulations on greenhouse gasses require SF_6 be handling carefully, and recycling where possible. This can create additional installation and repair costs, depending on local laws.” (Holman, 2013)

Although Oil filled CTs are not without their own inherent costs they are slightly cheaper to purchase then SF_6 CTs and maintenance staffs are confident with the established technology. Power utilities are also already equipped to handle and maintain the assets, making them a viable possibility.

Table 5-3 Oil Current Transformers Implications Summary

Item	SF6 CT	Oil CT
Case study units effected	138	-
$\mathbf{SF_6}$ (kg) total	4239	0
Annual Leakage emissions $\mathbf{SF_6}$ (kg)	37.72	0
Annual Leakage emissions CO_2 equiv (tonnes)	901.7	0
Typical unit cost ($)	9000*	8000*
Maintenance requirements	Limited	Periodical monitoring
Installation size	Comparative	Comparative

*Prices based on 132kV single phase units, 66-132kV range

5.4.3 Non-Conventional Current Transformers

The exciting new developments in non-conventional current transformers and their applications could comprise a separate dissertation in themselves. This small section seeks to present a brief summary of the technology and their relevance in reducing the use of SF_6 gas, in particularly in live-tank installations utilising SF_6 insulated adjacent post CTs.

"Today non-conventional current transformers (NCCTS) have achieved high performances with a very small volume. In addition their digital outputs comply with the most stringent requirements of protective relays and meters. The designs take into account the harshest environmental conditions of temperature, vibrations and electromagnetic compatibility." (Roussel, et al., 2001)

Two systems are commonly employed in the NCCT field. The first of which is known as a Rogowski coil, named after its operating principals definer in 1912, it has seen some high voltage applications since 1986 onwards. The second is based on the Faraday Effect of polarised light interacting with a magnetic field.

The Rogowski coil has been utilised in laboratories for many years but now also poses a case for continual industrialisation into high voltages. The Rogowski coil's linear voltage output takes advantage of Ampere's theorem and the instantaneous measure of the di/dt. Its inherent linearity gives it many advantages including the possibility of reducing winding ratio varieties (standardisation potential) and excellent response in transient states (zero saturation, hysteresis and residual flux).

"In 1845 Michael Faraday discovered that the polarisation plane of polarised light rotates as it passes through a piece of glass placed in a strong magnetic field and propagated parallel to this field. The polarisation rotation angle (F) is proportional to the circulation of the magnetic field (H) along the optical path (L)." (Teyssandier, 1995) (see fig 5.4).

The Faraday effect-based optical principal is achieved by means of optical crystals or fibres. In both cases a polarised, monochromatic light source with a single frequency is required. The optical information is conveyed to the protection, control or metering relays by means of optical fibre cabling.

"Converting the optical signal into an electrical signal is achieved by comparing the light beams emitted and received, generally using polarising- separating prisms combined with photodiodes which convert the light signal into an analogue electrical signal." (Teyssandier, 1995)

The optical crystal NCCT utilises one or more crystals surrounding (or in close proximity) to the conductor through which the current to be measured is flowing. Whereas, the fibre technique uses a monomode optical fibre wound several times around the primary conductor.

The primary insulation of NCCT is simplified relative to conventional free-standing CT. The insulation of NCCT is provided by means of conventional supporting porcelain or composite insulator. The composite insulator has an advantage that an optical fibre can wound through the polymer to ground. This is seen as reliable and non-expensive form of insulation.

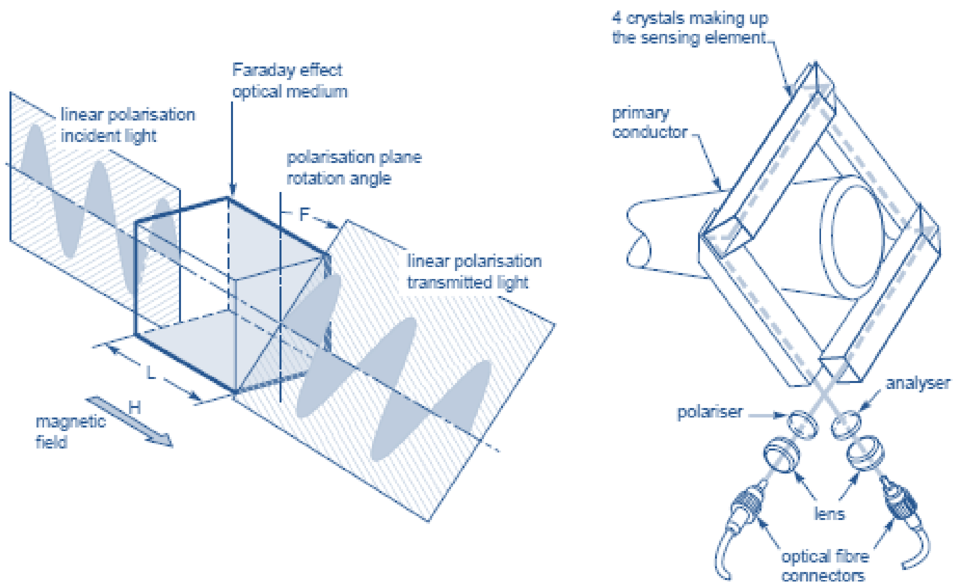


Figure 5-4 Graphic Representation of Faraday Effect (left) Faraday Effect Current Sensor (right)
Source: (Teyssandier, 1995)

5.4.4 Implications of Non-Conventional Current Transformers on Case Study Area

Not only could non-conventional current transformers possibly replace the 138 SF_6post CTs in the case study area but there are also design concepts to retro-fit NCCTs to live-tank conductor connections. This retro-fit concept could in affect benefit a live-tank circuit breaker with the incorporated CT advantages that modern dead-tank designs boast, however with one third the insulation gas requirements.

As stated previously the 138 SF_6 CTs account for 4239 kg of SF_6 gas in the case study area and contribute for more than 900 tonnes of equivalent annual CO_2 emissions in leakage. Any reduction in there usage would certainly be environmentally beneficial. A replacement dead-tank design with incorporated low voltage bushing CTs is one reduction strategy in replacing a SF_6 live-tank circuit breakers with SF_6 post CTs combinations. However, replacing the SF_6 post CTs with SF_6 free alternatives and keeping the existing live-tank circuit breaker with its reduced insulation requirements could result in further reductions then simple dead-tank replacement.

Substations with completely digital secondary systems are the next logical step in substation design. NCCTs offer HV hardware with digital, single wire outputs ideal for digitised modern protection and control relay systems. Another advantage is that CT ratios can be changed with software

With NCCTs direct bus mounting is possible, as well as horizontal mounting or assembly directly on the circuit breakers. “The total substation footprint can be reduced by as much as 15 to 25%.” (Alstom, 2012)

One of the main promising features of NCCTs is the possibility of their integration into the 330 kV plus ranged circuit breaker applications. This range is almost exclusively of live-tank construction in Australia. Oil CTs in the extra high voltage range (500 kV and above) were non-existent in the case study area and the 330kV oil CTs are extremely large. The adaption of NCCTs is this range could save large amounts of space as well as dramatically reducing SF_6 gas usage. An EHV dual interruption chamber SF_6 circuit breaker with integrated NCCTs on either end would also eliminate the problem known as blind spot that is inherent to most live-tanks with adjacent post CT installations.

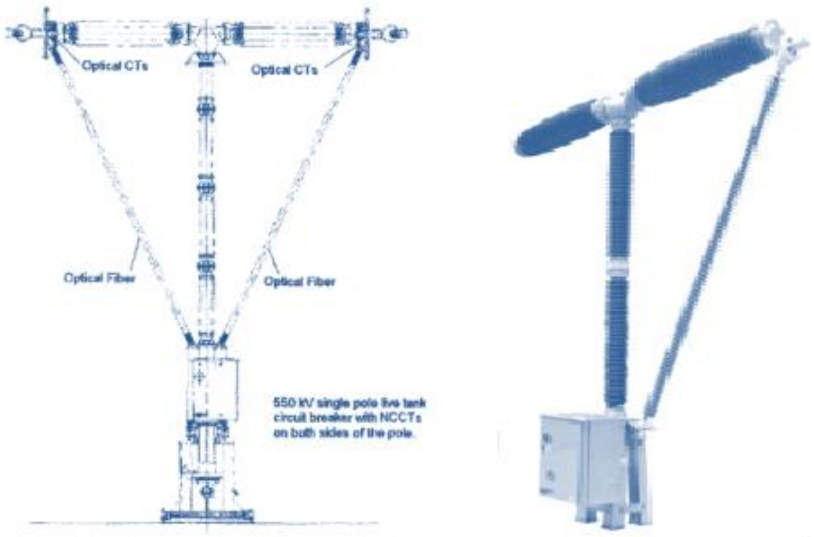


Figure 5-5 Draft Design of a Live-tank CB with Optical CTs (left) Prototype (right)
Source: (Roussel, et al., 2001) & (Alstom, 2012)

Unfortunately the cost of NCCTs, in particular the optical sensor varieties are extremely expensive when compared to traditional CTs. Their lower installation and maintenance costs may only be seen as completive alternatives in the higher voltage ranges.

Table 5-4 Non-Conventional Current Transformer Implications Summary

Item	SF6 CT	Non-Conventional CT
Case study units effected	138	-
$\mathbf{SF_6}$ (kg) total	4239	0
Annual Leakage emissions $\mathbf{SF_6}$ (kg)	37.72	0
Annual Leakage emissions CO_2 equiv (tonnes)	901.7	0
Typical unit cost ($)	9000*	40,000*
Maintenance requirements	Limited	Undetermined
Installation size	Standard	Significantly reduced

*Prices based on 132kV single phase units, 66-132kV range (SF_6 and optical sensor)

5.5 Octafluorocyclobutane (c-C_4F_8)

5.5.1 Octafluorcyclobutane as an Insulating Gas

There exist many fluorocarbons with a much lower GWP than SF_6. Octafluorocyclobutane ($c-C_4F_8$) also known as Perfluorocyclobutane is one such fluorocarbon that has been considered as an electrical insulation gas. Like SF_6, c-C_4F_8 is a very stable, electronegative gas.

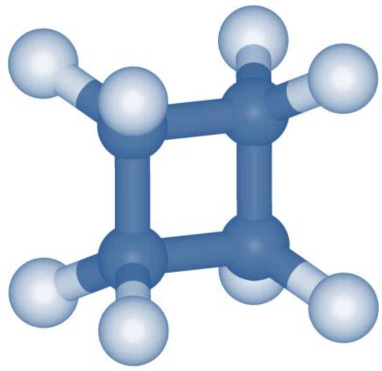


Figure 5-6 Molecular Model of Octafluorocyclobutante

"Its combination of electro negativity, high molecular weight, and chemical stability is responsible for its outstanding electrical properties" (Blodgett, 1959).

Properties of c-C_4F_8, like SF_6, greatly reduce the tendency of electrons to from a conductive path.

Unlike SF_6 however, c-C_4F_8 has been identified by the Australian Government Department of Climate Change and Energy Efficiency as having a GWP of 8,700 as opposed to the 23,900 rating of SF_6. The 64% less GWP of c-C_4F_8 corresponds to half as much warming effect as SF6 at an identical pressure considering the difference of molecular weight between c-C_4F_8 (200 g/mol) and SF6 (146 g/mol). The dielectric strength of c-C_4F_8 is suggested to be even greater to that of SF_6, about 3.6 times that of air as opposed to 3 times in the case of SF_6. A engineering paper from Kyoto University, Japan in 1999 found that it's dielectric strength can be anywhere from 1.11 to 1.80 times that of SF_6.

A possible disadvantage of the use of c-C_4F_8 is however the presence of the carbon atoms which create conductive dust particles post decomposition. This insulation deteriorating property limits c-C_4F_8 to applications where it would not typically be subject to intense electrical arcs that accelerate decomposition. Hence, c-C_4F_8 could be suitable for purely insulation purposes associated with circuit breakers (separate CTs, external insulation for VIs) but would be unsuitable as a specific current interruption medium.

An additional "disadvantage of c-C_4F_8 is it s high price, which is now several times higher than that of SF_6. However, this is considered mainly due to the fact that c-C_4F_8 is not used in large quantities. There is an enough possibility of considerably reducing the price by applying a large amount of c-C_4F_8 in power industry." (Takuma, et al., 1999)

5.5.2 Implications of Octafluorocyclobutane on Case Study Area

Although research in Octafluorocyclobutane as an insulation gas has been conducted for many decades the substances is still merely a consideration compared to the traditional SF_6. Industrialised applications of the gas in the power industry are at this stage experimental and the Australian power community is oblivious to any commercially available products. However, the reduced GWP of c-C_4F_8 could see the substance gain more attention as an intermediate technology medium given the rising GWP concerns associated with SF_6.

If the application of the gas was deemed appropriate for non-current-interruption insulation purposes, c-C_4F_8 could be utilised for a number of purposes in the case study area. Examples of which would include; replacement gas insulation for live-tank circuit breaker adjacent post CTs as well as the external insulation for VI circuit breakers requiring such a medium.

The case study area's 138 gas insulated post CTs could benefit from the replacement gas. The 4239 kg of CT insulating gas would when subject to the predictive annual leakage rate of 0.89% would only emit 328 tonnes of equivalent CO_2 emissions when filled with c-C_4F_8 as opposed to 902 tonnes when filled with SF_6.Filling with c-C_4F_8 equates to a reduction of 574 tonnes of equivalent CO_2 emissions annually.

Additionally, the 42 case study circuit breakers and the estimated 195 Re-closers in the medium voltage range that use SF_6 to externally insulate VI used for current breaking could benefit from c-C_4F_8 filling in these non-arc subjective applications. The 42 circuit breakers contribute 96.4 kgs of SF_6 insulation whilst the 195 Re-closers account for a further 350 kg. This 446.4 kg of SF_6 emits 94 tonnes of equivalent CO_2 emission annually in leakage. A c-C_4F_8 filled alternative network would emit only 34.5 tonnes, providing a reduction of 59.5 tonnes of annual CO_2 emissions

As mentioned earlier, the use of in Octafluorocyclobutane is only a consideration at this stage. The refilling of SF_6 equipment with c-C_4F_8 could result in warranty voids and is not recommended outside of dedicate approved trial experimentation.

Equipment Maintenance and monitoring regimes of c-C_4F_8 filled equipment would be expected to remain relatively similar to that of SF_6 equipment requiring periodical gas purity analysis. Additional carbon concentration sampling may be required in a similar fashion to the monitoring of oil filled equipment to monitor the deterioration of the gas. Similarly to oil, testing over time could predict the need c-C_4F_8 gas replacement given carbonising trends.

Table 5-5 Octafluorocyclobutane Implications Summary

Item	SF6 Equipment	c-C_4F_8 Equipment
Case study units effected:		
Current transformers	138	-
Substation Vacuum/$\mathbf{SF_6}$ Circuit Breakers	42	-
Re-closers Vacuum/$\mathbf{SF_6}$	195	-
$\mathbf{SF_6}$ (kg) total	4662	-
Annual Leakage emissions $\mathbf{SF_6}$ (kg)	41.49	-
Annual Leakage emissions $\mathbf{CO_2}$ equiv (tonnes)	991.7	361.0
Typical unit cost ($/kg)	55	150*
Maintenance requirements	Comparative	Comparative
Installation size	Comparative	Comparative

*Price based on international currency conversions

5.6 Leakage Monitoring

5.6.1 Leakage Calculation

Circuit breaker SF_6 gas leakage is an important issue which should be closely monitored. Circuit breakers containing SF_6 are fitted with "loss of gas" alarms however the alarms purpose is primarily for circuit breaker functionality reasons as opposed to environmental concerns. A SF_6 filled circuit breaker requires the correct amount of SF_6 for contact dampening, operation below a minimum amount of SF_6 can cause damage to contacts.

As an example of leakage amounts the popular 66 kV Siemens 3APDT1 dead-tank circuit breaker has been chosen for analysis. There was found to be 47 Siemens type 3APDT1 dead-tanks in the case study area which equates to 25% of the total 66 kV case study circuit breakers and 37% of all SF_6 filled circuit breakers in this range.

The 66 kV Siemens 3APDT1 contains 13.7 kg of SF_6 gas at a preferred in-service pressure of 6 bar at 20 degrees Celsius. The 3APDT1 has a low SF_6 alarm at 5 bar. The molecular weight of SF_6 from table 2.1 is shown as 146.05 g/mol

Number of moles:

$$n_1 = \frac{m_1}{mol\ weight} \tag{5.1}$$

Where:
n_1=initial number of moles
m_1=initial mass (g)
$mol\ weight$ =mol weight (g/mol)

$$n_1 = \frac{13700}{146.05} = 93.80\ moles$$

Utilising the Ideal Gas Law for the 6 bar normal condition to determine volume:

$$P_1V = n_iRT \tag{5.2}$$

Where
P_1= initial pressure ($\mathrm{N/m^2}$)
V = volume ($\mathrm{m^3}$)
n_1=initial number of moles
R = gas constant 8.314 (J/mol.K)
T= temperature (K)

$$V = \frac{n_1RT}{P_1} = \frac{93.80 \times 8.314 \times 293.15}{6 \times 10^5} = 0.381m^3$$

Now utilising the ideal gas law for the 5 bar alarm condition:
Where:
n_2= final number of moles
P_2= final pressure

$$n_2 = \frac{P_2V}{RT} = \frac{5 \times 10^5 \times 0.381}{8.314 \times 293.15} = 78.16\, moles$$

Remaining mass:

$$m_2 = n_2 \times mol\ weight \tag{5.3}$$

Where:
m_2 = final mass (g)
n_2= final number of moles
$mol\ weight$ =mol weight (g/mol)

$$= 78.16 \times 146.05 = 11415g = 11.415kg$$

Mass of leakage loss before alarm is raised:

$$m_{loss} = m_1 - m_2 \tag{5.4}$$

$$m_{loss} = 13700 - 11415$$

$$\boldsymbol{m_{loss} = 2.285\ kg}$$

5.6.2 Leakage Monitoring

From 5.6.1 it can be seen a typical 66 kV SF_6 circuit breaker installation could emit upwards from 2 kg of SF_6 gas before an alarm is raised, equating to almost 48 tonnes of equivalent C02 emissions $(2 \times 23{,}900)$. Thus, repetitive SF_6 leakage to the point of alarm is preferably avoided.

Leaks are most commonly found within the proximity of faulty vessel or bushing seals. Leaks are usually slow releasing and can take months to reach alarm activating levels.

