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## Insulation coordination in air insulated substations with vacuum circuit breakers

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# 1 Introduction

Insulation coordination is one of the most important aspects of the design of substations. The system operator must consider all service conditions and guarantee that no uncontrolled flashovers occur, which may damage the equipment in the substation. In particular, short-time events with the highest voltage amplitudes must be taken into account, as they determine the requirements for the equipment, e.g., circuit breakers (CB).

Historically, simple spark gaps have been integrated into substation layouts to create pre-determined points for electrical breakdowns to occur. These spark gaps chop the incoming high voltage wave and thus reduce the necessary withstand capability of the high voltage CBs. The dielectric withstand behavior of the CBs is demonstrated by the chopped wave tests required in the respective IEEE standards [1], [2]. The well-established gas circuit breakers (GCB) are unable to quench arcs after electrical flashovers without contact travel, so their withstand capability must be higher than the expected flashover voltage of the spark gaps used for voltage limitation. In the last decades, there have been drastic changes.
The common practice for insulation coordination of substations is to avoid spark gaps at line and transformer terminals in favor of metal oxide varistors (MOV) [3]. In addition, vacuum circuit breakers (VCB) tend to be used at transmission voltage levels. Comparatively to $SF_6$ or other GCBs, the VCBs have the clear advantage of quenching electrical arcs between the open contacts in a fixed position, without further motion or separation of the contacts. In this technical report, the adjusted requirements for usage of VCBs in modern substations are described.
The necessity of fulfilling the chopped wave withstand requirement of the open contact gap of VCBs requires special consideration, as stated in [2]. It is common practice at distribution voltage levels, but there may be technical and economic reasons to consider this requirement at the transmission voltage levels as well.

# 2 Impulse voltage protection in substations

Overvoltage protection within a substation layout is one of the most crucial topics to be addressed. In the past, gapped silicon-carbide surge arresters were state of the art technology. They were typically reserved for the most valuable component in the substation, the power transformer. This type of arrester also protects the other components in the substation, provided that the elements are electrically connected, i.e., devices (e.g., CBs, disconnectors) in the closed position.

In modern substations, surge arresters are installed adjacent to power transformers, shunt reactors, power cables, gas-insulated substations (GIS), and, in many cases, on incoming lines entering air-insulated substations, to protect the mentioned assets from lightning and switching overvoltages. These surge arresters serve to keep the overvoltages in the range for which the equipment is designed.

The coordination of the permissible overvoltages and protection levels for lightning and switching impulse overvoltages in relation to the system voltage is called insulation coordination and is defined in standard IEC 60071. Reference Guides are given by the CIGRE, IEC, and IEEE for coordination levels to be congruent in the design of substations.
Standardized test procedures and test levels depending on the rated voltage of the equipment have been defined. Typically, the following voltage tests must be performed to establish a certain standardized voltage withstand capability:

- Lightning impulse withstand voltage (1.2/50 µs)
- Switching impulse withstand voltage (250/2500 µs)
- Power frequency withstand voltage (50 Hz or 60 Hz)

Tests that are not generally required in international and national standards but that may be locally required include:

- Oscillating voltage
- Chopped wave lightning impulse with different chopping times

In the following sections, the occurrence of chopped wave impulses and, therefore the necessity to verify the withstand capability of the CBs against such impulses, depending on configuration, shall be discussed. The chopped wave requirement for CBs has been specified since 1960 in IEEE standard only. IEC standards do not define this testing requirement.

Two types of chopped waves are typically used: either a 2 µs chopped wave impulse with a crest value of 1.29 times the lightning impulse (LI) peak value, or a 3 µs chopped wave impulse with a crest value of 1.15 times the LI level. The 3 µs chopped wave requirement uses the same values as that of the transformer standards. In the year 2000, the 3 µs chopped wave requirement was removed from the IEEE Std. C37.06 because of the dielectric behavior of $SF_6$ and VCBs (see Figure 1).

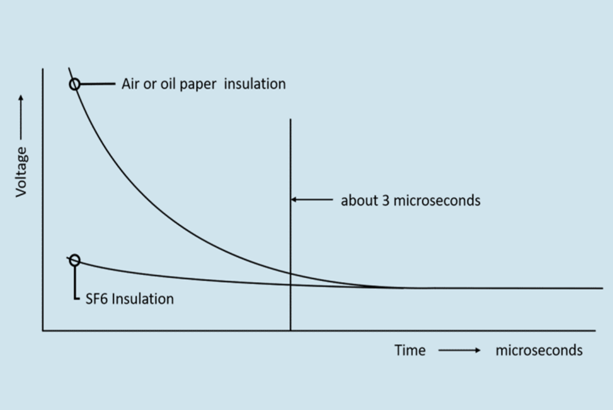


Figure 1: Dielectric behavior of different interruption media.

