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Review Article

# Recent Advances in Vacuum Circuit Breakers

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***Abstract***

The paper studies the basic elements of vacuum arc formation and interruption, the design and applications of vacuum switch technology as well as its limitations. Beginning with the description of the main components of a vacuum circuit breaker (VCB), the study moves on to its historical development throughout the years. The context analyzed next refers to the properties and the principles of electrical breakdown mechanisms in vacuum, based on Paschen's law and Townsend theory. The creation of the electrical vacuum arc and its different forms are also an important part of this study. Finally, the main applications of vacuum circuit breakers in electrical power systems, along with their recent advances are analyzed and profitable prospects are created for the coming years.

***Keywords:*** Vacuum, Circuit Breaker, VCB, Electric Arc, Breakdown Mechanisms, Electrical Power Systems, Future Technology

## 1. Introduction

The vacuum circuit breaker (VCB) plays a vital role in the distribution of electricity, acting as a means of controlling and protecting the electrical distribution system. It is due to significantly advantageous properties of vacuum circuit breakers such as high interruption capability, low voltage of vacuum arc, small contact electrical wear rate and long operation life. Starting from the structure of the VCB, we can observe that its contacts are enclosed in a vacuum chamber consisting of glass or ceramics and are closed by a mechanism connected to the movable member. The movable member is connected to the vacuum chamber by stainless steel bellows, allowing contacts to open and close while keeping vacuum at $10^{-4}$Pa (~$10^{-6}$ mbar) [1-3]. Such a vacuum must be maintained – without pumping – for the entire life of the unit.

Initially, air served as the medium, but in the 1920s oil became dominant and remained so until the 1970s, when vacuum appeared. Since then, vacuum has become the technology of choice challenged by a different technology, sulphur hexafluoride ($SF_6$), during the 1980s and 1990s. Both technologies are currently available but vacuum remains dominant [4].

The development of vacuum technology was based on the notion that vacuum is widely recognized as the leading insulating material at steady state, because quite simply vacuum "*has nothing to support conductivity*" [5]. Arc residues are naturally diffused in the vacuum, restoring the dielectric and interrupting current by natural means. This is different from pertinent technologies, such as gas switches, whose performance and design are dependent on the gas flow from the mechanical means activated from the outside.

The history of vacuum switching dates back to the 1890s with Enholm's first patent and continues with the practical invention in the 1920s by Sorensen and Mendenhall, resulting today in a very effective way of controlling the power flow in power supply networks. However, despite the initial observations, it took a long time for the vacuum circuit breaker to emerge as a reliable construction solution and to be accepted by the electric power industry [5, 6].

## 2. Electrical Breakdown Mechanisms In Vacuum

When a gas changes from being an insulator to conducting electricity within a gap, a transient process recognized as electric breakdown occurs, per Townsend's theory. Electron avalanche and cascade ionization multiplies primary electrons along the gap. The theory of electrical breakdown in gases existing within the space defined by two metal electrodes in parallel configuration was established by Townsend, based on the observations explained in [6-8].

An electric field drives primary electrons close to the cathode towards the anode when an external voltage source is applied along the gap. The background of neutral gas atoms is ionized. Positive ions are formed due to the exponential increase in electron population, which then moves towards the cathode and incurs secondary electron emission, thus affecting the surface of the electrode.

In 1899 Paschen formulated a law now named after him in a publication article, stating that the breakdown voltage $V_b$ between two conducting materials is defined by $V_b = f(pd)$, therefore a function of the product of gas pressure p and the gap length d [9].

Based on Paschen's curve, a significant breakdown voltage value is predicted for small pd values, corresponding to low pressure or short gap distance on the curve left branch. As pd gradually increases, a point on the curve with minimal breakdown voltage is reached. Any further increase in pd from this point leads to a gradual increase in the breakdown voltage as shown on the right branch of Paschen's curve in

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Figure 1.