Leaking SF_6 gas is transparent and odourless in nature making human detection extremely difficult. This detection difficulty is further compounded by the fact that entire sections of substations can sometimes experience months of non-personnel presence. By the nature of HV equipment also, SF_6 containing vessels are commonly situated outside safe HV clearance distances making access to equipment only possible during de-energised outages. Raising of the “loss of SF_6” alarms is the most common initial indication that a leak exists. Additionally, SF_6 filled CT’s “loss of SF_6” alarms are commonly grouped with the circuit breakers, there for leakage monitoring of such equipment is heavily reliant on periodical gauge inspections by means of personnel sighting and recording.

When a detected leak is pin pointed and repaired it is preferable to monitor the leakage area to determine if the leak has been rectified. Simply awaiting the activation of an additional “loss of SF_6” alarm months later should never considered a satisfactory leakage repair monitor. Specialist equipment including gas detectors and infra-red cameras are preferred methods.

Simple gas detectors known as “sniffers” may be low cost but can be inadequate as they rely on proximity to the leak to provide leak identification. Such proximity to SF_6 leaks in substation environment is often unavailable due to equipment arrangements and HV safe approach distances.

A far better option is infra-red camera technology. Infra-red cameras can visualize leaks in real time enabling inspection without the need for supply interruption. Cameras can trace leaks to the source and identify leaks meters away. Specialist models offer additional advantages such as temperature measurements, a range of gas detections and GPS coordinate recording.

“Infra-red SF_6 detection video technology operates in the 10.3-10.7 µm spectrum range.” (FLIR Systems, 2014)

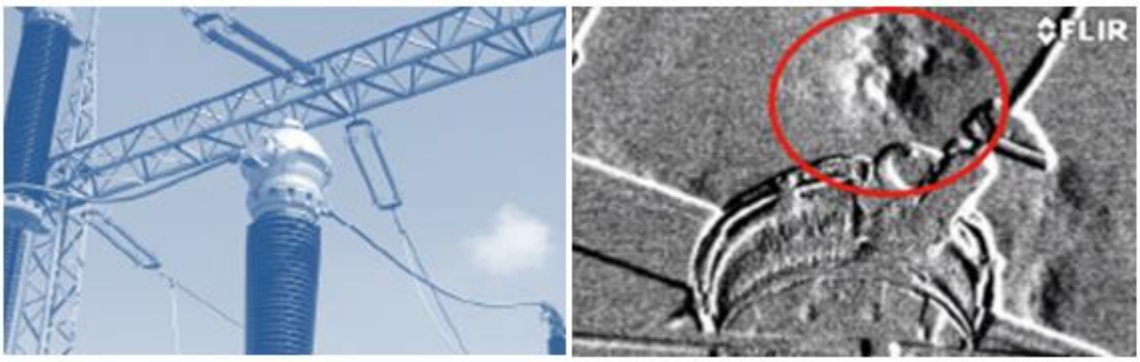


Figure 5-7 SF6 CT (left) Infra-red Imagery of Leaking SF6 CT (right)

5.6.3 Implications of Leakage Monitoring in Case Study Area

Unfortunately some utilities only own one or two infra-red cameras to monitor hundreds of SF_6 circuit breakers across substantial geographical distances. Camera monitoring is usually only considered after "loss of SF_6" alarms have been raised numerous times on an individual circuit breaker. Onus is directed onto maintenance staff to successfully identify and rectify any leaks using proximity detectors which can be understandable difficult.

With an estimated 0.89% of capacity expected to leak annually this equates to approximately 90 kg of the 10,216 kg case study area. At a rate of 2 kg loss before alarm indication per circuit breaker this insinuates 45 leakage alarm incidences per year in the case study area.

The cost of quality infra-red SF_6 leakage detection cameras is admittedly quite expensive. However, SF_6 leakage amounts prior to alarm activation are extremely costly to the environment not to mention the cost of SF_6 refilling and required maintenance staff labour. Camera monitoring of all leakage repairs would drastically reduce repetitive leakage and further maintenance staff call outs.

Upon the raising of a "loss of SF_6" alarm common practice with in the case study area is to call out a maintenance technician to top up the leaking circuit breaker. This is done immediately to avoid non-function of the circuit breaker which will normally "lock-out" with a further 0.2 bar pressure loss of SF_6 gas (typically). Lock-out renders the circuit breaker inoperable to avoid detrimental contact damage that can occur within the circuit breaker due to lack of the dampening medium. The secondary function of the SF_6 gas is to act as a dampening medium for the contact opening and closing operation.

From this point, an equipment outage for leakage repair is often scheduled. If this scheduling also prompted the coordination of the camera equipment's services a reliable leakage repair could be expected every time. Such scheduling arrangements could require further investment for additional cameras, however first time repairs, SF_6 consumables and environmental savings as well as reduced equipment revenue losses achieved may far outweigh additional purchasing costs.

For geographically large utility coverage areas a profitable strategy could be to base cameras at the centres of sub-regions to reduce travelling costs. A single camera based at a central location within the case study are could significantly reduce repetitive leakage events

Table 5-6 Leakage Monitoring Implications Summary

Item	SF6 detector	SF6 Camera
Case study units effected	795	795
$\mathbf{SF_6}$ (kg) total	5627	5627
Annual Leakage emissions $\mathbf{SF_6}$ (kg)	50.0803	Estimated 20% reduction
Annual Leakage emissions CO_2 equiv (tonnes)	1197	Estimated 20% reduction 837.9*
Typical unit cost ($)	200-300	130,000
Maintenance requirements	- Refill upon call out - Equipment outage - Leak identification/Repair - Await further alarms	- Refill upon call out/Leak ID - Equipment outage - Repair - Instant verification

5.7 Government Regulations

5.7.1 Government Regulations

Government regulations are a strong influence on the use of synthetic greenhouse gases in a particular country. Synthetic greenhouse gases (SGG) include refrigerants and insulating gases of which common types are hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and and most importantly for this report, sulphur hexafluoride (SF6).

On the 17th July 2014 the Abbott government repealed Australia's carbon pricing scheme better known as the carbon tax. The carbon tax, introduced 1 July 2014 by the Gillard government, sort to provide incentive to reduce the usage of environmentally potent substances. The tax required the country's largest polluters to purchase emissions permits based initially on a $23.00 cost per tonne of equivalent emitted $\mathrm{CO_2}$. Emissions were based on a substance's Global Warming Potential. Synthetic gases exhibit high GWP (23,900 in the case of $\mathrm{SF_6}$). The intent was to make their usage expensive and non-preferable in effort to encourage more environmentally friendly industry practices and developments. The cost of $\mathrm{SF_6}$ increased by a factor of ten per kilogram under the carbon tax legislation.

Post carbon tax repeal, synthetic gases in Australia are currently subject to the same regulations prior to the tax. Currently administrative arrangements under the Ozone Protection and Synthetic Greenhouse Gas Management Act 1989 require the licensing of manufacturers and importers of SGGs. In addition the Ozone Protection and Synthetic Greenhouse Gas (Import Levy) Act 1995 and Ozone Protection and Synthetic Greenhouse Gas (Manufacture Levy) Act 1995 require the payment of a levy based on the weight of gas imported.

" The application of a carbon price equivalent piggy-backed on these arrangements and required importers to continue to pay the existing levy on a quarterly basis and an additional levy based on the GWP of each gas and the relevant carbon price for the calendar year." (Swoboda, 2013)

In 2006 the European Union banned several uses of $\mathrm{SF_6}$ in its territories, including its use in double glazing, shoes and tires. The Union's reasoning for the exception in HV switchgear was that no viable alternative would be available. Recently however, several European Green political groups have put motions forward to ban the use of $\mathrm{SF_6}$ in MV switchgear given competitive alternatives exist. In 2013 Dutch Green Member of European Parliament Bas Eickhout put forward an amendment to ban $\mathrm{SF_6}$ in MV switchgear from 2020, he later compromised to only new MV switch gear beyond 2023 of which is still under debate.

Other countries and American states have also received public and political party pressure to reduce or ban $\mathrm{SF_6}$ in MV switchgear applications. Carbon pricing and tariffs are also being explored politically by the global community.

5.7.2 Implications of Government Regulations on Case Study Area

NSW utilities currently purchase $\mathrm{SF_6}$ at a rate of $55 per kilogram. A substantial rise in $\mathrm{SF_6}$ purchasing costs as a result of government regulations would undoubtedly pressure utilities to consider alternative technologies when budgeting new circuit breaker installations or maintenance regimes.

Additional $\mathrm{SF_6}$ costs would also see a more concerning response in terms of equipment $\mathrm{SF_6}$ leakage management. A price rise may see the re-evaluation of the importance of $\mathrm{SF_6}$ leakage detection cameras and alarm mechanisms. Continual refilling of leaking equipment could prove expensive. $\mathrm{SF_6}$ recovery and recycling from decommissioned equipment would also be regarded with a higher importance.

A European influenced ban on $\mathrm{SF_6}$ in MV switchgear in Australia would impact 23% (72 units) of substation circuit breakers in the case study area. The replacement of this moderate percentage within a specified time frame (say 10 years) with government incentives would actually be quite achievable. The estimated 195 $\mathrm{SF_6}$ filled field Re-closers would be a significantly larger task however. Fortunately modern Re-closer installations incorporate an overhead by-pass switch which could allow replacement without supply interruption. Cost reduced replacement strategies see only the tank portion of the existing installation replaced, leaving the control gear unaffected. Installation and commissioning costs would be an additional finance attached to any across the board replacement strategy.

Currently the NSW electrical distribution and transmission infrastructure is owned and maintained by the government. Selling or leasing of assets to private entities is however a current political debate that could affect the near future. Conservative government strategies could change when they are not personally responsible for financing the consequences of harsher regulations on $\mathrm{SF_6}$ pricing or equipment banning.

Chapter 6: Environmental, Cost & Life Cycle Analysis

Chapter Six analyses the environmental, cost and life cycle viewpoints of SF_6 in HV circuit breaker equipment with a particular focus on SF_6 equipment growth and emissions. To gain a better understanding of the benefits of the alternatives presented in Chapter Five an analysis of current SF_6 equipment growth trends and associated environmental consequences needs to be explored. Furthermore, projected outcomes of a future with no change in current HV SF_6 equipment practices and one in which SF_6 is banned tomorrow are presented in this chapter.

Emissions form SF_6 filled HV equipment is primarily proportional to the amount of stored SF_6 gas used in in-service equipment. Additional factors such as manufacturing, transportation and recycling further add to the emissions tally. SF_6 filled HV circuit breakers now form the overwhelming majority of circuit breaker infrastructure in modern HV electrical networks, particular in the higher voltage spectrum. Electrical infrastructure growths are normally projected to coincide with rises in electricity supply demands. However, despite Australia's recent reduction in demand, the continuing replacement of obsolete oil circuit breakers and investments in a greater percentage of a renewable energy generation mix has seen SF_6 circuit breaker numbers continue to grow.

Australia is currently aiming in to reduce its annual greenhouse gas emission levels to five percent below its year 2000 level by the year 2020. Although in the grand scheme, SF_6 emissions from electrical equipment currently amount to less than 1% of national emissions, projected growth rates are concerning and all reductions considered beneficial to the national objective.

With the continued replacement of all HV oil circuit breakers expected to be completed by 2025, HV networks, particularly in applications above 66 kV will most likely utilise SF_6 circuit breakers in near 100% of applications. This projected insulating medium monopoly will leave the industry extremely vulnerable in the event of any SF_6 reductions regulations or taxes imposed by the ever increasing environmentally concerned community. In an industry already over 70% comprised of SF_6 circuit breakers in applications 66 kV and above the costs of deferring from the SF_6 reliant networks could be unachievable without phased technologies changes and developments.

6.1 Australian Electricity Demand and Infrastructure Growth

6.1.1 Australian Electricity Demand

"Population and income growth were largely responsible for the steady increase in electricity demand in Australia prior to 2006. In recent years, growth in electricity demand has moderated and electricity consumption has declined in every year since 2009-10" (Australian Government Department of the Environment, 2013).

Pre 2009 peak demand growth was considerable steady at an approximate 2% pa.

"From 2009–10 to 2013–14, annual energy usage declined by 13,613 GWh (an annual average decline of 1.8%) to 181,239 GWh." (AEMO: Australian Energy Market Operator , 2014)

A number of recent events in Australia have contributed towards the moderation of the previously rising national electricity demand. The2010/11 Queensland floods, milder eastern state weather, strong growth in photovoltaic solar generation, strong growth in energy efficient technology and increased tariffs were all seen as initiators of the demand reduction.

Significant electricity demand reductions in Australia however, have been the result of the reduced production or closure of aluminium smelters in response to less favourable economic conditions. The closure of the NSW, 300 MW, Kurri Kurri aluminium smelter in 2012, and this year's closure of the 360 MW Point Henry aluminium smelter in Victoria, have seen a reduction of approximately 5700 GWh in annual demand. Other Australian smelters have reportedly reduced production by up to 50%. Projected national electricity demand is not expect to increase to previous trend levels until 2020.

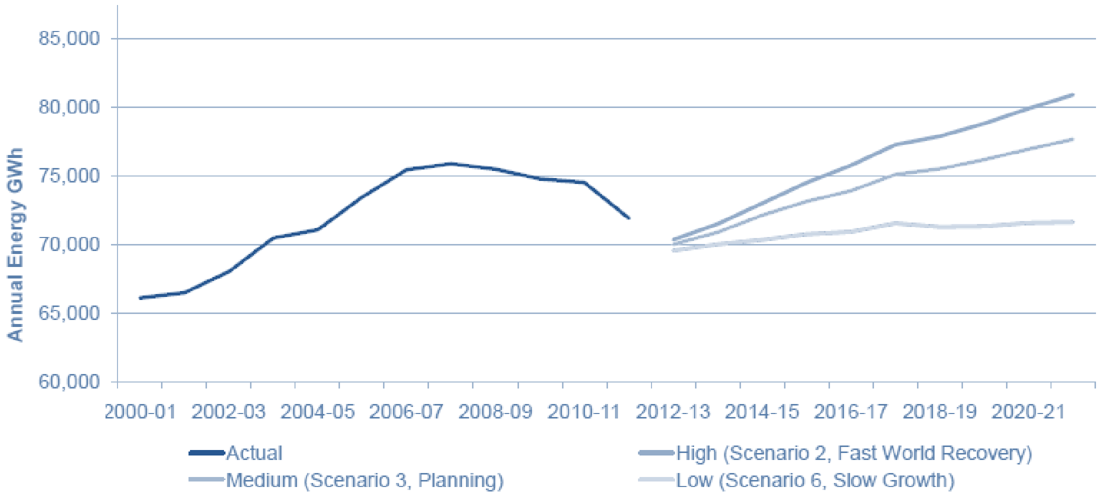


Figure 6-1 Australian National Electricity Demand Forecast
Source: (AEMO: Australian Energyy Market Operator, 2012)

6.1.2 Infrastructure growth

It is a reasonable assumption that beyond the replacement rates of aging equipment, new high voltage infrastructure in Australia would grow proportional to the national electricity demand. Aging equipment is certainly an issue in Australia's electricity infrastructure however, the 2014 AEMO Report projects a medium scenario based 0.3% demand growth in the next ten years (-1.6%min , 1.4% max).

Consequently all four NSW electricity network authorities (Ausgrid, Endeavour, Essential & Transgrid) have presented reduced to steady capital expenditure projections for the period of 2014-19. Of the four, the state transmission authority, Transgrid, presented the a brief rise in capital cost for the next three years primarily in asset replacement but trends back below its 2014 expenditure by 2019.

Prior to 2012 the aging NSW network experienced dramatic increases in capital expenditure. The coinciding of this upgrade with a number of other economic circumstances was seen to raise electricity prices. The media later termed the period "gold plating" of the network. Inevitably, public demand for a reduction in rising electricity prices, a change in government and a realisation of a newer, adequately reliable network has prompted network authorities to reduce spending.

Despite declining capital expenditure projections in immediate future new electrical infrastructure projects will still be undertaken where essential. A number of aspects will still prompt continual infrastructure upgrades but perhaps now at slightly slower than previously predicted uptakes. Additionally, many large projects budgeted and commenced prior to the 2014 expenditure reductions are still being undertaken. Many other projects that did not commence are simply being postponed, subject to post 2019 financial and electricity demand forecasts. Predictions of increased capital expenditure post 2019 are common to all NSW distribution and transmission authorities.

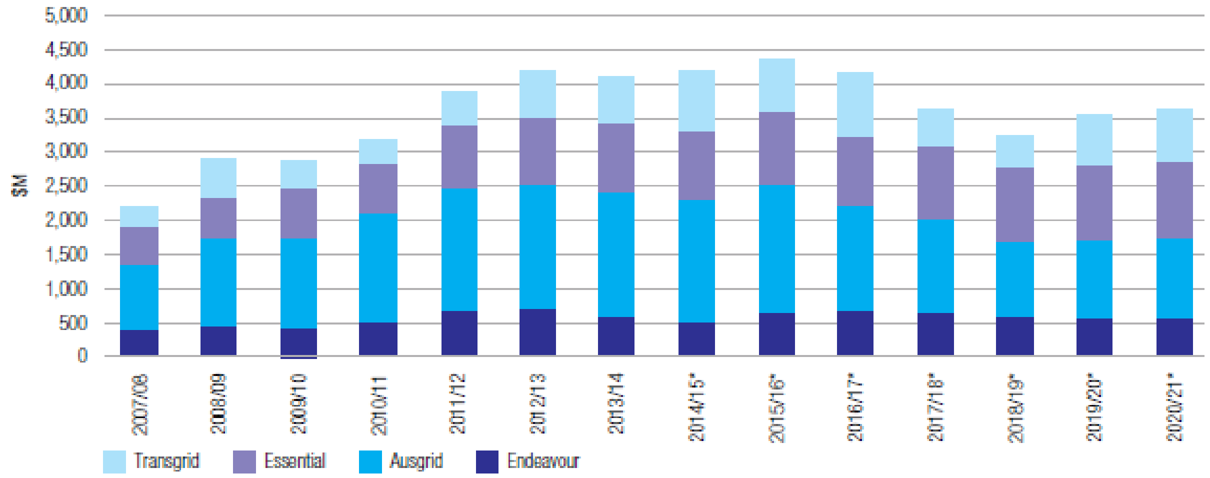


Figure 6-2 Planned Investment in Electricity Infrastructure 2008-2021

Source: (Infrastructure NSW, 2013)

6.1.3 Infrastructure Drivers

The following aspects are seen as the major infrastructure drivers in NSW's electrical networks in the coming years.