## 2.1 Chopped wave lightning impulses in substations with line arresters

Any transmission line entering a GIS is equipped with a line arrester at the interconnection between line and GIS. This is the reason why GIS has no rating for chopped wave lightning impulses that must be verified.
Since metal-oxide surge arresters have been established as reliable and cost-effective overvoltage protection, line arresters are also applied for new air-insulated substations (AIS); see Figure 2.
These arresters are also installed when existing AIS substations are refurbished.
Line surge arresters do provide sufficient protection from lightning impulse overvoltages, independently of form (full wave or chopped wave) and limit them to a level that has been verified by lightning impulse voltage type tests. For substations with line surge arresters on incoming transmission lines, the verification of a chopped wave lightning impulse withstand level is not necessary.

## 2.2 Chopped wave lightning impulses in substations with coordinating rod gaps on incoming lines

Many substations are still in service where coordination rod gap arresters protect the station from lightning surges by means of discharge. They are simple and cheap but, when they are activated for protection, there is always a fault current that must be cleared by tripping the affected line.
Chopped wave lightning impulses may travel in the station when such rod gap arresters are installed. They are generated when a full wave lightning surge approaches the station and is then chopped by the rod gap arrester. During normal system operation, either the line is connected, and the CB is closed, or the line is de-energized with the CB open, and the line is separated by a disconnector switch.

In the first case, a chopped wave lightning impulse voltage may hit the CB in closed position. This situation is covered when a chopped wave lightning impulse level has been verified in closed position of the CB.
In the second case, when the CB is separated from the line by a disconnector switch, lightning surges (full and chopped) stop at the open disconnector switch.
Hence, regarding the first case, the verification of a chopped wave lightning impulse withstand level may be required for closed CBs, in substations with coordinating rod gap arresters on incoming transmission lines.

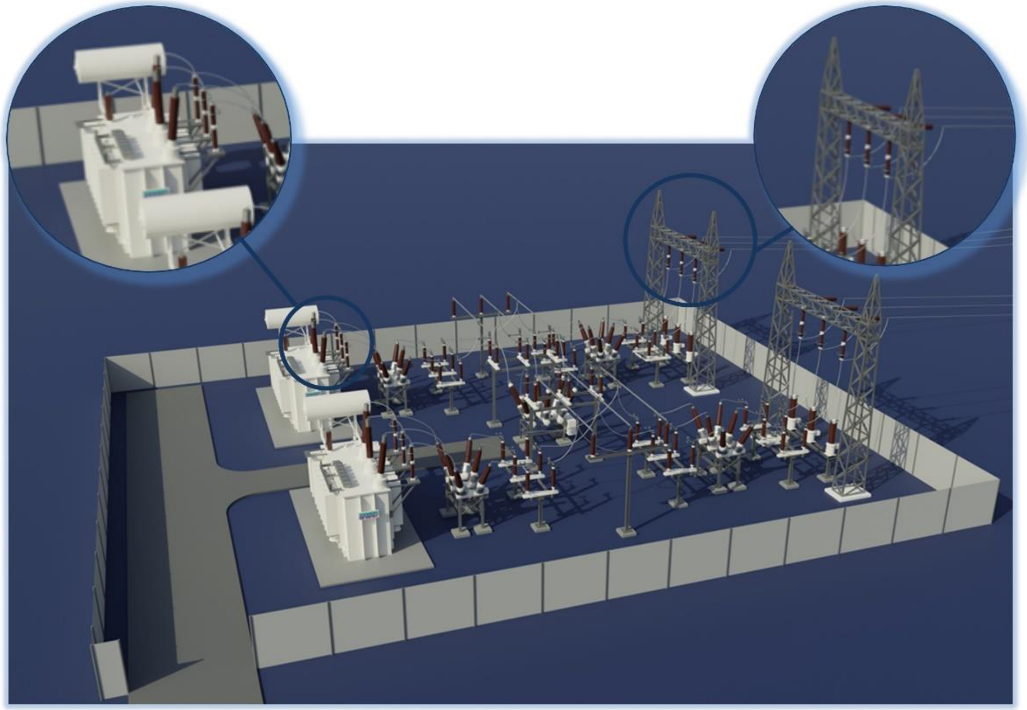


Figure 2: Typical substation layout.