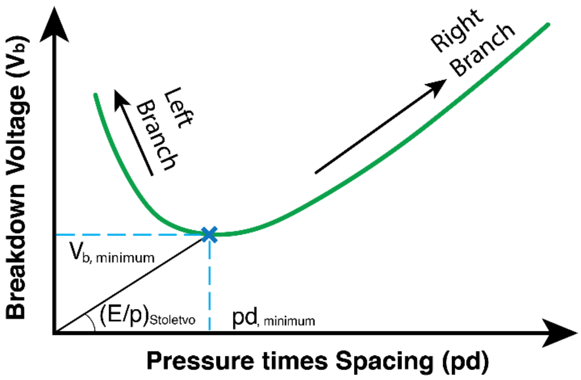


**Fig. 1.** Paschen's curve for breakdown in gas

Various vacuum breakdown mechanisms have been proposed since the 1950s, typically separated into three categories: Field Emission Mechanism, Clump Theory, and Particle exchange mechanism.

According to [11], the Particle Exchange Mechanism assumes that, under high electric field action, emission of charged particles from one electrode and impingement on the other liberates particles of opposite charge due to absorbed gas ionization. Applied voltage accelerates these particles back to the first electrode, releasing more original particles. Therefore, a chain reaction eventually occurs leading to what is called gap Vacuum Breakdown. Electrons, photons, positive ions, and gases absorbed at the surface of the electrode are involved in the Particle Exchange Mechanism. To reiterate, an electron accelerated towards the anode inside the vacuum gap releases A positive ions and C photons on impact. Each of these positive ions liberates B electrons and each photon liberates D electrons when impacting with the cathode. The Vacuum Breakdown will occur if the coefficients of production of secondary electrons exceed unity, mathematically written as: $(AB+CD) > 1$, where A, B, C and D were the same as before [11].

Field emission theory is divided into two types, depending on the role played by the electrodes.

The Anode Heating Mechanism postulates that micro-projections due to field emission on the cathode produce electrons which bombard the anode, heightening temperature and releasing vapors and gases into the vacuum gap. The atoms of the gas are ionized and in turn produce positive ions, which arrive at the cathode, resulting in primary electron emission increment owed to space charge formation. Surface bombardment produces secondary electrons. The process is reiterated until enough electrons are produced triggering Vacuum Breakdown, as in the case of a low-pressure Townsend type gas discharge [11].

The Cathode Heating Mechanism assumes that cathode surface sharp points near the gap breakdown voltages trigger pre-breakdown current, generated with respect to the field emission process, as mentioned below. Resistive heating is caused by this current at the tip of a point. Reaching a critical current density melts and explodes the tip, initiating vacuum discharge [11].

Therefore, initiating Vacuum Breakdown depends on the properties and state of the cathode surface. This process causes breakdown when the effective cathode electric field is of the order of $10^6$ to $10^7$ V/cm, as supported by experimental testing [12, 13].

The Clump Theory assumes the following:

- Existence of a loosely bound particle (clump) on at least one electrode surface.
- Applying high voltage charges this particle, detaching it from the mother electrode and launching it across the gap.
- Discharge in the gas or vapor released by this impact at the target electrode causing Vacuum Breakdown.

This theory was initially proposed by Cranberg [14]. An initial assumption is that when the energy per unit area W, delivered to the target electrode by a clump exceeds a value of a constant C′, characteristic of a given pair of electrodes, causes breakdown. W is the product of gap voltage (V) and clump charge density, which is proportional to the electric field intensity E at the electrode of origin. Therefore, Vacuum Breakdown occurs when $VE = C'$.

It is reasonable to conclude that there is no theory that can define a common vacuum breakdown process. It appears that each mechanism has significant dependence on the experimental conditions. Factors with the largest influence on the breakdown mechanism are: gap length, surface uniformity and treatment, electrode material and geometry, extraneous particle presence, and residual vacuum gap gas pressure. Correct choice of electrode material and thin insulating coating usage on electrodes with long gaps in between can increase the breakdown voltage of a vacuum gap, according to observations. Electrode area increase or particle presence in the vacuum gap may reduce the breakdown voltage.