1. Aging equipment –A significant proportion of NSW electrical infrastructure still in operation is fast approaching its 40 year end of life cycle. The 1970's and 80's were a period of significant electrical infrastructure undertaking in NSW. Taking HV circuit breakers as one example, of Transgrid's 1,483 units, 29% are approaching 30 years of service, whilst 4.5% are pre 1975 models.

2. Supply reliability demand- With the privatisation of NSW electricity retail and generation providers in 2010, the state authority effectively positioned itself as a network operating and maintenance providing utility only. Reliably connecting its two customer groups, generation companies to retail end users, has become the main business objective. Network operating authorities need to maintain, develop and extend upon exiting infrastructure to provide for stringent network reliability requirements. Such requirements for non-interrupted supply are driven by the private owners of the generation and retail sectors for their respective customers.

3. Inter-regional transmission connection – The eastern states of Australia are all interconnected with electrical transmission lines operated by the National Electricity Market (NEM).
   "The capacity of inter-regional electricity trade has a direct impact on the wholesale costs and competitiveness of the national market and therefore the prices paid by businesses and households. A recent study investigating increased inter-regional power transfer capabilities in the national electricity market has demonstrated potential market benefits" (Infrastructure NSW, 2013).
   The geographical positioning of NSW in the centre of the eastern states places the states electrical infrastructure as a vital component of the NEM grid. Infrastructure upgrades to facilitate larger and more efficient inter-regional transmission are predicted within the next 20 years

4. New generation mix – Currently Australia has in place a Renewable Energy Target (RET) scheme that is designed to ensure that 20 per cent of Australia's electricity comes from renewable sources by 2020. The scheme promotes both environmental benefits and job creation but will also raise electrical infrastructure requirements for the connection of the generation sites to the national grid. By their nature, renewable generation sites are often in isolated locations and require additional infrastructure to support their integration. NSW is currently committed to seven new renewable power stations, three wind and four solar, amounting to 616 MW of extra generation capacity by 2016. Generation infrastructure is also privately funded and constructed; positioning its expenditure outside the state governments reduced infrastructure budgets.

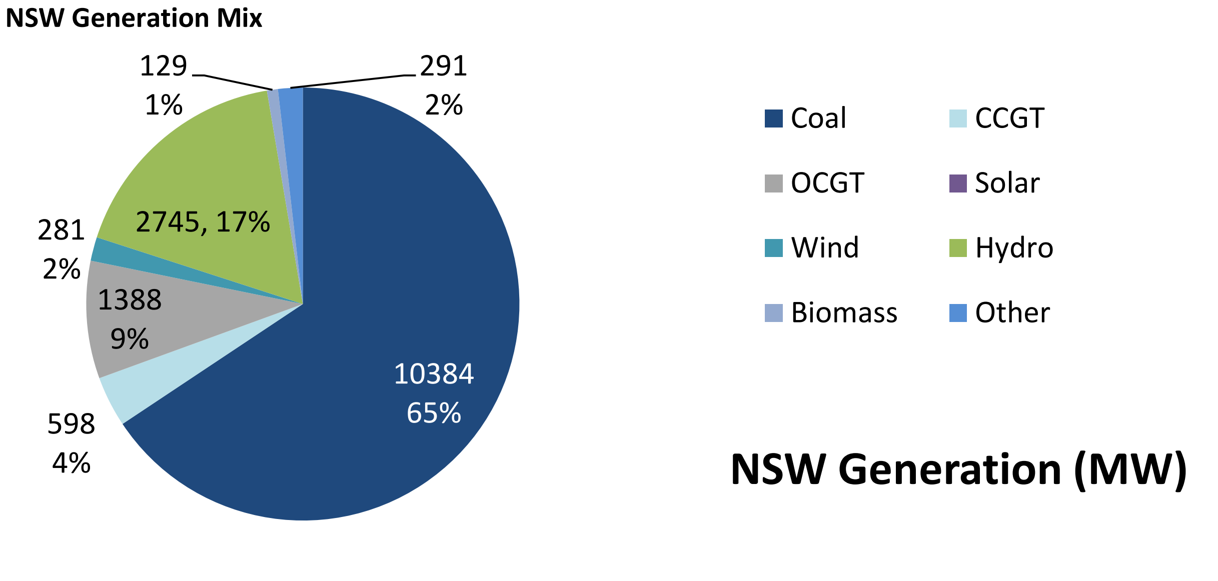


Figure 6-3 NSW Generation Mix
Source: (AEMO: Australian Energy Market Operator, 2014)

6.2 National Emissions

6.2.1 Australian Emissions

Australia is currently aiming in to reduce its annual greenhouse gas emission levels to five percent below the year 2000 level by 2020. "Over the period to 2020, the total emissions reduction required from projected baseline scenario emissions to achieve the minus five per cent emissions trajectory is 431 Mt CO_2. In 2020, the minus five per cent target equates to an emissions reduction, or abatement task, of 131 Mt CO_2 " (Australian Government Department of the Environment, 2013). The current annual emission rate of Australia is approximately 600 Mt CO_2.

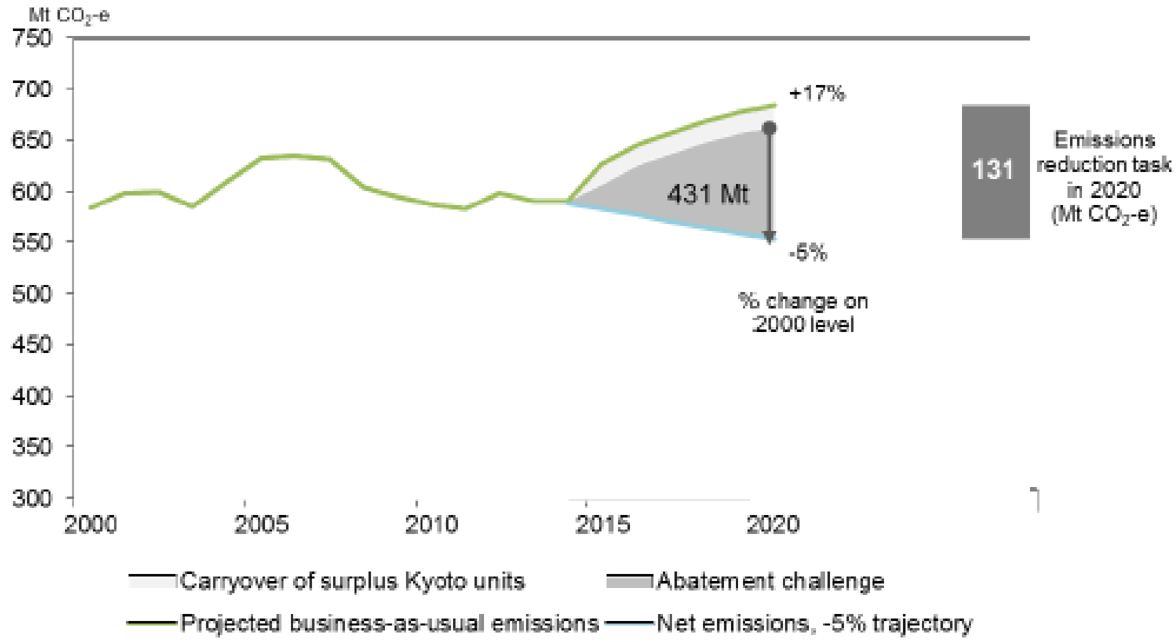


Figure 6-4 Australian Abatement Task to 2020
Source: (Australian Government Department of the Environment, 2013)

6.2.2 NSW Emissions & Case Study Perspective

Of the recently steady approximate 600 Mt CO_2 annual national emissions, the contribution of NSW in 2012 was reported to be 154.7 Mt CO_2 (NSW Government Environment & Heritage, 2012). Nearly half of all NSW emissions in 2011/12 were from the stationary energy sector, primarily from electricity production. Despite a reduction in this sector (2% decline since 2009), the burning of fossil fuels still amounts for 99% of the NSW energy sector emissions. Of the 154.7 Mt CO_2 emissions in NSW, coal fired power generation accounts for 36% (62 Mt CO_2).

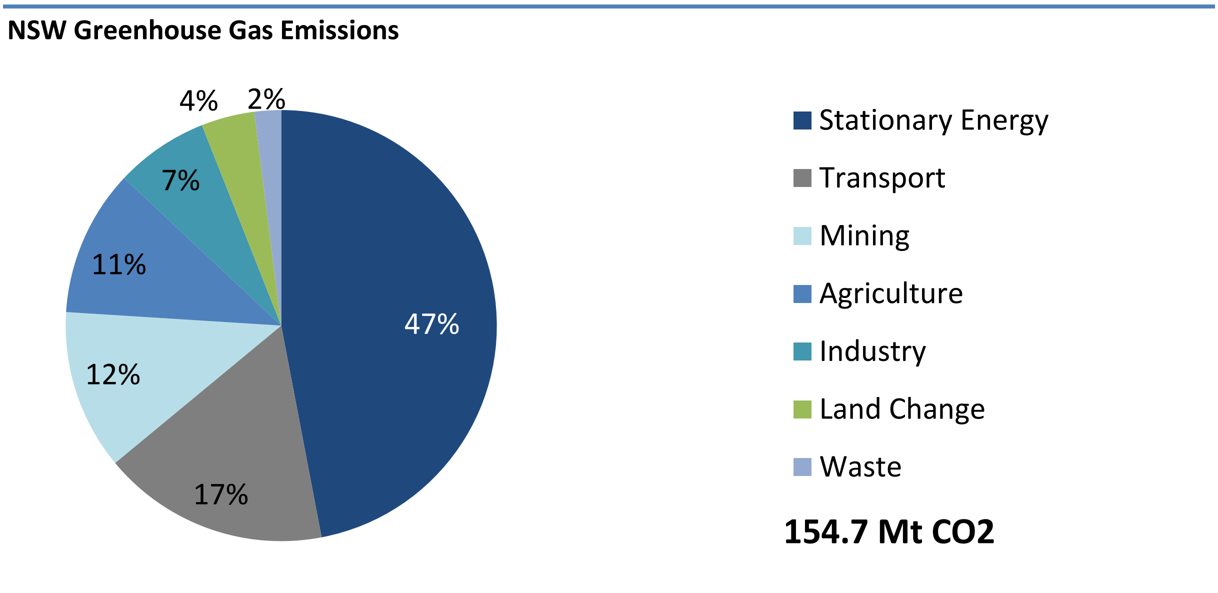


Figure 6-5 NSW Greenhouse Gas Emissions by Sector
Source: (NSW Government Environment & Heritage, 2012)

Although the niche application of SF_6 gas in high voltage switchgear would appear in a different league to the large CO_2 emission of the state's other sectors, the case study's almost three kilo tonnes of CO_2 equivalent emissions is none the less significant. With case study emissions based purely on static equipment leakage and handling activities, it is here that attention must be drawn to relative size of Chapter Four's case study area in regards to the state of NSW as a whole.

- The case study area accommodates 3.25% (237k) of the NSW population of (7.3 million)
- 9.05% (1449.2 MW) of NSW's generation capacity (16,000 MW)
- 4.88% (600 MW) of the state's power usage (12,300 MW)
- 15.8% (235) of the Transgird circuit breakers (1483)
- 9.1% (14) of the state's transmission substations (154)
- 6.2% (41) of the state's distribution zone substations (665)

Regardless of size and annual leakage amounts the case study area's 10,216 kg of stored SF_6 gas cannot be ignored. Its SF_6 filled circuit breaker equipment has a static emissions potential of 244 kilo tonnes of CO_2 equivalent (10.216×23900).

If the case study's SF_6 circuit breaker infrastructure percentage was estimated at 12% of the state's total, the NSW static emissions potential could be estimated at 2.03 Mt CO_2 equivalent. (Equating 244 kt to 12%)

Additionally the state's average leakage and handling losses could be estimated at 24.21 kilo tonnes CO_2 equivalent per year. (Equating 2.905 kt CO_2 equivalent from section 3.10 to 12%)

6.3 SF6 Equipment Emissions life cycle

6.3.1 Manufacturing of Equipment

Australia currently imports 10 to 20 tonnes of SF_6 annually, of which over 80% is estimated to be used for the filling of high voltage electrical equipment. Australia's SF_6 usage responsibility is not limited to purely its import inventory however. Consideration must also be given to the manufacturing process required to produce the HV SF_6 filled equipment servicing the Australian network whether it be manufactured locally or internationally.

Manufacturing wise, Australia accommodates very few large scale HV circuit breaker manufacturing companies. One of possible note is the Nu-Lec Industries manufacturing facility near Brisbane Airport which manufactures the SF_6 containing N-series Re-closer, however recent trends have seen their U-series solid-dielectric model become more popular. Typically the majority of HV circuit breaker equipment servicing the Australian electrical grid has been manufactured in either Europe or Japan.

"Various symposiums have reported that the emissions during the manufacturing of SF_6 equipment represent an average of 4.5% of the SF_6 used in the apparatus. This amount is aiming to be reduced by all manufacturers and may reach 1% in the future years."(Bessede, et al., 2006)

Smaller metal enclosure, dead-tank type circuit breaker models are often laser welded and then tight tested with helium. They are later filled with SF_6 and the filling mass recorded. Larger live-tank type circuit breakers require chamber insulators made of porcelain or composite. Elastomer sealing, made of ethylene propylene diene monomer (EPDM), are commonly used for the sealing of the breaker vessels. Of the final three pole design, individual pole columns are filled with rated SF_6 service pressure and tested in turn for service ability in a semi-automated process. After the test, filling gas from the insulator pole column is evacuated, stored and then reused for the next test.

Note: Emissions due to the synthesisation of SF_6 gas initially- have not been included in this emissions life cycle analysis.

6.3.2 Transportation of Equipment

Newly manufactured equipment is the filled with either nitrogen or a reduced volume of SF_6 at a pressure slightly above atmospheric to eliminate moisture ingression during shipping or storage. The filling medium is either replaced or topped with $SF_6$to the operational required amount and pressure once the circuit breaker is positioned in its installation location. Within the transportation process SF_6 emissions are most prevalent during gas handling tasks such as the multiple filling and reclaiming activities during the assembly and delivery stages. Gas can leak from fittings or hoses and is typically a result of poor practices or faulty connection hardware.

6.3.3 In-service Equipment

The primary purpose of SF_6 gas in HV circuit breakers is to extinguish quickly - extremely high temperature electrical arcs. Although SF_6 gas is one of the most reliable substances for arc extinguishment, decomposition will eventually occur and the gas purity will be compromised. Most utility companies test HV circuit breaker SF_6 gas for purity every four years (depending on individual company policy). This is achieved by the connection of a special gas analyser to the filling valve of the circuit breaker. Analysis requires a portion of the internal gas to be withdrawn, analysed, and replaced. Gas changes can be endorsed if purity is of concern.

Certain maintenance activities require the entirety of the equipment's SF_6 gas to be reclaimed by an appropriate gas recovery unit to allow for internal inspection. After the internal work is completed the equipment is placed on a vacuum for several hours and then re-filled with either new SF_6 gas or the previous SF_6 gas if deemed suitable. Emissions from equipment during their in-service life are primarily as a result of slow, long term leakage or poor gas handling activities. Leakage rates are advised at 0.89% of capacity annually and handling activities are suggested at between 2% and 0.4% of capacity each activity which occurs at a minimum every four years (handling losses taken as 1.2% per 4 yrs or 0.3% annually as average). Over a 40 year in-service life this equates to 35.6% of original capacity in leakage and 12% for handling activities.

6.3.4 Equipment Decommissioning

Once the equipment has eventually served its purpose decommissioning is required. During decommissioning, SF_6 emissions are again most prevalent during handling activities. Such handling activities include reclaiming gas, stock piling the gas at storage facilities and the recycling of the gas. The recycling stage itself can involve multiple gas movements to often clean and filter the old gas ready for re-use. A conservative estimate for emissions during entire recycling period is about 2% of recoverable SF_6. Deux, 2008, suggests modern facilities with state of the art process are advertising ambitions of less than 0.5% emissions of recoverable SF_6.

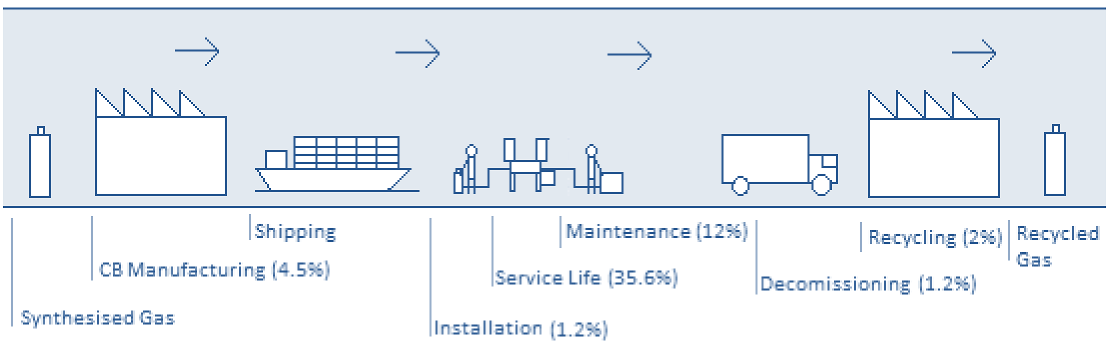


Figure 6-6 HV Circuit Breaker SF6 Emissions Life Cycle (% CB Capacity)

Life cycle emissions of a 13.7 kg SF_6 Siemens Dead-tank equate to 56.5% of its original capacity, producing 7.74 kg of SF_6 emissions or 185 tonnes of CO_2 equivalent emissions.

6.4 SF6 Usage if Nothing Changes

In a future where climate change is ignored, or simply where the percentage of SF_6 emissions as a result of high voltage electrical equipment is considered to be a limited contributor, a projected outcomes based on this dissertations findings can be examined.

Currently the case study area's SF_6 holdings for in-service HV circuit breaker equipment have been evaluated at approximately 10 tonnes. The Central Western NSW Region evaluated plays a vital part in connecting northern and southern NSW as well as linking across the Blue Mountains into western Sydney. This positioning increases its electrical infrastructure requirements of the region slightly, particularly in the transmission spectrum. With this is mind the case study area percentage of NSW SF_6 electrical infrastructure has been estimated at 12% despite its low population and zone substation numbers. This figure aligns more closely with the percentage of transmission level substations (9.1%) and Transgrid circuit breaker numbers (15.8%) considering that the majority of SF_6 equipment is in the high voltage ranges. It must be noted that the Sydney Metropolitan Area utilises numerous Gas Insulated Substations (GIS) for space saving purposes which additionally increases their SF_6 percentage.