## 2.3 Chopped wave lightning impulses on open circuit breaker contacts

The case of a CB in open position is different. The substation equipment is still protected by the arrester of the power transformer; however, the line entrance terminals are not protected by the arrester of the substation and no protection is provided to the CB. There are three options to solve the problem [4]:

1. An additional surge arrester on the line side.
2. The implementation of rod gap arresters on the line side.
3. No protection measures at all.

Option one is the most favorable solution [3] and is nowadays applied in nearly all new substations.
Options 2 and 3 may be implemented in older existing substations, and the effects on the design and withstand capability of the open contacts of the CB must be discussed.
Most commonly, if the CB is in open position, the disconnector will also be in an open position. The situation where the CB is in the open position and the disconnector is in the closed position is quite rare. If this specific situation were to occur, the contact gap in vacuum may break down at the crest of chopped wave impulse. At this moment, the VCB acts like a closed circuit and the wave travels to the arrester of the substation. The equipment of the substation is protected by this procedure. The current flow is interrupted at the next occurring current zero, since, intrinsically, the VCB interrupts currents in the open position, without contact movement. The situation is resolved without any negative impact on the VCB (see also chapter 3.2). This behavior is different to that of GCBs, which require contact movement for the current interruption process (pressure build-up needed).

# 3 Contact gaps in gas and vacuum

## 3.1 Breakdown mechanisms in gas and vacuum

In order to understand the difference between vacuum gaps and gas gaps, it is important to understand the breakdown mechanisms in both media. The generally accepted mechanisms for the theoretical description of lightning impulse breakdown in gases within contact gaps are based on high frequency behavior in electrical fields.
The evolution of the breakdown can be described as follows. Initially, it is assumed that a first electron is generated in the electric field by, for example, photoionization. This electron is accelerated in the electric field and, through ionization, will produce more electrons on its way from the cathode to the anode (Figure 3).

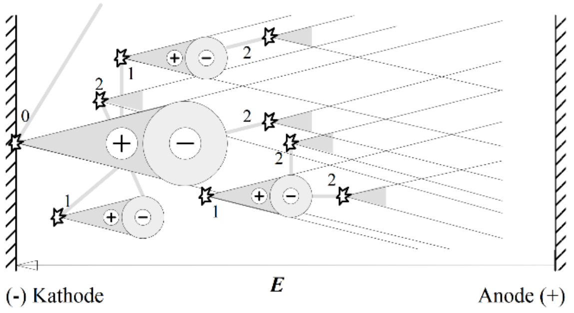
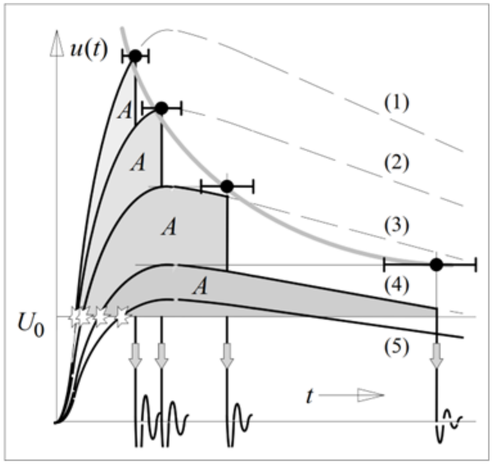


Figure 3: Breakdown avalanche in gas atmosphere [5].

This streamer mechanism (an avalanche-like production of electrons) generates a conductive channel, and the breakdown of the gap will be the consequence.
In the case of high frequency breakdowns, it is essential that both initial conditions are present: the first electron(s) and a sufficiently high electrical field.
Also, the longer the electrical field is present, the higher the probability of breakdown. In other words, the less time the electric field is present across the gap, the higher the field strength that the gap is able to withstand.
Summarizing, the impulse withstand capability of a gas gap depends on both: the voltage amplitude and the pulse duration. This behavior is commonly described by means of the critical area under the curve of the voltage temporal distribution, i.e., by evaluation of the integral of the curve (Figure 4).



$$\int_{t_0+t_S}^{t_0+t_S+t_A} \{u(t) - U_0\}\,\mathrm{d}t = A = \text{const.}$$

Figure 4: Dependence of breakdown time and amplitude for gas atmosphere [5].

Consequently, the dielectric stresses in gas gaps, e.g., in the internal design of the GCB, at 145 kV rated voltage are comparable to a 650 kV lightning impulse (1.2/50 µs) and an 838 kV, 2 µs chopped wave impulse, and one design meets both requirements. This is generally valid for all gas insulation devices, regardless of gas type.