## 3. Vacuum Arcs and Control Mechanisms

Once a fault current occurs in a circuit, switch contact separation has no direct impact on the current flow. The current density becomes very high at the last contact points level, causing melting locally and forming a liquid metal bridge between them. As contacts keep moving further from each other, current heats this bridge rendering it unstable. A subsequent rupture triggers the appearance of a metallic vapour arc, resulting from the explosion of the liquid bridge. Therefore, the vacuum arc is able to be reasonably defined as an arc that exists only within the metallic vapors released by the contacts, through the arc formation process itself. This creation of the arc by separating the contacts under the current load will result in a diffuse or constricted mode, maintained up to zero current and even evolve from one to the other.

In the diffuse mode of the vacuum arc, neutral plasma is emitted by the cathode into the electrode gap, through one or several spots. This plasma consists of fast ions and electrons, the velocity of which is mainly perpendicular to the cathode surface. The anode reacts as a passive current collector in current below about 10 kA, with its entire surface immersed in this plasma. The cathode spot area is very small, with a radius of 5 to 10 micrometers, whose emitted current can reach a few hundred Amperes.

When it comes to high currents, things are different. For currents above 5 kA, the arc shrinks and becomes a thin column, where all arc energy is concentrated in an area of a few square millimeters. The surface is then surrounded by a hot contact material, due to the very high local temperature at zero current. This hot material disperses like metallic vapor and reduces the dielectric strength of the vacuum between the contacts, which can lead to a restart due to Transient Recovery Voltage (TRV) [15, 16].

Two main phases can be distinguished in the arc current interruption process:

1) The arc phase, and
2) The post-arc dielectric recovery process.

The last stage has a critical impact on the entire current interruption process in the following way. As soon as the current is eliminated, the dielectric strength of the switching gap decreases and it takes time to recover from zero to its initial value. The reduction of the breakdown strength is a function of the energy input into the contacts, i.e., the amount of heat of the contact surface caused by the energy input of the previous arc. If the transiently recoverable mains voltage exceeds the reduced dielectric strength, then a reignition, i.e., a breakdown failure occurs. If the contacts can withstand the transient voltage and end up in vacuum again, then the current is successfully interrupted. The recovery period may take a few milliseconds until contacts are stabilized again [17].

There are no means of cooling to control the vacuum breaker mechanically, and affecting the arc channel is only possible through interaction with a magnetic field, which may be generated through contact geometry by creating a current path through the contact system.

Two different principles are used to avoid vacuum arc contraction during high current breakdown:

1) The radial magnetic field principle, and
2) The axial magnetic field principle.

Based on the radial magnetic field principle, the form of the constricted arc in vacuum can be considered as a conductor with a parallel to the contact axis current flow. Applying a radial magnetic field to this conductor develops electromagnetic force (Lorentz), causing rotation of the arc on the contact surface. Spiral-type contacts are used to achieve this result.

However, based on the axial magnetic field principle, the perpendicular mobility of the charge carriers is significantly reduced when a magnetic field is applied in the direction of current flow in the arc. The arc retains its diffuse mode, ensuring that only a small amount of energy reaches the contacts. Axial magnetic field (AMF) application leads to a stable arc tension behavior. The behavior of the vacuum arc makes the axial magnetic field contact systems better suited to high short-circuit currents (>50kA). Also, it was discovered that the vacuum arcs became more stable and evenly dispersed when axial magnetic fields were applied. This stabilization of the vacuum arc under AMF leads to the reduction in the arc voltage. It is because, under the AMF type electrodes, the plasma remains confined around the AMF lines of force, preventing the large anode drop, thereby resulting in low arc voltages, which further reduces the amount of heat that is dissipated in the electrodes and the inter-electrode area [18].