Without change the 2.905 kilo tonnes (CO_2 equivalent) of case study annual SF_6 equipment emissions will continue to affect the atmosphere unhindered. This corresponds to approximately 24,200 tonnes of NSW CO_2 equivalent emissions annually. The NSW electricity consumption for 2012/13 was 74,373 GW, which was 30% of Australia's 249,075 GW of consumption for that period (Australian Government Bereau of Resources and Energy Economics, 2013). Using demand as a rough basis for infrastructure, Australia's National SF_6 circuit breaker equipment emissions could be estimated at 80,700 tonnes of equivalent CO_2 emissions annually.

Without change current emissions will grow. Electrical infrastructure growth will continue to utilise SF_6 gas insulated circuit breakers as oil and air blast replacement technology as well as in new installations in future years. The case study area presented a total of 61 small oil volume circuit breakers in the 66-132 kV range that have been identified for replacement in the next five years. The 37 circuit breakers in the 66 kV category will most like be replaced with a popular 13 kg filled SF_6 dead-tank. Likewise the 24 circuit breakers in the 132 kV range would expect a 27 kg filled SF_6 dead-tank as their replacement. This equates to a 1,126 kg rise in SF_6 gas insulation in the case study area in the next five years (11% increases) or 2.2% increase annually.

Transgrid circuit breaker age profile reporting (see section 4.6 or Appendix D) suggests that 29% of its circuit breaker inventory is due for replacement in the next 10 years. Approximately 300 units (or 21%) of Transgrid's inventory are obsolete oil filled circuit breakers that fall within this replacement age profile. Under a pro-SF_6 scenario these 300 units would most likely be replaced with SF_6 filled equipment. This 20% increase over the next 10 years equates to a similar 2% annual increase in SF_6 circuit breaker infrastructure and associated emissions.

Based on aging profiles, beyond 2025 the states entire HV oil circuit breaker inventor will have been (most likely) replaced with SF_6 filled equipment. From here, SF_6 amounts of in-service equipment would typically be expected to be reduced as older SF_6 equipment is replaced with more compact modern designs. However, current design trends suggest that the future replacement of aging SF_6 live-tank circuit breakers (66-132kV range) installed in the 80's and 90's will be replaced with dead-tank type designs for the advantageous integration of their favourable bushing CTs. Dead-tank designs incorporate three times the SF_6insulation of the live-tank versions they seek to replace. With approximately one third of circuit breakers in the 66-132 kV range falling into this category the overall SF_6 increase can be projected at 28% for the period of 2025-2045.

Hence any reductions seen by modern designs in the higher voltages where dead-tanks are unappropriated or the reduced need for external SF_6 CTs would be more then countered by the dead-tank volume increase in the 66-132 kV range. It is noted that a small reduction would also been seen in the replacement of aging SF_6equipment in the sub 66kV range with more maintenance friendly vacuum designs preferred. Considering reductions due to modernising equipment but also increases due to the preference of dead-tank designs, the 2025-2045 SF_6 mass in HV circuit breakers due to aging equipment is estimated at still in increasing 1% pa.

Apart from the increases due to aging equipment replacements, increases are also expected from infrastructure expansions. Currently the drop in national electricity demand and rise in consumer prices has seen reductions in state infrastructure expenditure. However in an aim to diversities Australia's generation mix to 20% renewable by 2020, NSW is currently committed to seven new renewable power stations. Each station will require connection to the state grid and subsequently some form of substation and associated HV line and equipment protection circuit breakers. If an average of 200 kg SF_6 was utilised in each of the new generation site's circuit breaker equipment a further 0.3% pa state increase in the is expected over the next 5 years to 2020.

One of the big state infrastructure prospects for NSW is the extension of the 500 kV network to allow for greater state power transmission and also assist inter-regional electrical power transfer. Currently the Bannaby to Sydney South 500 kV line is in the consultation process. 500 kV circuit breakers and associated CT equipment is at this stage exclusively SF_6 insulated and requires large amounts of the gas (+200 kg for a 500 kV CB and associated CTs). Any eventual extension in the 500 kV network, wether just in NSW or along the entire east coast would significantly increase SF_6 usage in circuit breakers.

One topic this dissertation hasn't previously explored to any real extent is that of Gas Insulated Substations (GIS). This concept of entire bus and associated circuit breaker networks and cables being completely insulated with SF_6 for space saving circumstances is fast gaining popularity. Hay Market underground 330 kV Substation in Sydney CBD is entirely SF_6 insulated (even the transformers). Bathurst has a new outdoor GIS at its Russel St Substation that was not included in the scope of the case study. GIS preference is another SF_6 increasing factor that needs to be considered in a pro-SF_6 future as it will become more and more utilised. The 66 kV Siemens GIS at Ashmont Zone Substation in Wagg Wagga NSW replaced a possible five 13.7 kg SF_6 dead-tank design (68.5 kg total) with a 270 kg SF_6 five circuit breaker GIS installation.

Furthermore to the foreseeable SF_6 circuit breaker increases due to either infrastructure changes or ageing equipment replacements, infrastructure increases are expected to rise proportionally to electricity demand. The currently declining to steady demand is expected to begin to rise again post 2020 slightly less than pre 2008 levels (1-2% pa)

Maintenance and staffing wise with no altercation to current trends, utilities will still maintain SF_6 circuit breakers via a detailed inspection every four years, minor service every twelve years and a major service every 25,000 operations. The case study maintenance teams will still attend to their 45 leakage monitoring alarms every year increasing by the same percentage of in-service equipment numbers for subsequent years to follow. Oil maintenance will no longer be required by 2025 and maintenance staff particularly in the transmission ranges will deal exclusively with the OH&S concerning SF_6 more and more regularly.

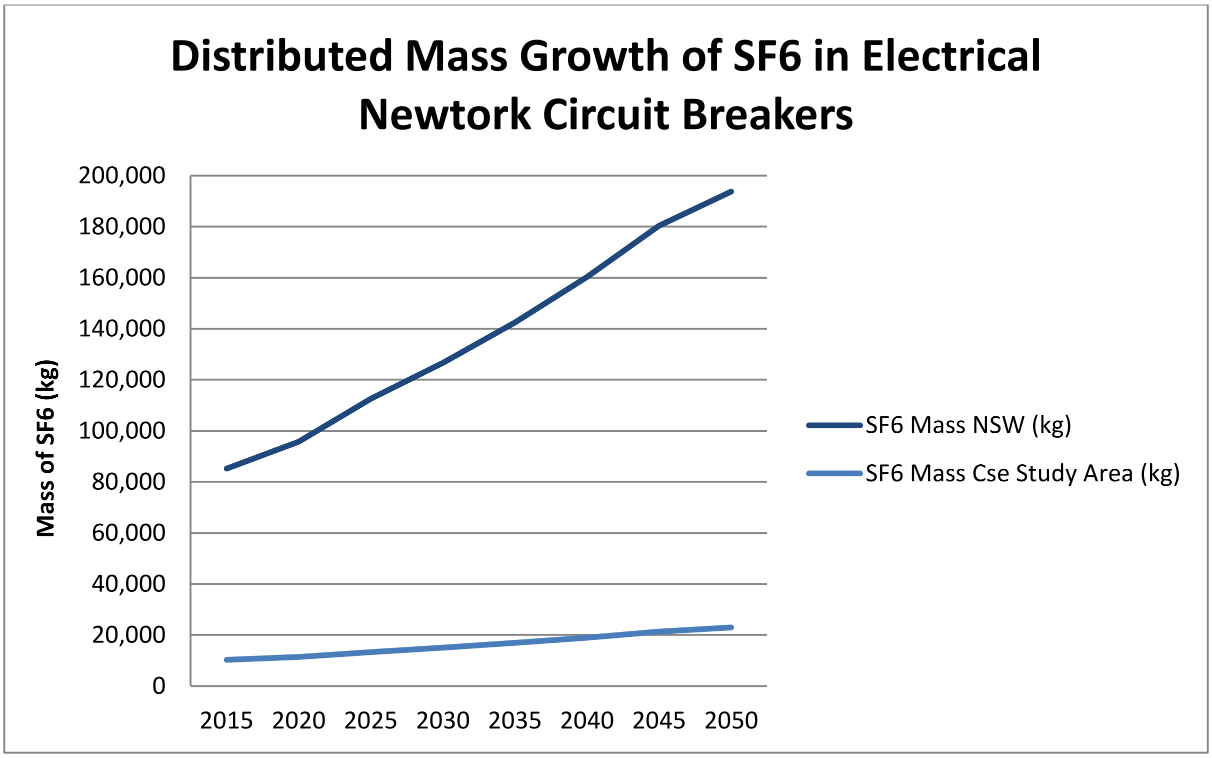


Figure 6-7 Theoretical Distributed Mass Growth of SF6 in Electrical Network Circuit Breakers

The case study area in 2035 could potentially accommodate a 923 HV circuit breakers (an increase of 264 units) and approximately 16,800 kg of in-service SF_6 (an increase of 6,600 kg)

6.5 SF6 Usage if SF6 is Banned Tomorrow

In contrast to a zero change future reality, analysis of an alternative future where the use of SF_6 in HV switchgear is banned tomorrow is worthy of assessment. Europe has already seen calls for the banning of SF_6 in medium voltage applications and with an increasingly environmentally concerned global community SF_6 bans are not entirely fictional concepts.

A complete banning of the use of SF_6in HV electrical equipment would almost be unthinkable at this stage. Over the past 30 years our electrical supply networks have become heavily invested, reliant and ultimately committed to SF_6 technology. Over 70% of our transmission network's circuit breakers utilise SF_6 gas for insulation. The infrastructure investment required to replace the banned equipment would be astronomical and could not possibly occur overnight or even within a decade.

With respect to the sheer magnitude of the proposal it is practical to break down the alternative into to sub-alternative plausible scenarios;

1. A European influenced banning of SF_6 in MV equipment
2. Phased replacement of all SF_6 insulated circuit breakers similar to that of oil and air-blast equipment replacements over the past 30 years.

6.5.1 Banning of SF_6 in MV equipment

If the case study's results are in any way representative of the nation as a whole, a nationwide ban on SF_6 in MV switch gear would actually be somewhat achievable in a reasonable time frame. Only 23% of substation circuit breakers less than 66 kV utilised SF_6 gas. These 72 SF_6units could be combined with the 26 bulk oil units that will be needed to be replaced anyway. Vacuum alternatives in this range boast just as adequate functioning capabilities and less maintenance intensive practices. Vacuum breakers do require slightly more frequent maintenance but this maintenance is less intrusive and less time consuming as a whole. Vacuum breakers are also not as susceptible to gas leakage callouts or circuit breaker lockouts.

A ten year proposal aligning with the replacement of MV oil technology would require a 400% increase in investment to extend the scope of the operation to include SF_6 circuit breaker replacements also. Further savings could be made in this field in situations where manufacturing companies offer solid-dielectric/vacuum interchangeable tanks with their current SF_6in-service designs. The Nu-Lec, N-series Re-closer falls into this category with 17 units (23%) of the required SF_6 units to be replaced in the case study area interchangeable with U-series solid-dielectric tanks. Reyrolle also offer a vacuum carriage replacement tank for their obsolete oil breaker rack-able carriage designs also.

Additional savings could also be made in situations where multiple outdoor MV SF_6 insulated circuit breakers could be replaced with indoor modular vacuum circuit breaker/bus designs. Such modular buildings can often be manufacture off site and supplied only requiring HV cable terminations and auxiliary power connection.

A non-SF_6 MV future would see reductions in maintenance call outs, gas handling activities, SF_6 filling replacement costs and equivalent CO_2 emissions.

6.5.2 Phased Replacement of all SF_6 Insulated Circuit Breakers

If a phased replacement of all SF_6 insulated switchgear was initiated the major cost component would be in the development of suitable replacements for the high voltage circuit breakers. Currently there is no mass produced non-SF_6 option for Circuit Breakers over 330 kV.

A phased replacement would see the relative immediate stop in purchasing of SF_6 circuit breakers for new and replacement installations. Much like the replacement of the oil and air-blast circuit breakers over the last 40 years, existing SF_6 equipment would see out its service life and then be replaced with a non-SF_6 alternative. This strategy initially would be quite challenging as there may not exist suitable non-SF_6 replacements for some circuit breakers in the high end voltages. This may result in specific equipment requiring staying in-service past its recommended life expectancy, increasing associated maintenance costs. Another consequence could be that new transmission developments are run at reduced voltages where reliable non-SF_6 circuit breaker designs do exist. Duplicate 132 kV transmission lines could be used instead of 330 kV lines for example while non-SF_6 technology in the +330 kV is developed. Large oil insulated or air blast designs could see a re-emergence to fill the void in the high voltage spectrum but they would need to be significantly re-designed to keep maintenance and reliability competitive.

Luckily the 500 kV network in NSW is relatively new and its circuit breakers still have a 30 plus year life expectancy allowing a larger window for technology developments in this area. Despite what strategies are employed the higher voltage spectrum is definitely the most vulnerable to SF_6 banning. Developments are undoubtedly needed in this area.

Sub 330 kV circuit breakers could be replaced as needed with the increasingly improving compressed dry-air/vacuum circuit breakers. If anything the increased investment in the technology could see it satisfy a larger proportion of the required replacement market. Perhaps using multiple vacuum interrupters in series could be an option in the higher end of the voltage spectrum. Gas insulated Substations would need to be re-thought, most probably resulting in relocating back into more space exhausting traditional sized outdoor sites.

Whatever the replacement strategy, it is quite evident that a total ban on SF_6 in switchgear would be extremely expensive and require extensive infrastructure altercations. Unfortunately this cost would also most like be passed down to electricity consumers, i.e. the general public. The reasons that SF_6 insulated switch gear has become the dominate technology in HV applications is no secret. Its cost effectiveness, minimal maintenance requirements, reliability and compact installation sizes were unrivalled and are all extremely hard to replicate and replace.

The staged banning of SF_6 is not such a fictional reality. Staying one step ahead is definitely recommended. By exploring and investing in environmentally and OH&S friendly alternatives to SF_6 where possible, utilities can reduce their vulnerability to SF_6.

Chapter 7: The Proposal

The following proposals comprises of a mixture of recommendations based on this dissertations research and findings whilst also taking into consideration economic and organisational objectives of modern Australian electrical network authorities.

The environmental and OH&S concerning attributes of SF_6 are evident. However, given recent electricity commodity price rises, future reduction or elimination strategies must be both reliable and cost effective as to not increase network operating costs.

The following proposals attempt to provide reasonable utility operating and infrastructure investment strategies that will both reduce SF_6 emission and personnel handling requirements whilst simultaneously being practical and affordable. SF_6 insulation still has a vital role to play in higher end voltage applications. To propose an all out SF_6 ban and across the board equipment replacements would be unrealistic. This dissertation's proposals seek to provide feasible, phased, achievable strategies that will position utilities in less consequential futures given the concerns associated with SF_6.

Another concerning trend with SF_6 insulated switchgear is the fast approaching market monopoly of the substance in applications 66 kV and above. Utilities could consequently be placing themselves in a vulnerable situation at the mercy of any harshly imposed SF_6 regulations or price rises. It makes sense to try and diversify the market where appropriate to avoid any such market ambush.

The following realistic proactive actions and trial initiatives are recommended with project cost and environmental benefits for utility consideration:

Primary Proposals: Proactive Actions

1. Medium Voltage (MV) SF_6 Switchgear Purchasing Suspension
2. Dry-air to SF_6 50% market Share (66 kV) by 2035
3. Regional Leakage Detection Cameras

Technology Trial Initiatives

4. Optical Current sensors Trials
5. Octafluorocyclobutane Trial

7.1 Primary Proposal: Proactive Actions

Based on these dissertation's findings the following proactive proposals are presented for utility considerations.

7.1.1 Medium Voltage (MV) SF6 Switchgear Purchasing Suspension

This proposal is pretty much a win win initiative for utilities. A self imposed or regulated, indefinite suspension of medium voltage SF_6 insulated switchgear purchasing demonstrates environmental responsibility to the general public with no real reliability loss or dramatic cost increases. In fact this is actually a cheaper option for utilities. Ample manufacturing companies produce more than adequate vacuum and solid-dielectric/vacuum MV circuit breakers that cater for all applications less than 40 kV. The technology is reliable, cost effective, requires less intensive maintenance and is the trending medium of choice in the MV range anyway. Existing SF_6 insulated equipment in this range could remain with intentions to be replaced with an alternative mediums when due.

A move such as this by utilities would not only attract environmental accolades but also eventually reduce maintenance costs, SF_6 stockpile requirements, employee call outs, employee OH&S concerns, installation footprints and most importantly SF_6 leakage emissions. With most utilities seeming to be moving in this direction anyway, a company regulation and public announcement would give purchasing offices zero choice. The result would drive investment into the already stable solid-dielectric /vacuum industry which may consequently produce developments in the high voltage ranges.

With recent calls in Europe for a regulated ban of SF_6 in MV switchgear it makes sense to position Australia one step ahead. Especially within a market that the case study of this dissertation suggests is only 23% catered for by SF_6 equipment. Self imposed suspended purchasing by utilities would position themselves in profitable circumstances given any eventual government regulated suspension.

Building from this concept, phased replacement of existing MV SF_6 insulated circuit breakers five to ten years ahead of life expectancy would totally eradicate SF_6 in the MV equipment by 2035. The eradication of MV SF_6 equipment would drastically reduce the SF_6 maintenance and monitoring equipment amounts required by distribution authorities. Such authorities would subsequently only require such equipment for their 66 kV and above zone substation in-coming feeder circuit breakers

Currently solid-dielectric/vacuum circuit breakers are typically \$1000-\$2000 cheaper than SF_6 models, projecting installation cost savings of between five and ten percent. The reduced call out and required maintenance activities in an MV SF_6 free future in the case study area is estimated at 15% (given that only 23% of circuit breakers in this range are currently SF_6 insulated)

As mentioned in earlier chapters many MV circuit breaker manufacturing companies offer new replacement solid-dielectric/vacuum interruption chamber tanks that can be interchanged with their previous SF_6 insulated models. This initiative reduces change over cost for utilities that can still utilise the existing control mechanisms whilst maintaining company loyalty to the existing manufacturer.

An interesting point of note is that in the case study area more than half of MV SF_6 circuit breaker designs utilised vacuum interrupters for current interruption and SF_6 purely for phase-to-ground insulation which is now completely unnecessary in this range.

