

Efficiency of high voltage circuit breaker



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Abstract

A circuit breaker is essential in any electrical protection system. By measuring an imbalance in a circuit's current, it will trip open in order to protect the wires and equipment from overheating. Circuit breakers, like most electrical equipment, have become increasingly efficient with implementations of new materials. Since an electrical arc can reach temperatures over

20,000 °F

, there is a need for an insulating material inside the bushing to help rapidly extinguish the arc and keep temperatures in an ideal range. The four main insulating materials for high voltage breakers are: air blast, oil, vacuum, and SF₆

. Of those, the most commonly used in modern installations is SF₆

. With the addition of an insulating material, the temperatures within the circuit breaker falls into a tolerable range when an arc is caused by the opening of the breaker. However, over the lifespan of a piece of electrical equipment that is exposed to high voltage arcing, the contact points either need to be able to withstand such conditions, or will need to be replaced over time.

A circuit breaker is a very valuable component in any electrical system acting as a protection device. Circuit breakers can be found in every home and are used to protect expensive appliances and everyday electronics. A circuit breaker detects a current on the line that is either too low or high, and

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opens the circuit. A circuit breaker can be reset to close the circuit again, where a fuse protection simply burns up from a high current in order to open the circuit which would need a replacement to reclose. On the high voltage side of things, circuit breakers are used in substations to protect much more expensive equipment and ensure that a safe level of power is delivered to various populated areas. There are 4 main types of insulation used in the high voltage circuit breakers ranging in efficiencies and specific uses.

Oil filled circuit breakers are one of the oldest types. In these circuit breakers, mineral oil is typically used since it has a high dielectric strength. When the circuit breaker detects a fault, the contacts inside the circuit breaker separate that creates an arc between the two contacts. The oil, typically mineral oil, in contact with the arc begins to vaporize, producing hydrogen gas which cools and ionizes the arc. In the early 1940's the oil filled circuit breakers had a maximum interrupting capacity of 3.5 GVA with an interrupting time rating of five to eight cycles [1]. With an increasing load, there is a need for an increase in power and protection. By the early 1950's the maximum interrupting capacity increased to 10 GVA with an interrupting time rating of 20 cycles [1]. These circuit breakers were mostly found at high generation substations, but the two substations that contained these 10 GVA circuit breakers were at the Grand Coulee Dam in Washington and the Hoover Dam in Nevada. The rest of the large generation substations contained 5 GVA maximum circuit breakers with a maximum reclosing rate of three-cycles. At this time, the efficiency of the 10 GVA circuit breaker was far behind the 5 GVA circuit breaker, but the power out of that generation plant was necessary. Within 5-7 years the interruption rate of the 10 GVA

circuit breaker had the ability to match the 5 GVA breakers at a maximum reclosing rate of three-cycles. These, however, were the maximum available at the time and therefore very expensive. Most generation plants could afford to have reclosing times around 25 cycles. These circuit breakers are rated to withstand up to 40 kA of current. It was found that silver-tungsten contacts had the ability to handle such a large current without welding or cause excessive pitting of the contacts [1]. One of the advantages to using a circuit breaker instead a fuse-type protection, is that circuit breakers can simply reclose the circuit either manually or automatically. For the high voltage oil circuit breakers in the 1950's, it was common for circuit breakers across the board to have a common reclose time of 20-cycles. There is a short delay between when the circuit breaker interrupts the circuit and when it recloses the circuit. Various tests are performed to ensure the circuit breaker is operating correctly. To verify its current rating, 25kA is passed over four second intervals and is then checked for deterioration. To test its heat retention, a continuous load of 1. 2kA is passed while monitoring the temperature to ensure it stays within desired limits [1]. Even though all of these tests seem promising, there is a reason there was a shift from oil circuit breakers in the mid to late 1960's. The reaction producing hydrogen gas is effective, but over time that reaction causes impurities in the oil, decreasing its dielectric strength, making it less efficient over time. Also, in the engineering world, there is always a push for smaller size and higher efficiency. Typical high voltage oil circuit breakers were very large and the oil posed an environmental threat if the tank were to leak. The interrupter assemblies inside the 230kV, 10 GVA circuit breakers could be as large as 40 inches tall [1]. The oil tank has to consist of enough oil to insulate the

interrupter from the steel exterior. The mineral oil was commonly used because of its high dielectric strength; however, it is also very flammable so there is always a chance of combustion. In order to improve on the current design of the circuit breaker, a new insulating medium had to be implemented.