Thus, the use of AMF type electrodes for vacuum circuit breakers helps in achieving high current interrupting capability, reduced duration of constricted arc and low arc voltages.

## 4. Applications of Vaccum in Medium, Low and High Voltage

Out of all the fields of application of vacuum breakers, Medium Voltage (MV) is the most widely known and constitutes their main field of application. More specifically, due to the high electric strength of the vacuum using either radial or axial magnetic field technologies, higher breakdown capacities required for MV are achieved. Also, as is the case with vacuum, $SF_6$ it offers in this application the advantages of an encapsulated breakdown without external aspects and a high electrical strength and maintenance-free design. Vacuum breakers require less power than $SF_6$ circuit breakers, since an external power supply is not necessary for vacuum switching. The main examples of such vacuum breakers in MV are breakers, disconnectors, and contactors.

Vacuum switching is extensively employed in MV contactors and circuit breakers. It may also be employed in similar LV applications but is rarely used. Firstly, it competes with the breakdown technique through air that is simpler, cheaper and better adapted, and secondly, the disadvantages that have occurred in MV are more apparent in LV.

So far, several attempts have been made to apply vacuum in High Voltage (HV) without significant success. It appears that the vacuum switching characteristics do not allow equal competition with the breakdown technique through $SF_6$.

Since the insulation level across the vacuum gap was more or less saturated, the feasible voltage for a single vacuum interrupter in high voltage applications had previously been restricted to 100 kV. As a result, two high voltage vacuum interrupters were adopted and were used in transmission networks [19]. In order to further increase the rating of these high voltage interrupters, other than vacuum technology i.e., $SF_6$ gas insulation has been used to maintain the insulation outside vacuum. Inside, conventional vacuum switchgear was built but the exterior insulation of the vacuum interrupters was sealed with $SF_6$ gas at atmospheric pressure. It was shown that a total reduction in size was significantly accomplished using this method [20]. These types of Gas Insulated Switchgear (GIS) varieties were adopted in indoor as well as outdoor substations.

Synergy increases in static insulation and dynamic dielectric recovery strength (DDRS) have been observed when comparing multibreak to single break VCBs. Series-connected small vacuum gaps solve the breakdown voltage versus vacuum gap saturation also multibreak VCBs have faster and greater DDRS recovery. The synergy effect in multibreak VCBs describes the interaction of arc memory, current zero (CZ) characteristic, and postarc characteristic. The Synergy management between dynamic dielectric recovery strength and postarc dynamic voltage distribution can maximizes breaking capacity of the VCB [21].

The nonlinear dependence of the breakdown voltage on the contact gap and the control of vacuum arcs with wide contact gaps are the main challenges of single-break technology [22]. Multiple breaks in series give the other technique excellent voltage tolerate. Japan has multiple 168/204 kV installations [23]. Multiple-break technology must handle synchronized opening and closure, uniform stressed voltage distribution, and a failure rate that rises with the number of series-connected breaks. Despite these obstacles, multiple break designs up to 750 kV and a prototype of 363 kV/5000 A - 63 kA multiple-break FVCB (Fast Vacuum Circuit Breaker), with two parallel-connected circuit branches in each phase and three breaking units in each branch, have been recorded to improve the transient stability of the system[24,25].

Recently, researchers have replaced the $SF_6$ gas in the gas insulated vacuum circuit breaker with a gas mixture of 30%:70% $CF_3I$-$CO_2$ gas at 0.4 bar pressure and have performed standard lightning impulse test voltages up to withstand voltages and indicated that the application of this gas mixture insulated vacuum breakers in medium voltage switchgear is truly promising and can form a potential alternative insulating medium to $SF_6$ [26]. With further advancements in their design, the gas mixture insulated vacuum breakers can also be used for high voltage applications.