Table 7-1 Case Study Area Proposal Implications: MV SF6 Switchgear Purchasing Suspension

Stage	1	2	3
Timeline	2015	2015-2035	2035
Action	Immediate suspension of MV SF_6 switchgear purchasing	Phased early replacement of MV SF_6 switchgear	Last of MV SF_6 insulated switchgear decommissioned
Units Effected	Zero initially	267	-
SF_6 (kg)	485.4	transitional	Zero
CO_2 emissions (tonnes)	103.2	transitional	Zero
Installation Cost ($)	-	5-10% cheaper then SF_6 alternatives	-
Ongoing Maintenance Cost ($)	-	transitional	15% overall operating cost reduction

7.1.2 Dry-air to SF6 50% Market Share (66 kV) by 2035

Initially a recommendation of dry-air insulated circuit breaker technology in the 66 kV range was intended to be a trial initiative. However, installations of two Sumotomo 66 kV dry-air insulated circuit breakers have been in service within Essential Energy's network in Junee since 2011. These installations' issue free applications and reduced costs have seen Essential Energy invest further in the technology with up to 12 subsequent units intended for Albury and other regional sites.

The dry-air/vacuum technology which is examined in detail in section 5.3 utilises compressed dry air as the insulation medium and vacuum interrupters for current breaking. The now proven reliable designs are available in the popular dead-tank types with integrated LV bushing current transformers and utilise zero SF_6. They have been designed in such a way that their installation footprints mimic that of current SF_6 insulated dead-tanks in the 66 kV range.

A wider up-take of the SF_6 eliminating design is recommended as a proactive strategy in reducing network reliance on SF_6 as well as offering other substantial benefits. A notable benefit is obviously the reduction of future in-service SF_6 amounts and their associated potent leakage emissions, but the technology also offers much needed diversification in the industry and is actually lower in price.

Currently all obsolete oil circuit breakers approaching the end of their in-service lives are being replaced exclusively with SF_6 designs. With the last of the oil insulated breakers in this range installed pre 1985, within 10 years the replacement scheme will render the 66 kV range exclusively SF_6 insulated. Diversification in this range would be extremely advantageous considering the concerns associated with SF_6 and calls internationally for its banning in the lower voltage spectrums.

Besides diversify the 66 kV range, dry-air/vacuum circuit breakers offer no real disadvantage when compared to SF_6. Maintenance wise vacuum circuit breakers presently require similar regimes to SF_6 but just utilise different terminology. The four yearly "detailed inspection" for SF_6 circuit breakers comprises of a similar amount of activities required for a four yearly minor maintenance on a vacuum circuit breaker. Additionally, leakage from a dry-air insulated circuit breaker would require a similar staff call out activity but is of substantially less environmental consequence. Installations sizes of the two designs are similar and offer all the same functions. Currently, Japanese company dry-air/vacuum designs are leading their European competitors and their units are typically $30,000 cheaper than the established European SF_6 dead-tank alternatives.

Alstom and other companies are also now offering live-tank style dry-air/vacuum designs. Currently both obsolete oil insulated and aging SF_6 insulated live-tanks and their associated CTs are expected be replaced with SF_6 insulated dead-tanks. Modern dead-tanks are preferred as they offer an all-in-one circuit breaker and CT installation. In a continual budget restricting future replacing old live-tanks with new live-tanks and utilising the existing post CTs could be a cheaper option. Installations of new CTs require additional CT accuracy, polarity and saturation commissioning checks to be conducted where as a straight live-tank swap over does not. However, in situations where the existing post CTs are SF_6 insulated it may be more environmentally friendly to replace both the circuit breaker and CTs with a dry-air dead-tank.

In any case it is evident that considerations of new 66 kV circuit breaker installations should include either dry-air insulated dead-tanks or live-tanks in low to medium fault level installations. In extremely high fault level installations such as large power transformer breakers, it may still be appropriate to utilise the high current breaking strength of SF_6 insulations. However, there is no reason why the now proven dry-air technology can't occupy an expanding share of the industries feeder and medium level substation 66 kV circuit breaker range.

A 20 year expanding uptake of dry-air/vaccum circuit breakers in new 66 kV applications is recommended by this dissertation. In replacing both obsolete oil and aging SF_6 units in this range a consideration of dry-air technology is advised, aiming for a 50% dry-air/vacuum to SF_6market share by the year 2035. Currently the case study area has 188 of 66 kV units, 69 of which are oil insulated and will be due for replacement in the next 10 years. If a further 25 SF_6 insulated live-tanks are due for replacement by 2035 and new installations increase at a rate of 2% annually up to 120 new 66 kV circuit breaker installations are expected before 2035. A 50% market share of the of the then 264 total units would reduce a projected case study annual CO_2 emissions by up 364.6 tonnes and installation costs by $4,752,000

Table 7-2 Case Study Area Proposal Implications: Dry-air to SF6 50% Market Share (66 kV) by 2035

Stage	1	2	3
Timeline	2015	2025	2035
Action	Intention of 50% market share dry-air to SF_6 by 2035	Last of the 66 kV Oil circuit breakers decommissioned	50% market share dry-air to SF_6 achieved
Units in-service	188	226	264
Units Effected	Zero	69 oil replacements 38 new installations	extra 25 SF_6 replacements extra 38 new installations
Market Share	69 Oil 50 SF6 LT 69 SF6 DT 0 Dry-air LT 0 Dry-air DT	transitional	0 Oil 25 SF6 LT 107 SF6 DT 25 Dry-air LT 107 Dry-air DT
SF_6 (kg)	1121.7	transitional	1466 (3180 if 100% SF_6)
CO_2 emissions (tonnes pa)	238.6	transitional	311.8 (676.4 if 100% SF_6)
Installation Cost ($)	Zero	transitional	13,098,000 (17,850,000 if 100% SF_6)

7.1.3 Regional Leakage Detection Cameras

The investment into infra-red leakage detection cameras capable of operating in the micro meter spectrum required to visualise SF_6 gas is considerable, in the order of $130,000. A recommendation of regionally based equipment in distributed locations is advised on the basis of current maintenance practice regularity and associated long term benefits of camera acquisitions.

Currently, utilities in NSW typically utilise one or two infra-red camera units based out of metropolitan Sydney. In numerous instances maintenance staffs rely on proximity detectors for both leakage detection and repair validation. Considering the current operating costs of individual SF_6 leakage identification and repair activities as well as the associated equipment outages, additional detection cameras may be warranted.

Currently, each equipment gas leakage repair operation is generally considered to cost in well in excess of $2000 and includes;

1. The initial call out of a singular maintenance technician in response to a “loss of SF_6” alarm. Alarms can be raised at any time and need to be attended to immediately to avoid equipment “lock out”. Of the normal eight hour working day there is a 66% chance that technician response will be required outside of standard hours. Typical utility pay award agreements are usually negotiated such that technicians on call receive a minimum four hours overtime pay for out of hours call out activities ($320 for technician on $40/hr)
2. Gas refilling costs. “Loss of SF_6”alarms are generally raised when the vessel pressure has reached less than five bar. An example substance loss is calculated in sections 5.6.1 as up to 2 kg of SF_6. Gas replacement in such a case required upon call out amounts to $110 ($55/kg)
3. Equipment revenue loss. Now that leak existence has been established an equipment outage is scheduled for closer inspection, leak detection and repair. Depending on the circumstance the utility is liable to revenue losses from customer supply outages or penalties from the Australian Energy Market Operator for network redundancy losses.
4. Leakage repair. Typically, for safety reasons, at least two qualified technicians are required to hold an access authority to work on de-energised HV equipment and in any case repair the leak. The leaking equipment’s SF_6 is evacuated, the leak repaired and then refilled, within an eight hour working day at a labour cost of $640.
5. Transportation. If the centralised infra-red camera is required for repair assistance then the transportation cost of the unit to the leakage site could be quite substantial including fuel and driver labour for multiple hours to reach regional locations.
6. Equipment depreciation. Additionally the deprecating cost of the required maintenance equipment such as gas evacuation pumps, hoses and cylinders as well as ladders, harnesses, elevated work platforms and technician vehicles add to the total activity cost.

At a designated leakage rate of 0.89% annually the slightly above 10 tonne case study area leaks approximately 90 kg of SF_6 in losses each year. If a typical leakage loss prior to repair was reasonably assumed at 2 kg, this equates to 45 leakage repair activities per year. Granted there is both an environmental and financial case to try and reduce leakage repair activities amounting to $90,000 and 2,100 tonnes of CO_2 equivalent emissions. Not to mention the reduction of personnel exposure to the OH&S concerning SF_6 insulation gas.

Often repair attempts can subsequently fail due to poor validation equipment such as hand held proximity detectors or "sniffers". Of the forty odd annual leakage repair activities required, up to one third can be due to repeat offenders that have been difficult to validate repair effectiveness. Infra-red detection cameras not only offer real time monitoring and repair validation but could also significantly reduce repeat repair activities. Currently centralised Sydney based units are only dispatched to regional locations in the event of multiple repair failings.

If camera acquisition in regional centres could achieve even a 20% reduction in maintenance costs, a single unit could justify its initial investment in less than eight years. The NSW electrical grid outside of the Sydney metropolitan area accounts for approximately %50 of the states electrical infrastructure. This regional grid is typically segmented into Northern, Central West and Southern, of which the sub-regional centres of Tamworth (north), Orange (central west) and Wagga Wagga (southern) could substantial benefit from infra-red detection camera placements. Cameras operating out of these regional centres could easily service their respective areas. Units could possibly be shared between, or service both the needs of, regional transmission and distribution authorities (Transgrid and Essential Energy). Leakage reduction initiatives such as these could see the national leakage estimate of HV SF_6 equipment reduced from 0.89% which could ease concerns associated with SF_6 in HV equipment.

Table 7-3 Case Study Area Proposal Implications: Regional Leakage Detection Camera

Stage	1	2
Timeline	2015	2023
Action	Purchasing of regional based infra-red leak detecting cameras	Camera purchase paid off
Units Effected	520	603
Annual leakage Repair Activities	45	41 (52 if no camera purchase)
SF_6 (kg)	10,216	11,850
CO_2 emissions (tonnes pa)	238.6	252.1
Installation Cost ($)	130,000	-
Maintenance Cost ($)	90,000	82,000 (104,000 if no camera purchase)

7.2 Technology Trials Initiatives

7.2.1 Optical Current Sensor Trial

From the case study area results in Chapter Four it is evident that a significant contribution of SF_6 in the region was a result of transmission level live-tank circuit breakers utilising SF_6 insulated adjacent post current transformers. Although oil insulated CTs are slightly cheaper and offer less life-cycle emissions, their high monitoring and maintenance regimes are deemed less desirable in the current operating cost driven industry answerable to rising electricity commodity prices. Not only do maintenance activities cost in terms of personnel and equipment but they also imply reduced revenue from out of service equipment intended for supplying electrical power to paying customers. For this reason this dissertation's proposals seeks modern alternatives with additional benefits. One such alternative that this dissertation recommends as a trial initiative is that of non-conventional current transformers, particularly optical current sensors.

Despite their substantially higher initial cost, $40,000 compared to $9,000, HV optical current sensors offer significant benefits additional to that of SF_6 elimination. Although their investment may not be warranted in the lower voltage applications, higher end HV to EHV applications could benefit from their space-saving and maintenance reducing attributes.

The Alstom Grid Optical Solutions website informs that individual optical current sensors offer wide dynamic sensing ranges with each unit capable of replicating numerous CT ratios (altered via software) which in turn reduces inventory stock requirements. They are light weight (approximately 10% of oil filled transformer) and are capable of flexible installations such as HV bus mounting and direct circuit breaker terminal attachment. Their usage can reduce the total substation footprint by as much as 15 to 25%. Transportation of units is far easier and personnel are no longer at risk to ferro-resonance and dangerous open secondary concerns associated with magnetic transformers. Furthermore they attribute reduced secondary wiring requirements and next to zero maintenance. They are extremely accurate, do not suffer the saturation limitations of magnetic transformers and are either analogue or "smart-grid" IEC 61850 ready.

Modern optical current sensor protection and metering accuracies exceed that of traditional CTs and it appears their integration into modern HV networks is only a matter of time. The technology has the potential to reduce the current dependence on both oil and SF_6 insulated CT's. What's more, its integrated use on live-tank circuit breakers terminals could replace all benefits attributed to dead-tank integrated CT designs. A SF_6 live-tank requires one third the insulation gas its counterpart and also boasts a significantly smaller installation footprint (50% reduction). Currently the only set back of the live-tank design is its large adjacent post CT requirements that could be eliminated by optical sensor integration. The benefits are even more substantial in higher voltage ranges (500 kV) where typically all circuit breakers are live-tanks with adjacent SF_6 insulated CTs

Given these benefits but also the conservative nature of network utilities possibly concerned with the associated investment required, it is recommended that a trial of the technology be undertaken. Initially a feeder bay with existing CT's could be modified to incorporate a set of optical current sensors in addition. The outputs of the traditional and modern technologies could be monitored and compared, with the traditional CTs eventually removed after a given time frame (say 6 months).

Building from this, five to ten percent of new feeder bays over the next five years could be designed utilise optical current sensors. If utilities would prefer to keep the new technology centralised perhaps a one off new substation ear marked for smart grid demonstrations could be designed to incorporate the new current sensors.

Table 7-4 Case Study Area Trial Implications: Optical Current Sensors

Stage	1	2	3
Timeline	6 months	5 years	Future
Action	Trial of optical sensors in series with traditional CTs	Designated feeder bays or complete substation applications	Optical current sensors replace all post CT applications
Units in-service	3 single phase	15-20	138-All enclusive
Redaction of SF_6 (kg)	Zero	approx. 300	4239
CO_2 emissions (tonnes pa)	-	approx.	902
Installation Cost ($)	120,000	600,000-800,000	+5,440,000

7.2.2 Octafluorocyclobutane Trial

Octafluorocyclebutane ($c-C_4F_8$) exhibits about one third of the global warming potential of SF_6 and could be a “go to” substance in the event of any sudden SF_6 restrictions. Due to carbon content of $c-C_4F_8$, which can form conductive particles post arc initiated decomposition, it is not appropriate for current interruption applications. Despite this short fall, the use of $c-C_4F_8$ could still be beneficial in non-current interrupting dielectric applications such as gas insulated current transformers and gas insulated VI circuit breakers. In these situations the gas would rarely be subject to intense electrical current arcs unless in a significant design fault. Even in the rare event of arc exposure, $c-C_4F_8$ is more than capable of extinguishing the arc but subsequently would require monitoring or gas changing afterwards.

The significantly reduced GWP rating of $c-C_4F_8$, position the substance as a worthy trial medium in HV dielectric applications. Although the price of $c-C_4F_8$ is high in comparison, its application would primarily be in high voltage CTs which exhibit significantly less leakage regularity due to their static installation nature. Unlike a HV circuit breaker a CT does not have any fast acting, highly forced operating mechanisms to stress or vibrate the apparatus, emphasizing vessel integrity failures.

The superior dielectric strength of $c-C_4F_8$ compared to SF_6 (1.2 times that of SF_6) indicates that the substance could be easily interchanged with SF_6 in non-current interrupting HV equipment. Such a dielectric strength also implies that no altercation to vessel sizes would be required. Its gaseous nature additionally allows the utilisation of existing filling valves and equipment.

Investigations into the in-service capabilities of $c-C_4F_8$ could assist government or private high voltage network operators aiming to reduce their emissions contributions. In an uncertain future that could eventually impose harsh penalties on company emissions the substance could be utilised as an intermediate solution to electrical equipment gas insulation leakage emissions.

A five year trial of $c-C_4F_8$ is recommended in exclusively designated applications such as two to three sets of HV gas insulated post CT’s and MV gas insulated vacuum interrupter circuit breakers. Medium voltage gas insulated vacuum interrupter circuit breakers that currently use SF_6 to insulate the internal interrupter from the ground (vessel enclosure) would be better replaced entirely with a solid dielectric model. However a trial of $c-C_4F_8$ in this application with positive results could leave utilities with the option of replacing the gas in such equipment to obtain a greater service life out of the existing enclosure and interrupter infrastructure.

Table 7-5 Case Study Area Trial Implications: Octafluorocyclebutane

Stage	2	3
Timeline	5 years	Future
Action	Trial of $c-C_4F_8$ in gas CTs and SF_6/vac CBs	All remaining SF_6 CTs and SF_6/vac CBs
Units in-service	6 CTs 2 SF_6/vac CBs	138 CTs 42 $\mathbf{SF_6}$/vac CBs , 195 Re-closers
Redaction of SF_6 (kg)	124	4662
Reduction CO_2 emiss. (tonnes pa)	26.4	991.7
Installation Cost ($)	18,000	699,300

7.3 Company Strategies

The final proposed recommendations are for overall electrical network authority company approaches to eliminating or reducing reliance on SF_6 insulation in HV circuit breakers and associate apparatus. The pro-active proposals and trial initiatives recommended in sections 7.1 and 7.2 are great starts in company SF_6 reduction s but further strategies would also be beneficial.

It is vitally important for all network authorities utilising SF_6 insulated switchgear to make conscious efforts to maintain current awareness of developing technologies that could aid SF_6 reduction and their associated benefits and costs. Environmentally friendly, cheaper, and less OH&S concerning insulation technologies are rapidly been introduced into the HV switchgear market. Additional to alternative circuit breaker and current transformer designs are also advances in handling equipment, such as gas evacuation systems, gas analysis devices and recycling methods. In an uncertain future regarding SF_6 regulations staying in tune with alternatives could not only save companies a lot of money but also better compliment environment and staff well being.

Company instigated professional development and staff training in regards to better SF_6 handling and equipment maintenance practices could also greatly reduce SF_6 emissions and dangerous exposure to personnel. Keeping staff up to date with the latest safe operating methods and gas handling expectations can reduce gas losses which can subsequently save operating companies money in SF_6 stockpile amounts and also in equipment time revenue losses.

An important company strategy that was brought about due to the introduction of the carbon tax in 2012, due to SF_6 rise in price, was that of accurate SF_6 gas inventory monitoring. Gas cylinders used for equipment filling are weighed prior to and after each use and the mass of SF_6 utilised is recorded. Every six months an inventory check is conducted and the obtained mass compared to that of inventory records. This is a great company imitative and should be continued in any SF_6 utilising future.

A final recommended company strategy is the adjustment of “loss of SF_6” alarms to perhaps include a lower tolerance level for emission reduction and savings in SF_6 mass replacements. Real time data monitoring of SF_6 pressures in HV equipment by SCADA systems is being considered as an advancement on simple low gas alarm triggering points. Company instigated developments in this system could lead to more reliable and robust, emission reducing networks.