There was a European push to find a new insulating medium in the late 1930's after suffering multiple explosions from high voltage oil circuit breakers. However, it wasn't until post World War II when they could implement any sort of design [8]. The air blast circuit breaker uses a current transformer to monitor the current in the circuit to ensure it is operating in a correct range. One main advantage of the air blast circuit breaker is that it is oil-less so there is no danger of combustion. The speed of arc-interruption and automatic reclosing is much faster than the oil circuit breaker. Even in the mid to late 1940's, researchers were able to limit the duration of the arc to 0.007 seconds and obtain a full close-open-close cycle of approximately 0.05 seconds on a 142kV, 640 MVA rated circuit breaker. Because the duration of the arc was so small, it resulted in a much shorter arc length than when compared to the oil circuit breaker. This, in turn, allowed for a much smaller piece of equipment that took up less real estate in the substation. The 150KV, 1.8 GVA air blast circuit breaker automatically reclosed with a delay of under 0.2 seconds. This shows that at the same voltage but nearly a three times higher power rating, or a higher current carrying capacity, the delay for reclose is still relatively short being between 10-12 cycles. For the same style breaker rated at 230kV and 2.5 GVA, it was able to reclose with a delay of 16 cycles. This delay is shorter than what is needed for the oil circuit

breaker is 20 cycles at the same rating [6, 13]. If the fault happens to remain present when the circuit recloses, the circuit breaker will reopen and stay open. The blast of air used is a short pulse with high velocity ensuring the first arc is extinguished. However, if the contacts are still within clearance, the arc has the ability to restrike multiple times until it loses its energy. This can cause a loss in efficiency of the breaker at higher current applications.

Once the high voltage air blast circuit breaker began to be phased out of common installation, the vacuum style circuit breaker became more popular. Unlike the high voltage oil circuit breaker and the air blast circuit breaker, the vacuum circuit breaker had little to no threat of combustion or explosion, making it a safer medium of insulation. Also, the high voltage vacuum circuit breakers have a substantially longer operating life and nearly zero environmental impact making them more appealing to new installations [4]. However, unlike the previous mentioned circuit breakers, the vacuum circuit breaker relies more on the shape and material of the contacts to extinguish the arc instead of the actual medium that insulates the circuit breaker. Since there is essentially no medium that interacts with the arc, other means of adaption have to be taken into consideration. By increasing the radius of the contacts 1.3 times, the maximum dielectric strength was increased 10% [4]. By adding a ring to the back of the electrode the maximum dielectric strength was increased by 30% [4]. Since the contact gap is relatively short, typically between 30mm and 80mm for high voltage, there is a lot of heat present at the surface of the contacts. When comparing materials, CuCr40 was able to maintain its physical properties after multiple arcs, where CuCr40 Fe

showed signs of strain and deformation via microscopic holes [9].

The high voltage S F 6

circuit breakers are currently the most popular to be installed in new and existing substations. Since the introduction of the oil circuit breaker, the interruption capability and efficiency has continually increased, and the S F 6

circuit breakers have been found to be the most effective at interrupting up to 20 GVA. It has been found that S F 6

is 100 times more effective at extinguishing an arc than the air blast circuit breaker at voltages ranging from 33kV up to 800kV. This is important because as we move into the future, the Earth's population increases, which ultimately results in an increase in power demand and power transmission safety. To protect the main contacts, there are rounded arcing contacts in place to take the arc once the main contacts slide behind a certain point [2].

This not only protects the main contacts, but the entire circuit breaker as well. If the charge remained on the main contacts cannot be extinguished and would ultimately lead to breaker failure [2]. When the arcing contacts take control of the arc, the S F 6

gas rapidly absorbs all of the free electrons present in the arc to extinguish it at a fast rate. When reacting with the free electrons, the S F 6

molecule can either take on the electron and become negatively charged, S F 6 –

, or a fluorine can break its bond with sulfur and bond with a free electron creating SF_5^-

and F [10]. Along with a short arc time, the SF_6

gas also has the ability to dissipate heat most effectively and since there is no loss of pressure during the extinguishing process, unlike the air blast circuit breaker, the pressure inside the SF_6

tank is easily monitored and maintained. These breakers can operate reliably with internal temperatures ranging anywhere from $300^\circ K$ to $3000^\circ K$

at around 30 psi. When the temperature is at or below $1000^\circ K$

, SF_6

is the dominant molecule at 99.97%. However, as the temperature of the gas increases there is a breakdown into multiple different combinations of SF_6