Environmentally friendly switchgear for the high-voltage level consists of a series connection between a gas circuit breaker (GCB) and a vacuum circuit breaker (VCB), both of which are alternatives to the hazardous Sulfur hexafluoride ($SF_6$) gas. GCBs can resist high amplitudes of recovery voltage, while VCBs can withstand very steep rising transient recovery voltages after current zero (CZ). A series connection of GCBs and VCBs with $CO_2$ as an alternate insulating and quenching gas works as envisaged in the hybrid circuit breaker (HCB) idea. VCBs compensate for the GCB's reduced thermal interruption capabilities. The VCB helps the GCB interrupt current and can withstand the transient recovery voltage's peak value, making it useful for situations involving high current interruption and short-line fault interruption with a high rate of rise of recovery voltage (RRRV). If the current is low enough, the GCB can trip and endure the TRV without any additional protection [27].

Further reduction in size of switchgear can be achieved by tightly molding the vacuum circuit breaker with solid insulating material like epoxy resin, as the dielectric strength of a solid insulating material is significantly higher than that of $SF_6$ at normal atmospheric pressure. Recently, a solid insulated switchgear (SIS), in which the main circuits of the vacuum circuit breakers are insulated by molding into epoxy composites. The epoxy composite has been reinforced with $SiO_2$ fillers for providing low coefficient of thermal expansion (CTE) and MgO fillers for providing high thermal conductivity [28].

The main obstacle to obtaining a vacuum breaker with a high voltage value is the dielectric efficiency peak value of about 500 kV. R&D's efforts during this century for vacuum breakdown in HV have gained strong momentum, due to concerns over global warming caused by the very powerful greenhouse gas $SF_6$. Also, the global warming potential (GWP) of $SF_6$ has emerged to be 23,900 times that of $CO_2$ [29]. In this aspect, Chinese HV vacuum breaker research and its ensuing development has provided China with a strong lead, with the publication of single circuit breaker designs up to 252 kV and conceptual designs of future ultra-high voltage (UHV) modular circuit breakers for 550 kV and even for 765 kV

Other authors have mentioned that the improved high voltage vacuum circuit breakers can be designed by considering the following aspects: carefully selecting the external insulation of vacuum interrupter; adopting long contact gaps and axial magnetic field technology for interrupting high short circuit currents; improving nominal current level. Also, the opening and closing characteristics of operating mechanism should be in accordance with the vacuum arc characteristics, for achieving an optimum performance and employing contact bouncing damping technology is essential as the closing velocity and contact stroke on the circuit breaker are higher especially in case of HV vacuum breakers [30].

## 5. Future Prospects & Conclusions

According to current estimates, the vacuum circuit breakers market is expected to grow at a compound annual growth rate of 5.54% to reach USD 2,132,436,000 by 2025 from USD 1,543,027,000 in 2019. Vacuum circuit breakers are mainly used in auxiliary power transmission systems, power plants, and power distribution systems in various industries, such as railways and industrial facilities. One of the main reasons for the development of this market is the need for vacuum circuit breakers in the most demanding electrical circuit protection devices in order to mitigate the possibility of loss caused by electrical overloads.

However, the high costs combined with the risk of malfunction associated with this product constitute a limiting factor for this market. The high cost of a vacuum circuit breaker compared to the available alternatives is expected to be a major impediment to the development of this market. Moreover, the device is prone to malfunction during work and causes difficulties in its general use. However, thanks to technological improvements, this limitation is also expected to disappear.

After its initial release, the vacuum circuit breaker quickly adapted to the present-day requirements and became the technology of choice for circuit breakers in MV applications. This predominance is based on the extended electrical lifetime in load and short-circuit currents, on the ease of maintenance and the occurrence of minimal contact corrosion during operation. Issues concerning the relatively large contact gap, required for HV applications, prevented the initial incorporation of vacuum in HV circuit breakers, except for a few specialized applications. Further high-power tests have shown that vacuum circuit breakers in HV retain the advantages observed in MV applications, such as very long electrical lifetime and minimal contact corrosion.