Chapter 8: Conclusion

8.1 Conclusion

Australia is an environmentally concerned developed western nation; however it is also subject to local high cost of living pressures as well as international competiveness for industry investments and job creation. Currently, high global warming potential emission reductions from SF_6 insulated switchgear unfortunately does not top Australia's "to do list".

Australia's has a highly innovative nature and is a proficient accepter of new technology which was sparked from its geographical separation from the western world during its development years. Australia is also proudly influenced by its indigenous heritage and its 40,000 year strong sustainability practices. As a united community, Australia is generally concerned for the environment and our effects on future generations. The modern nation seeks a sustainable mix of industrial and technological progress, economic security and competiveness, as well as environmental conservation. It is the combination of Australia's acceptance of new technology and sustainability motivations that will drive future change in the field of SF_6 insulated HV switchgear.

Australia also does not seem afraid to lead global conversations, implementing progressive decisions and policies such as the Carbon Tax. The Carbon Tax, despite its short comings sparked major changes in industry practices. The argument stands that the tax was evidently inappropriate for Australia at the time; however the dramatic price rise in SF_6 (even for a short period) prompted utilities to reconsider the substance's previously instinctive application. If SF_6 insulation was to gain an eventually monopoly in the HV range a Carbon Tax like price rise in the order of ten times current value again would dramatically effect electricity network costs.

Sulphur hexafluoride still has a vital role to play in Australia highest voltage applications. Australia is a geographically dispersed nation. Efficient EHV inter-regional transmission networks' connecting the nation's major load centres along its eastern seaboard is the future of Australia's electricity grid. In 330 kV and above applications SF_6 unfortunately has no practical alternative. It is the trending growth of SF_6 in HV applications below 330 kV that is concerning.

The 2,905 tonnes of CO_2 equivalent emissions from the case study area's SF_6 insulated circuit breakers each year suggest 24,200 tonnes for NSW and 80,700 tonnes annually for Australia. With an expected increases at above 2% per year these amounts could more than double in the next half century.

Reductions or eliminations of SF_6 in MV and non-current interrupting HV applications are highly warranted. This dissertation has demonstrated comprehensively that alternative technologies and strategies do exist and in many instances is actually the more cost effective option.

There is realistically no credible reason why SF_6 insulation needs to be utilised in medium voltage switchgear applications anymore. Solid-dielectric/vacuum MV alternatives are far superior on all criterion including price, maintenance and environment. Dry-air/vacuum circuit breakers are also implying an increasing lack of relevance of SF_6 in 66 kV applications. A major market share swing away from SF_6 in 66 kV circuit breakers is fast approaching with price and environmental compliance playing a major role. Digital substation control and monitoring is promising to be the next big innovative revolution in electricity grids. Non-conventional current transformers and other instrumentation are positioning themselves as the new space saving, maintenance reduced and environmentally friendly options.

With these design changes establishing a foot hold in modern networks a future where the use SF_6 is limited to high end voltage live-tank circuit breakers only is not unrealistic. Disassociating itself with SF_6 in MV and non-current interrupting HV applications is a practical and economical viable option for Australia. The limited use of SF_6 in EHV applications would significantly reduce personnel contact with the OH&S concerning substance as well see the assumed leakage emission rate of 0.89% possibly fall.

A concerning SF_6 trend that is however the gaining popularity is that of Gas Insulated Substations (GIS) for their space saving benefits. The substantial increase in required SF_6 insulation gas of these installations can be upwards from five times that of a traditional substation yards. A further up take of space saving non-conventional current transformers and other digital HV instruments could see GIS applications reconsidered.

The use of sulphur hexafluoride in MV and non-current interrupting HV applications has run its course. Future harsh SF_6 restrictions, regulations and price raises associated with the global warming potent substance are highly plausible in the modern environmentally concerned world. Additionally, the OH&S concerns associated with the decomposition by-products of SF_6 are alarming. Given the previous four decade strong hold of SF_6 insulated circuit breakers and their perceived benefits the eventual alternatives needed to be extraordinary to compete, and they are. The modern alternatives speak for themselves; reduced - costs, reduced safety concerns, reduced environmental impacts and reduced maintenance requirements.

The time for the consideration of alternatives is over. It is no longer a question of aiming to be one step ahead by embracing the new SF_6 alternatives - but rather being one step behind if you don't!

8.2 Further Work

The following items are noted as desirable further work objectives:

1. Expanding the case study area – Expanding the case study are to that of entire NSW would give an greater picture of the use of SF_6. Current, estimates based on the rural case study region alone could be drastically underrating the real usage in greater metropolitan Sydney

2. Real instance leakage recording – A six to twelve month leakage recording according study of the case study area would be beneficial as a comparison to the prescribed leakage rate or 0.89% of equipment capacity. Obtain data or developing a mechanism for the case study utilities to record data concerning equipment leakage call out instances and leakage loss amounts could determine whether the prescribed leakage rate is conservative, accurate or misleading.

3. Analysis of leakage repair – An analysis a current leakage repair activity could give further insight into the current methods, equipments used, handling techniques and SF_6 loss amounts. Actual leakage repair success rate with traditional equipment would also be an interesting data collection in terms of validating infra-red camera technology.

4. Alarm level tolerances – An investigation into any benefits offered from reduced "loss of SF_6" alarm tolerances. A detailed look at whether less forgiving alarm levels would produce an increased cost in call outs compared to environmental and SF_6 stock pile savings.

5. Installation trials alternatives – A real installation trial of either optical current sensors or Octafluorocyclebutane gas replacement suggested in section 7.2 would be produce realistic data on the benefits of such installations. An interesting trial would be that of a live-tank circuit breaker with optical current sensors fitted to its terminals in an attempt to compare the installation with the current benefits of dead-tank circuit breakers.

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Appendix A: Project Specification

ENG 4111/4112 Research Project

PROJECT SPECIFICATION

FOR: MICHAEL MARLAND

TOPIC: ALTERNATIVES TO SF6 INSULATION IN HV CIRCUIT BREAKERS

SUPERVISORS: Mr Andreas Helwig

ENROLMENT: ENG 4111 –S1, External 2014
ENG 4112 –S2, External 2014

PROJECT AIM: This Project seeks to investigate the increasing relevance of alternative HV circuit breaker insulation as opposed to SF6 gas as well as safety, cost and environmental benefits associated with SF6 gas alternatives. The project seeks to explore circuit breaker design features that could aid SF6 reductions as an effective, practical and environmentally friendly alternative.

PROGRAMME: Issue A, 16th March 2014

1. Research - the environmental impacts of SF6, in particular production footprints, global warming potentials and greenhouse effects
   - brief background of HV circuit breaker designs as well as HV circuit breaker standards
   - Circuit breaker designs eliminating SF6 as either the current breaking or phase-to-ground insulation medium
   - Circuit breaker designs utilising SF6 for phase-to-ground insulation
   - The Insulation effectiveness of alternatives and desired characteristics of insulation in HV circuit breakers
   - Occupational health and safety aspects associated with SF6 when utilised as HV circuit breaker insulation gas
   - Alternative designs that replace SF6 and the design components that enable SF6's effective replacement
2. Survey a case study region to obtain data on the quantity of SF6 insulated HV circuit breakers in existing infrastructure and their associated costs/maintenance
3. Explore alternative circuit breaker designs eliminating or reducing the reliance on SF6 gas insulation and evaluate the outcomes of alternative design inclusions based on the case study area results
4. Explore the maintenance and cost consequences of alternative designs as opposed to existing SF6 circuit breakers
5. Propose effective designs and strategies that could minimise SF6 gas insulation in circuit breakers to the same effectiveness
6. Conduct a benefit and life cycle comparison analysis of replacing SF6 insulated existing equipment with alternatives

As time and resources permit

7. Test alternatives researched above and evaluate effectiveness compared to SF6 alternative design.

AGREED

M.Marland___________(Student) __A. Helwig___, ________________(Supervisors)

Appendix B: SF6 MSDS

AIR LIQUIDE	MATERIAL SAFETY DATA SHEET	Page : 1 Revised edition no : 3 Date : 7 / 11 / 2012 Supersedes : 24 / 10 / 2012
Sulphur hexafluoride		AL016

Warning

SECTION 1. Identification of the substance/mixture and of the company/undertaking

1.1. Product identifier

Trade name : Sulphur hexafluoride
SDS Nr : AL016
Chemical formula : SF_6

1.2. Relevant identified uses of the substance or mixture and uses advised against

Relevant identified uses : Industrial and professional. Perform risk assessment prior to use.
Test gas / Calibration gas. Laboratory use Contact supplier for more uses information
Use : Industrial applications.

1.3. Details of the supplier of the safety data sheet

Company identification : Air Liquide Australia Limited
Level 9 / 380 St. Kilda Road
Melbourne VIC 3004 Australia
Tel: + 61 3 9697 9888
Fax: + 61 3 9690 7107
ALAEnquiries@AirLiquide.com

1.4. Emergency telephone number

Emergency telephone number : 1800 812 588

SECTION 2. Hazards identification

2.1. Classification of the substance or mixture

Hazard Class and Category Code Regulation EC 1272/2008 (CLP)

- Physical hazards : Gases under pressure - Liquefied gas - Warning - (CLP : Press. Gas) - H280

Classification EC 67/548 or EC 1999/45

: Not classified as dangerous substance/mixture.

2.2. Label elements

Labelling Regulation EC 1272/2008 (CLP)

- Hazard pictograms

- Hazard pictograms code : GHS04
- Signal word : Warning
- Hazard statements : H280 - Contains gas under pressure; may explode if heated.
- Precautionary statements
  - Storage : P403 - Store in a well-ventilated place.

2.3. Other hazards

: None.

Air Liquide Australia Limited
Level 9 / 380 St. Kilda Road Melbourne VIC 3004 Australia
Tel: + 61 3 9697 9888
Fax: + 61 3 9690 7107
ALAEnquiries@AirLiquide.com

In case of emergency : 1800 812 588

SECTION 3. Composition/information on ingredients

3.1. Substance / 3.2. Mixture

Substance.

Substance name		Contents	CAS No	EC No	Annex No		Classification
Sulphur hexafluoride	:	100 %	2551-62-4	219-854-2	-----	* 2	Not classified (DSD/DPD) Liq. Gas (H280)

Contains no other components or impurities which will influence the classification of the product.
* 1: Listed in Annex IV / V REACH, exempted from registration.
* 2: Registration deadline not expired.
* 3: Registration not required: Substance manufactured or imported < 1t/y
Full text of R-phrases see chapter 16. Full text of H-statements see chapter 16

SECTION 4. First aid measures

4.1. Description of first aid measures

First aid measures

- Inhalation : In high concentrations may cause asphyxiation. Symptoms may include loss of mobility/ consciousness. Victim may not be aware of asphyxiation.
Remove victim to uncontaminated area wearing self contained breathing apparatus. Keep victim warm and rested. Call a doctor. Apply artificial respiration if breathing stopped.

- Skin/eye contact : Immediately flush eyes thoroughly with water for at least 15 minutes.
In case of frostbite spray with water for at least 15 minutes. Apply a sterile dressing. Obtain medical assistance.

- Skin contact : Adverse effects not expected from this product.

- Eye contact : Adverse effects not expected from this product.

- Ingestion : Ingestion is not considered a potential route of exposure.

4.2. Most important symptoms and effects, both acute and delayed

: Refer to section 11.

4.3. Indication of any immediate medical attention and special treatment needed

: None.

SECTION 5. Fire-fighting measures

5.1. Extinguishing media

Extinguishing media

- Suitable extinguishing media : All known extinguishants can be used.

5.2. Special hazards arising from the substance or mixture

Specific hazards : Exposure to fire may cause containers to rupture/explode.

Hazardous combustion products : If involved in a fire the following toxic and/or corrosive fumes may be produced by thermal decomposition :
Hydrogen fluoride.
Sulphur dioxide.

5.3. Advice for fire-fighters

Specific methods : If possible, stop flow of product.
Coordinate fire measure to the surrounding fire. Cool endangered containers with water spray jet from a protected position. Do not empty contaminated fire water into drains.
Move away from the container and cool with water from a protected position.

Special protective equipment for fire fighters : Use self-contained breathing apparatus and chemically protective clothing.

AIR LIQUIDE	MATERIAL SAFETY DATA SHEET	Page : 3 Revised edition no : 3 Date : 7 / 11 / 2012 Supersedes : 24 / 10 / 2012
Sulphur hexafluoride		AL016

SECTION 6. Accidental release measures

6.1. Personal precautions, protective equipment and emergency procedures

: Try to stop release.

Personal precautions : Evacuate area.
Wear self-contained breathing apparatus when entering area unless atmosphere is proved to be safe.
Ensure adequate air ventilation.

6.2. Environmental precautions

: None.

: Try to stop release.
Prevent from entering sewers, basements and workpits, or any place where its accumulation can be dangerous.

6.3. Methods and material for containment and cleaning up

: None.

Clean up methods : Ventilate area.

6.4. Reference to other sections

: See also sections 8 and 13.

SECTION 7. Handling and storage

7.1. Precautions for safe handling

Safe use of the product : Use only properly specified equipment which is suitable for this product, its supply pressure and temperature. Contact your gas supplier if in doubt.
Only experienced and properly instructed persons should handle gases under pressure.
The product must be handled in accordance with good industrial hygiene and safety procedures.
Do not smoke while handling product.
Ensure the complete gas system was (or is regularily) checked for leaks before use.

Safe handling of the gas receptacle : Refer to supplier's container handling instructions.
Do not allow backfeed into the container.
Protect cylinders from physical damage; do not drag, roll, slide or drop.
When moving cylinders, even for short distances, use a cart (trolley, hand truck, etc.) designed to transport cylinders.
Leave valve protection caps in place until the container has been secured against either a wall or bench or placed in a container stand and is ready for use.
If user experiences any difficulty operating cylinder valve discontinue use and contact supplier.
Never attempt to repair or modify container valves or safety relief devices.
Damaged valves should be reported immediately to the supplier.
Keep container valve outlets clean and free from contaminates particularly oil and water.
Replace valve outlet caps or plugs and container caps where supplied as soon as container is disconnected from equipment.
Close container valve after each use and when empty, even if still connected to equipment.
Never attempt to transfer gases from one cylinder/container to another.
Never use direct flame or electrical heating devices to raise the pressure of a container.
Do not remove or deface labels provided by the supplier for the identification of the cylinder contents.

Handling : Suck back of water into the container must be prevented.
Do not allow backfeed into the container.
Use only properly specified equipment which is suitable for this product, its supply pressure and temperature. Contact your gas supplier if in doubt.
Refer to supplier's container handling instructions.

7.2. Conditions for safe storage, including any incompatibilities

: Keep away from combustible materials.
Keep container below 50℃ in a well ventilated plac e.
Observe all regulations and local requirements regarding storage of containers.
Containers should not be stored in conditions likely to encourage corrosion.
Containers should be stored in the vertical position and properly secured to prevent toppling.
Stored containers should be periodically checked for general condition and leakage.

Air Liquide Australia Limited
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Tel: + 61 3 9697 9888
Fax: + 61 3 9690 7107
ALAEnquiries@AirLiquide.com

In case of emergency : 1800 812 588

SECTION 7. Handling and storage (continued)

Container valve guards or caps should be in place.
Store containers in location free from fire risk and away from sources of heat and ignition.

Storage : Keep container below 50℃ in a well ventilated pla ce.

7.3. Specific end use(s)

: None.

SECTION 8. Exposure controls/personal protection

8.1. Control parameters

Occupational Exposure Limits

Sulphur hexafluoride
: MAK (AU) Tagesmittelwert (ml/m³) : 1000
: MAK (AU) Kurzzeitwerte (mg/m³) : 12000
: MAK (AU) Tagesmittelwert (mg/m³) : 6000
: MAK (AU) Kurzzeitwerte (ml/m³) : 2000
: TLV© -TWA [ppm] : 1000
: LTEL - UK [mg/m³] : 6070
: LTEL - UK [ppm] : 1000
: LTEL - UK [ppm] : 7590
: STEL - UK [mg/m³] : 1250
: VME - France [mg/m³] : 6000
: VME - France [ppm] : 1000
: AGW (8h) - Germany [mg/m³] TRGS 900 : 1000
: AGW (8h) - Germany [ppm] TRGS 900 : 6100
: Exceeding factor AGW - Germany TRGS 900 : 8
: VLA-ED - Spain [ppm] : 1000
: VLA-ED - Spain [mg/m3] : 6075
: NGV - [ppm] : 1000
: NGV - [mg/m³] : 6000
: Grænserværdier (DK) (ppm) : 1000
: HTP-värden (FI) - 8 H - [ppm] : 1000
: HTP-värden (FI) - 8 H - [mg/m³] : 6100
: HTP-värden - 15min - [ppm] : 1300
: Grænserværdier (DK) : 6000
: HTP-värden - 15min - [mg/m³] : 7900
: GV Value Limit (Norway) [ppm] : 1000
: GV Value Limit (Norway) [mg/m³] : 6000
: TLV-TWA (Belgium) (ppm) : 1000

DNEL: Derived no effect level : None available.

PNEC: Predicted no effect concentration : None available.

8.2. Exposure controls

8.2.1. Appropriate engineering controls : Systems under pressure shoud be regularily checked for leakages.
Provide adequate general and local exhaust ventilation.
Consider work permit system e.g. for maintenance activities.

8.2.2. Individual protection measures, e.g. personal protective equipment : A risk assessment should be conducted and documented in each work area to assess the risks related to the use of the product and to select the PPE that matches the relevant risk.
The following recommendations should be considered.
Wear safety glasses with side shields
Wear leather safety gloves and safety shoes when handling cylinders.

Personal protection : Ensure adequate ventilation.
Do not smoke while handling product.

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SECTION 8. Exposure controls/personal protection (continued)

8.2.3. Environmental exposure controls	: Refer to local regulations for restriction of emissions to the atmosphere. See section 13 for specific methods for waste gas treatment.