. Once the temperature reaches over $2000^\circ K$

, neutral fluorine, a F^+

is bonded with an e^-

, is the dominant molecule at 64%, followed by SF_4 , SF_5 , and SF_6

as the next most abundant molecules with SF_6

being only 3% prevalent [10]. This results in a lower dielectric strength and a less effective arc interrupter because the subset molecules of SF_6

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are much weaker in those areas. Therefore, at internal temperatures above 2000 °K

there is a decrease in efficiency of the SF₆

circuit breaker. However, SF₆

has very good cooling properties, so this phenomenon only happens for a short period after it extinguishes an arc. When the pressure is dropped to around 3 psi, the SF₆

could reliably operate up to 1 000 °K

[10]. This follows Paschen's Law stating that the breakdown voltage of an arc is correlated with the pressure of the insulating gas multiplied by the contact gap distance. Because of this law, when the breaker is in its closed position, the contacts are surrounded by SF₆

at roughly 40 psi, once the contacts separate and open the valve to the stored SF₆

the pressure increases to nearly 200 psi. This ensures that the circuit breaker can safely operate at and above 20 GVA. The SF₆

high voltage circuit breakers are the most commonly installed breakers today in new and existing substations because of their efficiency, size, and power handling capability. However, even though the gas is not harmful to animals or humans, it is considered a potent greenhouse gas because of its long lifetime and strong infrared absorption [6]. With global warming

becoming a continuously growing issue, there is a clear motive to move past using such harmful greenhouse gases.

The move away from SF₆

is not necessarily an easy step due to its high dielectric strength and its interruption capability. However, it being a greenhouse gas makes the transition seem logical for the environments sustainability. Since

SF₆

has such superior properties as an insulation medium, naturally found gases cannot simply be substituted for the greenhouse gas since their dielectric strength and current interrupting properties are far inferior. This led to the idea of mixing SF₆

with an environmentally-friendly gas. Since CO₂

has already been manufactured in lower voltage circuit breakers, it is the most viable candidate. This raises the dielectric strength and current interrupting capability of CO₂

when mixed with SF₆

. Since CO₂

has a lower temperature molecular breakdown than SF₆

, at around 1200 °K

a 75%- SF₆

to 25%- CO₂

mixture breaks down into SF₆, CF₄, and SO₂F₂

with both SF₆ and CF₄

being potent greenhouse gases [6]. This indicates that the mixture would not be able to return back to the initial gaseous mixture at a convenient rate during the cooling process. Another option is to completely remove SF₆

as a gas used inside the circuit breaker. Mixtures containing CO₂, N₂, and CF₃I

have been considered [5]. However, the dielectric strength and current interrupting capability of this gaseous mixture is much lower than pure SF₆

. Another main issue is the voltage breakdown of the compound is also lower. On top of that, when the molecule CF₃I

breaks down, it prefers to lose either a fluorine ion or an iodine ion to water in the air. This results in either the production of HF or HI which are very corrosive acids and dangerous to humans and animals.

When circuit breakers were first introduced in the early 1900's, the power handling capability far exceeded the power supplied. However, they were and still are a vital piece to all of our energy systems. Like most things, circuit breakers have evolved and adapted along with the growing demand for electrical power. The high voltage oil circuit breakers rated at 230kV and 10 GVA that monitored the power produced by the Hoover Dam, have been continuously improved with new insulating mediums and technology. Today

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we have high voltage circuit breakers with near immediate interrupting times and automatic reclosing rated over 35 GVA. Along with improvements to efficiency and power increase, engineers have been able to decrease the size of the circuit breaker unit. This in turn has decreased the size of space needed in a substation. For future applications, a push from using harmful greenhouse gases seems apparent in case there is a leak or another type of disaster that could lead to harming the planet. There are other means available, it is just a matter of being able to match the superior properties of SF₆

gas. I would like to see an improvement in vacuum circuit breakers in the high voltage realm since they can be much more compact and are currently very efficient at lower voltages. It seems that this is a material property issue since the high temperatures in a compact area destroy the contacts at the high currents needed in high voltage transmission.

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