Since, the thermal conductivity of the vacuum is lower than that of the $SF_6$ gas, forced cooling using silicone oil can be considered. Silicone oil will not only be employed for cooling purpose but also for insulating the outside vacuum of the interrupter. Also, it is well known that the multi-gap configuration provides substantially high breakdown strength. Thus, the new conceptual design of vacuum circuit breakers by combining the multi-gap configuration idea along with the silicone oil immersed vacuum switchgear, can potentially lead to the development in HV vacuum breakers with higher voltage ratings and better design flexibility [19].

High-voltage switches currently use pneumatic, spring, hydraulic, permanent magnet, and motor operating mechanisms [31]. These mechanisms open in tens or hundreds of milliseconds because of multiple parts, large moving parts, delayed response time, and other factors. None of the conventional working methods can fulfil the high-voltage DC circuit breaker's quick mechanical switch's few-millisecond action time. Recently, electromagnetic repulsion has been researched as a rapid operating mechanism for vacuum switches and hybrid DC circuit breakers with lower voltages [32].

High-voltage circuit breakers need more mechanical force and faster breaking speed than medium and low-voltage ones to reliably break current. Within a few hundred microseconds, the circuit breaker must be able to endure an electromagnetic impact force of more than 70 kN [33, 34]. Because of this, high-voltage rapid circuit breakers requires further development from the present method of electromagnetic repulsion.

Increment in circuit breaker operating speed and breaking capacity is essential for fast control and protection of the modern power grid. Recent advancements such as hybrid fast operating mechanisms in vacuum circuit breakers highlighted that the closing operation driven by mono-stability permanent magnetic mechanism and the opening operation driven by electromagnetic repulsion mechanism, ensured faster switching operation, in accordance with the vacuum arc characteristics [35]. Also, the vacuum circuit breakers are gaining popularity to be used in power system network coupled with renewable energy sources such as wind energy farms [36, 37]. Thus, the recent advances have increased the scope of vacuum breakers to a great extent.

In order to achieve a remarkable high current interruption performance, Yu and co-workers hypothesized that an intricately constructed opening travel curve would be helpful. This curve has the potential to do two things: diffuse an intense arc and stop an anode spot from forming during arc interruption drawing. A thorough understanding of plasma physics and the development of VCBs toward transmission voltage relied heavily on prior research [38].

Since the FVCB typically opens in less than 2 milliseconds, it can clear a short-circuit fault in half a fault current cycle. The electrical grid's transient stability might improve greatly. Also, the FVCB opens far faster (by over 3 m/s) than the standard VCBs that use either a permanent magnetic actuator or a spring mechanism for opening [39]. Controlled switching of a short-circuit fault current in a brief arcing time makes the FVCB electrically durable [40]. Therefore, setting a minimal arcing time for a successful current break in this case necessitates further research into the correlations between arcing behaviors and short-circuit current breaking abilities.

The ever-growing electricity grid requires not only increased efficiency and reliability, but also sustainability. Vacuum is a medium with excellent properties when it comes to short-circuit current control and dielectric power recovery. Applications that are currently found mainly in MV distribution networks could be widely spread to HV distribution networks, avoiding the environmental impacts of $SF_6$. The future for vacuum is bright, with new developments extending the potential of vacuum circuit breakers ranging from 145 kV and lower to transmission levels of 245 kV and above [41]. However, it is necessary to introduce changes in the design and materials used to ensure the proper operation of the vacuum circuit breaker at higher voltage values [42]. The list of advantages and disadvantages of $SF_6$ and vacuum circuit breakers in HV is quite balanced. Therefore, it seems that coexistence of both $SF_6$ and vacuum technologies of up to 245 kV appears to be the case for the near future. Choice is dependent on technical requirements, general economic considerations and environmental concerns, regulations, and market price developments.

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