SECTION 9. Physical and chemical properties

9.1. Information on basic physical and chemical properties

Appearance	
- Physical state at 20℃ / 101.3kPa	: Gas.
- Colour	: Colourless gas.
Odour	: No odour warning properties.
Odour threshold	: Odour threshold is subjective and inadequate to warn for overexposure.
pH value	: Not applicable for gas-mixtures.
Molar mass [g/mol]	: Not applicable for gases and gas-mixtures.
Melting point [℃]	: -50.8
Boiling point [℃]	: -64 (s)
Critical temperature [℃]	: 45.5
Flash point [℃]	: Not applicable for gas-mixtures.
Evaporation rate (ether=1)	: Not applicable for gas-mixtures.
Flammability range [vol% in air]	: Not applicable for gas-mixtures.
Vapour pressure [20℃]	: Not applicable. 21 bar
Relative density, gas (air=1)	: 5
Relative density, liquid (water=1)	: 1.4
Solubility in water [mg/l]	: 41
Partition coefficient n-octanol/water	: Not applicable for gas-mixtures.
Viscosity at 20℃ [mPa.s]	: Not applicable.
Explosive Properties	: Not applicable.

9.2. Other information

Other data	: Gas/vapour heavier than air. May accumulate in confined spaces, particularly at or below ground level.
Molecular weight	: 146

SECTION 10. Stability and reactivity

10.1. Reactivity

: No reactivity hazard other than the effects described in sub-sections below.

10.2. Chemical stability

: Stable under normal conditions.

10.3. Possibility of hazardous reactions

: None.

10.4. Conditions to avoid

: None.

10.5. Incompatible materials

: None.

10.6. Hazardous decomposition products

: Under normal conditions of storage and use, hazardous decomposition products should not be produced.

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Level 9 / 380 St. Kilda Road Melbourne VIC 3004 Australia
Tel: + 61 3 9697 9888
Fax: + 61 3 9690 7107
ALAEnquiries@AirLiquide.com

In case of emergency : 1800 812 588

SECTION 10. Stability and reactivity (continued)

: Thermal decomposition yields toxic products which can be corrosive in the presence of moisture.

: Stable under normal conditions.

SECTION 11. Toxicological information

11.1. Information on toxicological effects

Toxicity information	: No known toxicological effects from this product.
Acute toxicity	: No known toxicological effects from this product.
Rat inhalation LC50 [ppm/4h]	: No data available.
Skin corrosion/irritation	: No known effects from this product.
Serious eye damage/irritation	: No known effects from this product.
Respiratory or skin sensitisation	: No known effects from this product.
Carcinogenicity	: No known effects from this product.
Germ cell mutagenicity	: No known effects from this product.
Toxic for reproduction : Fertility	: No known effects from this product.
Toxic for reproduction : unborn child	: No known effects from this product.
STOT-single exposure	: No known effects from this product.
STOT-repeated exposure	: No known effects from this product.
Aspiration hazard	: Not applicable for gases and gas-mixtures.

SECTION 12. Ecological information

12.1. Toxicity

: No data available.

12.2. Persistence - degradability

: No data available.

12.3. Bioaccumulative potential

: No data available.

12.4. Mobility in soil

: No data available.

12.5. Results of PBT and vPvB assessment

: No data available.

12.6. Other adverse effects

Ecological effects information	: Contains Fluorinated greenhouse gases covered by the Kyoto protocol.
Effect on the global warming	: Contains fluorinated greenhouse gases covered by the Kyoto protocol. Calculated GWP of mixture : 22200. For quantities refer to cylinder label.
Global warming potential [CO2=1]	: 22200

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SECTION 13. Disposal considerations

13.1. Waste treatment methods

: May be vented to atmosphere in a well ventilated place.
Do not discharge into any place where its accumulation could be dangerous.
Refer to the code of practice of EIGA (Doc. 30/10 "Disposal of Gases, downloadable at http://www.eiga.org) for more guidance on suitable disposal methods
Contact supplier if guidance is required.

General : Do not discharge into any place where its accumulation could be dangerous.
Contact supplier if guidance is required.

13.2. Additional information

: None.

SECTION 14. Transport information

UN number : 1080

Labelling ADR, IMDG, IATA

: 2.2 : Non flammable, non toxic gas.

Land transport (ADR/RID)

H.I. nr	: 20
UN proper shipping name	: SULPHUR HEXAFLUORIDE
Transport hazard class(es)	: 2
Classification code	: 2 A
Packing Instruction(s)	: P200
Tunnel Restriction	: C/E Tank carriage: Passage forbidden through tunnels of category C, D and E; Other carriage: Passage forbidden through tunnels of category E
HAZCHEM - Emergency Action Code	: 2TE

: *2 = Fine water spray.*
T = Recommended personal protective equipment : Full fire kit and breathing apparatus. Appropriate measures : dilute.
E = There may be a public safety hazard outside the immediate area of the incident, and that the following actions should be considered :
1. People should be warned to stay indoors with all doors and windows closed, preferably in rooms upstairs and facing away from the incident. Ignition sources should be eliminated and any ventilation stopped.
2. Effects may spread beyond the immediate vicinity. all non-essential personnel should be instructed to move at least 250 metres away from the incident.
3. Police and fire brigade incident commanders should consult each other and with a product expert, or with a source of product expertise.
4. The possible need for subsequent evacuation should be considered, but it should be remembered that in most cases it will be safer to remain in a building than to evacuate.

Sea transport (IMDG)

Proper shipping name	: SULPHUR HEXAFLUORIDE
Class	: 2.2
Emergency Schedule (EmS) - Fire	: F-C
Emergency Schedule (EmS) - Spillage	: S-V
Packing instruction	: P200

Air transport (ICAO-TI / IATA-DGR)

Proper shipping name (IATA)	: SULPHUR HEXAFLUORIDE
Class	: 2.2
Passenger and Cargo Aircraft	: Allowed.

SECTION 14. Transport information (continued)

Packing instruction - Passenger and Cargo Aircraft : 200

Cargo Aircraft only : Allowed.

Packing instruction - Cargo Aircraft only : 200

Special precautions for user

: Avoid transport on vehicles where the load space is not separated from the driver's compartment.
Ensure vehicle driver is aware of the potential hazards of the load and knows what to do in the event of an accident or an emergency.
Before transporting product containers :
- Ensure there is adequate ventilation.
- Ensure that containers are firmly secured.
- Ensure cylinder valve is closed and not leaking.
- Ensure valve outlet cap nut or plug (where provided) is correctly fitted.
- Ensure valve protection device (where provided) is correctly fitted.

- IMO-IMDG code

- ICAO/IATA

Other transport information : Avoid transport on vehicles where the load space is not separated from the driver's compartment.
Ensure vehicle driver is aware of the potential hazards of the load and knows what to do in the event of an accident or an emergency.
Before transporting product containers :
- Ensure that containers are firmly secured.
- Ensure cylinder valve is closed and not leaking.
- Ensure valve outlet cap nut or plug (where provided) is correctly fitted.
- Ensure valve protection device (where provided) is correctly fitted.
- Ensure there is adequate ventilation.
- Compliance with applicable regulations.

SECTION 15. Regulatory information

15.1. Safety, health and environmental regulations/legislation specific for the substance or mixture

EU legislation

Seveso directive 96/82/EC : Not covered.

National legislation

: Ensure all national/local regulations are observed.

15.2. Chemical Safety Assessment

: A CSA does not need to be carried out for this product.

SECTION 16. Other information

Indication of changes : Revised safety data sheet in accordance with commisssion regulation (EU) No 453/2010

Training advice : Asphyxiant in high concentrations.
Receptacle under pressure.
Keep container in well ventilated place.
Do not breathe the gas.
Ensure all national/local regulations are observed.
Contact with liquid may cause cold burns/frostbite.
The hazard of asphyxiation is often overlooked and must be stressed during operator training.

List of full text of H-statements in section 3. : H280 - Contains gas under pressure; may explode if heated.

Further information : Classification in accordance with calculation methods of regulation (EC) 1272/2008 CLP / (EC) 1999/45 DPD.
This Safety Data Sheet has been established in accordance with the applicable European Union legislation.

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SECTION 16. Other information (continued)

Note	: This Safety Data Sheet has been established in accordance with the applicable European Union legislation.
DISCLAIMER OF LIABILITY	: Before using this product in any new process or experiment, a thorough material compatibility and safety study should be carried out. Details given in this document are believed to be correct at the time of going to press. Whilst proper care has been taken in the preparation of this document, no liability for injury or damage resulting from its use can be accepted.

The contents and format of this SDS are in accordance with EC Commission Directive 2001/58/EC.

DISCLAIMER OF LIABILITY The information in this SDS was obtained from sources which we believe are reliable. However, the information is provided without any warranty, express or implied, regarding its correctness. The conditions or methods of handling, storage, use or disposal of the product are beyond our control and may be beyond our knowledge. For this and other reasons, we do not assume responsibility and expressly disclaim liability for loss, damage or expense arising out of or in any way connected with the handling, storage, use or disposal of the product. This MSDS was prepared and is to be used only for this product. If the product is used as a component in another product, this MSDS information may not be applicable.

End of document

Appendix C: Transgrid Maintenance Plan Excerpts

TransGrid

Maintenance Plan – Substation Assets

Summary:

This plan applies to the maintenance of substation assets owned and managed by TransGrid

Revision no: 0	TRIM No: 2003/1447 (D2003/2312) Enter No: GM AS S1 001	Approval/Review Date: 26 August 2014	
Business function: Strategic Asset Management		Document type: Maintenance Plan	
Process owner: Manager/Asset Performance			
Responsible Manager: Substation Systems Engineer		Inform: EGM/Network Planning and Performance	
Author:	K Wyper - SSSE	*Electronic approval via workflow 21389*	*18 August 2014*
Contributors:	Substation Working Group	*Electronic approval via workflow 21389*	*18 August 2014*
Reviewer:	T Gray - SSE	*Electronic approval via workflow 21389*	*18 August 2014*
Approver:	G Chubb – M/AP	*Electronic approval via workflow 21389*	*26 August 2014*

When referring to TransGrid's policies, frameworks, procedures or work instructions, please use the latest version published on the intranet.

Tale of Contents

7.3 **Required actions**

The following guidelines for required action to be taken shall apply to all Thermographic Survey measurements carried out on any equipment at any time.

7.3.1 Conductors, Connections and Disconnectors (Contact Interfaces)

Connections remade due to a hot joint should be reinspected by Thermographic Survey within 1 month. Guidelines for repair timeframes and priorities for hotspots at bolted aluminium palm to palm joints and at compression fittings, disconnector fingers etc are detailed in the Condition Monitoring Manual (GM AS S1 008). The table contained in the Condition Monitoring Manual categorises response time based on possible loads and the recorded hotspot temperature.

Time to repair any hot spots identified during a Thermographic survey will depend largely on load conditions at the time of check since heating is a function of the square of the load current and this should be considered in the application of the Condition Monitoring Manual guidelines.

7.3.2 Oil filled Bushings, Oil Filled CTs and Power Transformer/Reactor cooling circuits

For measurements made of the external surface temperatures of transformer or reactor bushings, Oil Filled CTs and Power transformer/Reactor cooling circuits, any unexplained abnormalities evident that are more than 5°C above ambient shall be reported and investigated by the Substation Manager, particularly if the adjacent equipment is of similar make, carrying similar loads and does not exhibit the same abnormality. These investigations are required within one month from the date of the check.

7.4 Diesel Generators

To be maintained in accordance with the manufacturer's recommendations unless otherwise advised.

7.5 Pressure Vessels

Inspection of all Pressure Vessels is to be carried out in accordance with Pressure Vessel Inspection standard GM AS S2 009.

8 Routine (Preventative) Maintenance - Circuit Breakers

8.1 General

HV Circuit Breakers (CBs) will be maintained on a time, operations or I^2t (fault energy) basis as defined below. Requirements for maintenance on circuit breakers fitted with a functional ELCON online monitoring system is defined in section 8.3.

8.2 Servicing Plan for Circuit Breakers (excluding GIS)

Servicing of a CB will be as follows:

(a) **Warranty period checks** - Refer to Section 14 of this Implementation Plan.

(b) **Operational Checks** - All CBs must be operated at least once per year.

(c) **Inspection and maintenance** - To be carried out as per table 2:

TransGrid

Maintenance Checks Required	Interrupter Type								
	Oil Insulated Types		SF6 Types normal application			SF6 Types Reactive Plant		Vacuum Types 8.3.3)	
	Minor	Major	Detailed Inspection	Minor	Major	Minor	Major	Minor	Major
Timing measurement (See Note 1)	X	X		X	X	X	X	X	X
Insulation resistance across breaks and to earth where the insulation medium comprises fibre board and/or oil	X	X							
Alarm, interlocks and indication	X	X	X	X	X	X	X	X	X
Energy source measurements(mechanical tolerance and accumulator pressures)	X	X		X	X	X	X	X	X
Lubrication (where appropriate) without dismantling	X	X		X	X	X	X	X	X
Air or hydraulic oil consumption on trip and close	X	X	X	X	X	X	X		
SF6 gas density checks and pressure switch settings (see 8.3.3)			X	X	X	X	X		X
Close and trip checks:									
• Operation checks (includes CO checks)	X	X	X	X	X	X	X	X	X
• Point on Wave operation checks (See Note 1)						X	X	X	X
Operating Mechanism Cut-in, cut-outs	X	X	X	X	X	X	X	X	X
Replace Hydraulic Oil	X	X		X	X	X	X		
For Small Oil-Non Pressurised CB units change the oil	X	X							
For Small Oil Pressurised CB units change the oil		X							
Bushing DDF (where DDF point fitted)	X	X							
Contact resistance measurements (See Note 2 & 5)	X	X			X	X	X		
Dynamic Contact Resistance measurements (See Notes 2 & 4)					X	X	X		
Interrupter Inspection (See Note 3)		X			X		X		
Condition Monitoring Device checks (See 8.3.5)			X	X	X	X	X		

Note 1: Timing Measurements

For CBs with mechanical operating mechanisms (spring/spring), close/open timing measurements must be carried out in addition to regular closing and opening timing tests. Close/open timing measurements should not be carried out in-service due to the possibility of system disturbance. All Reactive plant CBs fitted with Point on Wave relays require an in service timing measurement of voltage and current waveforms to confirm correct operation/settings of the POW relay.

Note 2: CBs with Internal CTs (Dead Tank types)
Primary DC current injection through the CTs may result in magnetisation of the CT magnetic core. The CT secondaries are to be shorted and earthed according to approved procedures prior to injection of DC current to measure contact resistance (dynamic and static). The use of instruments employing demagnetising techniques for this measurement require prior approval by the SSE.

Note 3: Interrupter Inspection
For circuit breakers (other than SF6 or vacuum), dismantle interrupter chambers of the phase with the worst contact resistance results and inspect arc control devices and contacts. If results are satisfactory then reassemble and re-test timing, contact resistance and insulation resistance as required. If results of inspection are not satisfactory, then undertake dismantling and/or inspection of remaining interrupters and repair as necessary.

For SF_6 circuit breakers with diagnostic testing results outside the operating limit for the circuit breaker (refer to GM AS S1 008 Substation Condition Monitoring Manual), dismantling and inspection of the interrupter(s) is required. Where SF_6 circuit breaker interrupters are dismantled, a formal Inspection report shall be completed and copies provided to the Substation Systems Engineer for comment, review and filing.

Note 4: Dynamic Contact Resistance
Contact resistance of SF6 CB Interruptors should be measured using Dynamic Contact Resistance methods where possible.

Note 5: Vacuum Circuit Breakers
Vacuum circuit breakers shall be maintained to the same regime as SF6 circuit breakers. Interrupter inspection is not required. Contact resistance measurements are not required. SF6 pressure checks may be required where SF6 is used to provide primary insulation.

8.3 CB Type Specific Maintenance Requirements

Specific additional maintenance may be required on particular circuit breakers. The following type specific maintenance has been identified and shall be completed as described below. Where the need for further type specific routine requirements is determined, approval of the Substation Systems Engineer is required prior to implementation and the additional requirements shall be subsequently added to this section of the Maintenance Plan.

8.3.1 Sprecher & Schuh HGF215/2B CB with mechanism FKF2-9(2-12)

Operating rods to be replaced at 500 operations. Refer to OER-0504 for details of management plan.

8.3.2 SOV CB's

Where a SOV CB has reached 80% of the recommended I^2t at the time of a Minor Service, a Major Service shall be carried out.

8.4 Service Interval for Circuit Breakers

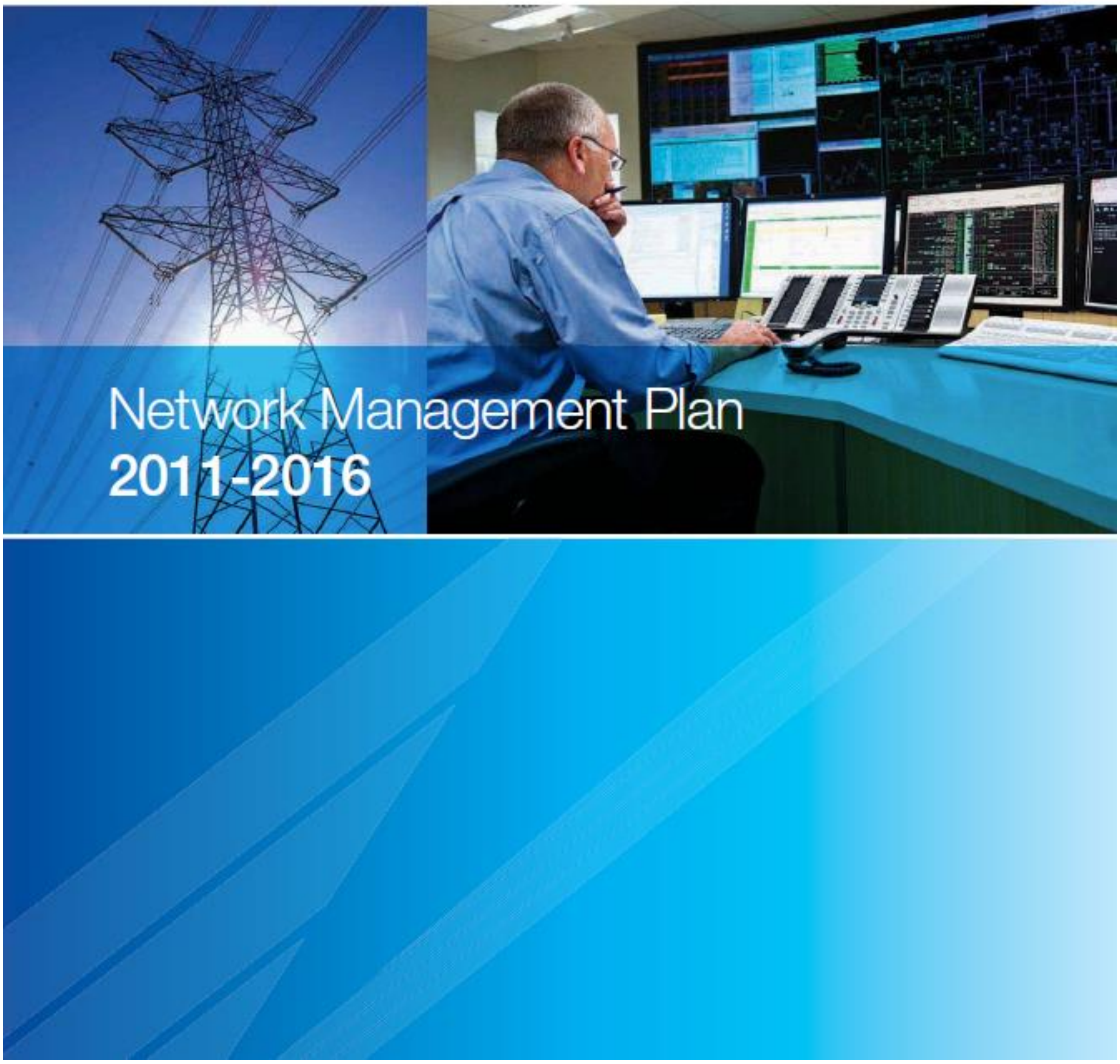
Circuit Breaker inspections and maintenance will be carried out at either intervals recommended for that CB in the table below, or when the number of operations of that CB exceeds the limit for that CB (whichever comes first). The first Minor Service will be carried out just prior to Warranty Expiry or four years after commissioning (whichever comes first) and thereafter at an interval recommended for that CB in the table below.

Major Service Work for any similar group of CB within TransGrid will be spread over the major service cycle to distribute workload. This programming should ensure that at least 1 of each type of CB receives a major service at four yearly intervals where more than 3 CBs exist, so as to ensure monitoring of the general condition of each group of CBs. This process shall start after the first major maintenance and will be coordinated by the Substation Systems Engineer.

Where a CB has reached a predetermined number of fault operations or interrupted a predetermined amount of fault energy (I^2t - refer to manufacturer's recommendations) a documented review shall be carried out to determine if these maintenance requirements should be changed (eg. convert Minor Service to Major Service). CB types so affected (and remedial action required) shall be listed in section 8.3

Circuit Breaker Service Intervals (All Voltages)					
CB Interrupter Type	Operational Checks	Detailed Inspection	Minor Service	Major Service	Online Data recording
SF_6 (see Note 1)	Annual	4 yrs	8 yrs	2,500 ops	4 yrs
SF_6 on reactive plant	Annual	N/A	4 yrs	12 yrs or 800 ops	N/A
SF_6 on capacitor >=80MVAr	Annual	N/A	2yrs	12 yrs or 800 ops	N/A
Small Oil	Annual	N/A	4 yrs	12 yrs, 800 ops	N/A
Vacuum	Annual	N/A	4 yrs	12 yrs or 800 ops	N/A
Bulk Oil	Annual	N/A	4 yrs	12 yrs or 800 ops	N/A

Appendix D: Transgrid Management Plan 2011-16 Excerpts



About TransGrid

TransGrid is the owner and manager of one of the largest electricity transmission networks in Australia, connecting generators, distributors and major end users in NSW and the ACT.

TransGrid, with 91 substations and over 12,600 kilometres of transmission lines, facilitates interstate energy trading and forms the backbone of Australia's National Electricity Market, one of the most extensive electricity systems in the world.

Our Objectives

TransGrid is a State Owned Corporation (SOC) with its principal objectives stated in Section 6B of the Energy Services Corporations Act 1995 No 95:

→ To be a **successful business**, and, to this end:
  - To operate at least as **efficiently** as any comparable businesses
  - Maximise the net worth of the **State's investment** in it
  - Exhibit a sense of **social responsibility** by having regard to the interests of the community in which it operates

→ Protect the **environment** by conducting its operations in compliance with the principles of ecologically sustainable development contained in section 6 (2) of the *Protection of the Environment Administration Act, 1991.*

→ Exhibit a sense of responsibility towards **regional development** and decentralisation in the way in which it operates.

→ Operate **efficient, safe and reliable facilities** for the transmission of electricity and other forms of energy.

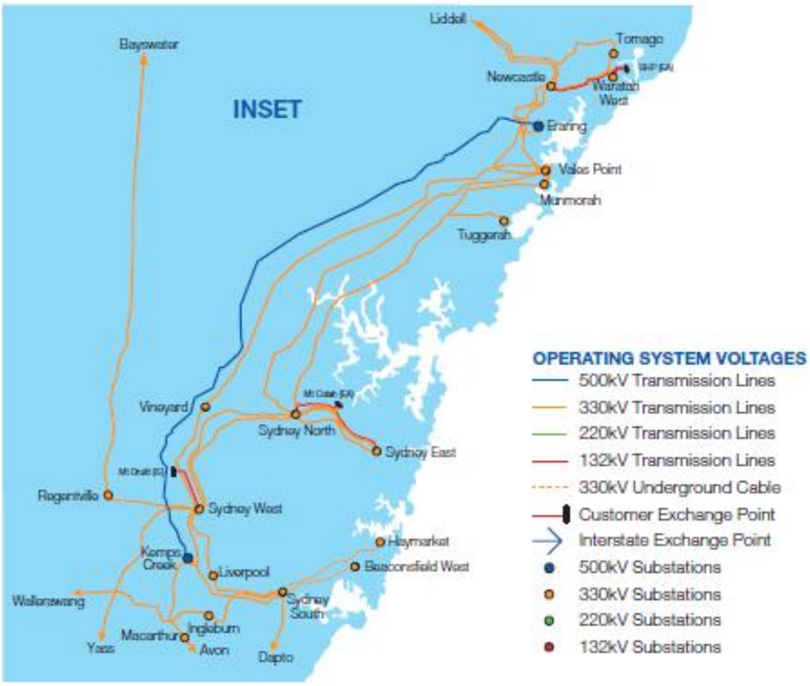
→ **Promote effective access** to those transmission facilities.

Our Network

The system, which has a replacement value of almost $10 billion, operates at voltage levels of 500, 330, 220 and 132kV. The substations are normally located on land owned by TransGrid, with the transmission lines generally constructed on easements acquired across private or public land.

TransGrid has staff strategically based at locations throughout NSW in order to meet day to day operation and maintenance requirements as well as being able to provide emergency response. The head office is located at the corner of Park and Elizabeth Streets in Sydney. Field staff are co-ordinated from major depots located in Western Sydney, Newcastle, Tamworth, Orange, Wagga Wagga and Yass.

TransGrid's network is shown on the electricity network maps below.

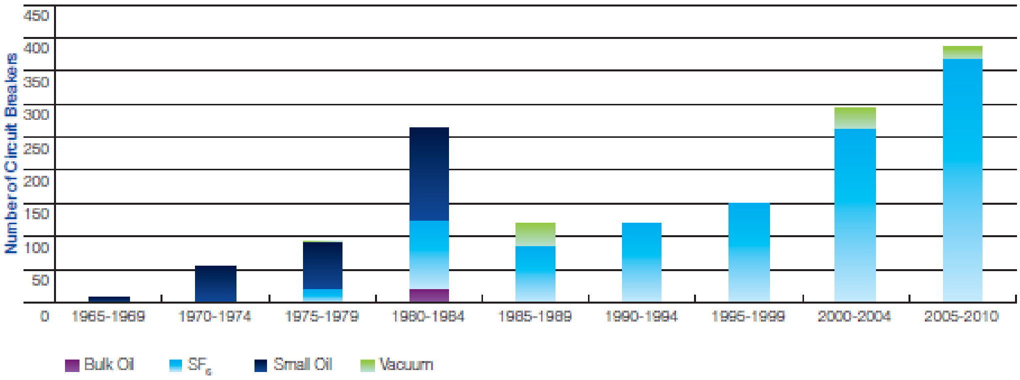


Chapter 1 Part 4

Circuit Breakers

TransGrid's circuit breaker population comprises 1483 units in the voltage range from 11kV to 500kV. The types of circuit breakers used include Bulk Oil (BO), Small Oil Volume (SOV), Vacuum and SF_6.

Circuit Breaker Age Profile



All recent circuit breaker purchases at 66kV and above are of the SF_6 type with a preference for spring operating mechanism. The type and age profiles given above reflect the various numbers and types of circuit breakers installed on the network as at 1 January 2011.

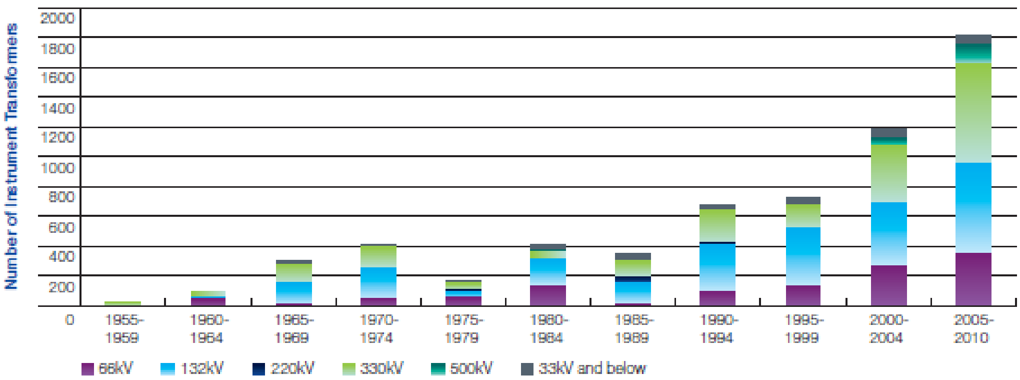
Instrument Transformers

TransGrid manages a total instrument transformer population of 6157 units ranging in voltage from 11kV to 500kV, comprising:

- 3850 Current Transformers (approximately 63% of population)
- 692 Magnetic Voltage Transformers (approximately 11% of population)
- 1615 Capacitor Voltage Transformers (approximately 26% of population)

The age profile shows that 7% of these units were manufactured before 1970 and some of the oldest units before 1957. All of the above units are of the post freestanding type and any instrument transformers contained within metal clad switchgear, gas insulated switchgear, power transformers and oil filled reactors are not included in the above statistics.

Instrument Transformers Age Profile



Circuit Breakers

TYPE	MANUFACTURER	TYPE	VOLTAGE (kV)	QTY	FIRST INSTALL DATE	LAST INSTALL DATE
Small Oil	ASEA	HLC72.5 1600	66	61	1978	1982
Small Oil	ASEA	HLD145	132	55	1968	1981
Small Oil	ASEA	HLR145/2501E	132	74	1980	1989
Small Oil	ASEA	HLR145/2502B	132	2	1980	1980
Small Oil	ASEA	HLR145/3152C	132	22	1980	1984
Small Oil	ASEA	HLR170/2502	132	2	1972	1972
Small Oil	ASEA	HLR84/2501B	66	17	1983	1983
Small Oil	DELLE	HPGE 9/12/E	66	50	1973	1975
Small Oil	MAGRINI	38MGE1500	33	17	1978	1982
Small Oil	MAGRINI	12MG500	11	4	1980	1981
Small Oil	SPRECHER	HPF515C6FS	330	3	1976	1981
Small Oil	SPRECHER	HPF509K	66	1	1978	1978
Small Oil	SPRECHER	HPF512N/2FS	132	4	1980	1980
SF_6	ABB	EDFSK1	66	22	1996	1997
SF_6	ABB	EDFSK1	33	2	2003	2003
SF_6	ABB	LTB145	132	68	1996	1997
SF_6	ABB	LTB170	132	17	2004	2005
SF_6	ABB	LTB420	330	3	2009	2009
SF_6	ABB	HPL145	132	58	1990	2001
SF_6	ABB	HPL170	132	4	1987	1992
SF_6	ABB	HPL245/25B1	220	17	1986	1988
SF_6	ABB	HPL362/31A2	330	29	1992	1997
SF_6	ABB	HPL420	330	5	2001	2002
SF_6	AREVA	GL312	132	3	2009	2009
SF_6	AREVA	GL315	330	71	2003	2010
SF_6	AREVA	GL309F1	66	17	2002	2010
SF_6	ALSTOM	FX22D/CIN	500	1	2000	2000
SF_6	ALSTOM	S1-72.5F1/2520	66	30	2000	2008
SF_6	ALSTOM	FXT-15	330	128	2000	2008
SF_6	ALSTOM	FXT-16	330	5	2001	2002
SF_6	ALSTOM	SF145F1	132	86	2000	2007
SF_6	BROWN BOVERI	HB.24.16.25L	22	4	1986	1986
SF_6	BROWN BOVERI	HB.36.12.25L	33	3	1988	1990
SF_6	BROWN BOVERI	ECK132	132	18	1975	1978
SF_6	MAGRINI	36GB20	33	2	1984	1984
SF_6	MAGRINI	36GIE	33	15	1996	1997
SF_6	MERLIN GERIN	PFA1	66	3	1986	1986
SF_6	MERLIN GERIN	FA1	132	6	1980	1986
SF_6	MERLIN GERIN	FA2	330	48	1980	1984
SF_6	MERLIN GERIN	FA4	500	11	1982	1983

TYPE	MANUFACTURER	TYPE	VOLTAGE (kV)	QTY	FIRST INSTALL DATE	LAST INSTALL DATE
SF_6	MITSUBISHI	DEAD TANK	132	10	2009	2010
SF_6	MITSUBISHI	DEAD TANK	66	13	2009	2010
SF_6	SIEMENS	3AQ2	330	36	1991	1993
SF_6	SIEMENS	3AS2	330	37	1982	1984
SF_6	SIEMENS	3AP1-FG	132	22	2000	2007
SF_6	SIEMENS	3AP1-FG	66	20	2005	2009
SF_6	SIEMENS	DEAD TANK	66	42	2001	2010
SF_6	SIEMENS	DEAD TANK	132	79	2001	2010
SF_6	SIEMENS	8DN8	132	18	2005	2005
SF_6	SIEMENS	8DN8	330	4	2005	2005
SF_6	SIEMENS	3AP2	330	24	2009	2010
SF_6	SIEMENS	3AP3	500	17	2009	2009
SF_6	SPRECHER	FXT9	66	9	1992	1993
SF_6	SPRECHER	HGF309	66	4	1986	1991
SF_6	SPRECHER	HGF112/1C	132	27	1986	1996
SF_6	SPRECHER	HGF312/1C	132	20	1992	1994
SF_6	SPRECHER	HGF215/2B	330	40	1986	1989
Bulk Oil	REYROLLE	LMT/X	11	20	1980	1980
Vacuum	JOSLYN	VBU-4	220	2	1978	1978
Vacuum	ALSTOM	0X36	33	48	2000	2007
Vacuum	ALSTOM	G42883	22	3	2001	2001
			Total	**1483**		

Appendix E: Australian National Greenhouse Gas Accounts Excerpts

AUSTRALIAN NATIONAL GREENHOUSE ACCOUNTS

National Greenhouse Accounts Factors

July 2012

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$\boldsymbol{Stock_{jk}}$ is the stock of HFC or SF_6 contained in equipment, by equipment type (tonnes of CO_2-e); and

$\boldsymbol{L_{jk}}$ is the default leakage rates by equipment type.

For the factor $\boldsymbol{Stock_{jk}}$, an estimation of the stock of synthetic gases contained in an equipment type may be based on the following sources:

(a) the stated capacity of the equipment according to the manufacturer's nameplate;

(b) estimates based on:

(i) the opening stock of gas in the equipment; and

(ii) transfers into the facility from additions of gas from purchases of new equipment and replenishments; and

(iii) transfers out of the facility from disposal of equipment or gas.

Table 24: Leakage rates for synthetic gases

Equipment type	Default annual leakage rates of gas	
	HFCs	SF_6
Commercial air conditioning—chillers	0.09	
Commercial refrigeration - supermarket systems	0.23	
Industrial refrigeration including food processing and cold storage	0.16	
Gas insulated switchgear and circuit breaker applications		0.0089

Source: National Greenhouse and Energy Reporting (Measurement) Determination 2008 (Section 4.102).

Example: Calculation of emissions generated from the operation of a commercial chiller

A company operates a commercial air conditioning-chiller, which contains 160 kg charge of HFC134a.

Convert HFC134a into a CO_2-equivalent using the global warming potential of 1300 (from Appendix 1)

$$= 160 \times 1300/1000$$

$$= 208 \text{ tonnes } CO_2\text{-e}$$

Applying the annual leakage rate of 0.09 (i.e. 9%) gives:

$$= 0.09 \times 208$$

Total scope 1 GHG emissions = 19 tonnes CO_2-e

The Global Warming Potential (GWP) is an index used to convert relevant non-carbon dioxide gases to a carbon dioxide equivalent (CO_2-e) by multiplying the quantity of the gas by its GWP in the table below.*

Table 26: Global Warming Potentials

Gas	Chemical formula	Global Warming Potential
Carbon dioxide	CO_2	1
Methane	CH_4	21
Nitrous oxide	N_2O	310
Hydrofluorocarbons HFCs		
HFC-23	CHF_3	11,700
HFC-32	CH_2F_2	650
HFC-41	CH_3F	150
HFC-43-10mee	$C_5H_2F_{10}$	1,300
HFC-125	C_2HF_5	2,800
HFC-134	$C_2H_2F_4$ (CHF_2CHF_2)	1,000
HFC-134a	$C_2H_2F_4$ (CH_2FCF_3)	1,300
HFC-143	$C_2H_3F_3$ (CHF_2CH_2F)	300
HFC-143a	$C_2H_3F_3$ (CF_3CH_3)	3,800
HFC-152a	$C_2H_4F_2$ (CH_3CHF_2)	140
HFC-227ea	C_3HF_7	2,900
HFC-236fa	$C_3H_2F_6$	6,300
HFC-245ca	$C_3H_3F_5$	560
Perfluorocarbons PFCs		
Perfluoromethane (tetrafluoromethane)	CF_4	6,500
Perfluoroethane (hexafluoroethane)	C_2F_6	9,200
Perfluoropropane	C_3F_8	7,000
Perfluorobutane	C_4F_{10}	7,000
Perfluorocyclobutane	c-C_4F_8	8,700

NATIONAL GREENHOUSE ACCOUNTS (NGA) FACTORS

Gas	Chemical formula	Global Warming Potential
Perfluoropentane	C_5F_{12}	7,500
Perfluorohexane	C_6F_{14}	7,400
Sulphur hexafluoride	SF_6	23,900

*These GWP factors are those used for calculating emissions in Australia's National Greenhouse Accounts.