The mechanisms in vacuum gaps are completely different. Since there is no gas in the gap, all initial effects must occur very close to the contact surface. In principle, the response of the cathodic and of the anodic contact surfaces to high electric fields plays a major role in the breakdown. In the case of the cathode, micro-protrusions on the surface yield high, up to a factor of 1000, local enhancements of the electric field, as well as an inhomogeneous heat flux from the protrusion into the bulk material of the contact. The two mechanisms, acceleration of electrons in a very high electric field and a low dissipative heat flux, result in an overheating of the protrusion and thus a micro-explosion at the surface. The latter vaporizes the contact material and ionizes the metal vapor. This process is commonly called explosive electron emission and will lead to a complete breakdown of the gap. In the case of anode-initiated breakdown, electrons released from the cathode surface are accelerated in the electric field towards the anode and, once they hit the contact surface, may also evaporate anode material, starting a metal vapor-based breakdown from this electrode [6].

Both cases of breakdown initiation depend on the structure of the contact surface and on the applied electric field. Since the processes in the vacuum gap are instantaneous on a nanosecond timescale, the breakdown mechanism is nearly independent of the duration of the electric field; thus, the design criterion of the vacuum gap is only defined by the amplitude of the incoming voltage wave. Taking the chopped wave amplitude of 838 kV into consideration, the design of a vacuum interrupter would (through scaling with the peak value) lead to a voltage level of 187 kV (rated voltage) rather than 145 kV. Such an overdesign of the vacuum interrupter is not relevant for most applications.
Another physical and technological aspect that distinguishes the GCB and the VCB is the recovery behavior in the CB after electrical breakdown.

## 3.2 Recovery after electrical breakdown in gas and vacuum gaps

The conducting channel immediately turns into an arc when an electrical breakdown between the open contacts of a GCB ($SF_6$, $CO_2$ etc.) occurs. Depending on the current magnitude and the properties of the used gas, different reactions of the switching gap are possible. For low currents and good arc extinction properties of the gas (for example $SF_6$), the arc could be extinguished at the current zero following the breakdown. For gases with worse arc extinction properties, like $CO_2$ (or gas mixtures with $CO_2$ or air), there will only be a minor, or no possibility at all, for the arc to self-extinguish after breakdown. Consequently, only in the case of $SF_6$ will there be a chance for GCBs to not be destroyed by the breakdown. However, some damage can occur, e.g., in the insulation nozzle. Some types of GCB chambers will be destroyed by the breakdown and completely lose their arc extinction capability. In such a case, the affected circuit breaker needs to be isolated by circuit breaker failure protection or backup protection. Therefore, it is common practice to submit all GCBs to full wave LI and chopped wave LI tests, in closed and open position, to ensure rated insulation levels.

In contrast to GCBs, the vacuum interrupter can easily extinguish the arc following breakdown. Here, the big advantage of vacuum interruption becomes obvious: the switching arc can be extinguished without any movement of the contacts, simply as a result of the contact geometry and the physics of the vacuum arc. The conditions are very similar to vacuum spark gaps so that a reliable extinction of the discharge is achieved.
In those cases of unforeseen and unwanted breakdown events, the vacuum contact gap can also be considered as an additional intrinsic protective measure for the CB, since the breakdowns are clearly controlled within the gap.
All other insulation distances where hazardous consequences of breakdowns may occur are also protected by the vacuum gap. The system with an open VCB gap and a transformer terminal surge arrester acts the same way as a line side spark gap with a silicon carbide surge arrester. Therefore, the open contact gap can be handled differently when compared to open gaps in GCBs. This is remarked in the standards: IEC 62271-1, which allows preconditioning breakdowns of the open vacuum gap, and IEEE C37.04, which specifically addresses the chopped wave withstand of open contacts in vacuum.

# 4 Conclusion and Recommendations

The occurrence of chopped wave lightning impulses within substations which are equipped with line surge arresters on the incoming transmission lines is not necessary. The non-linear resistance of the arrestor provides a highly conductive path to ground at overvoltage impulses, but it is not conductive at operating voltage. The overvoltage surges are diverted to ground without an outage of the circuit. It is thus not necessary to verify a chopped wave lightning impulse withstand level for CBs, or any other equipment installed in the substation, whether AIS or GIS. Supporting this statement, the standard IEC 60071 for insulation coordination does not consider chopped wave impulse voltage as a relevant factor. Insulation Coordination Guides, Surge Arrester Application Guides, Circuit Breaker Standard Recommendations, Substation Guides etc. from recognized power and utility organizations throughout the globe have standardized the return-on-investment of surge arrester protection. It is internationally recognized that surge arresters are the most effective overvoltage protection for substation equipment.

In substations where incoming lines are equipped with coordination rod gap arresters, chopped wave impulses are generated by the gap itself or may pass it before the arrester responds.

Consideration may be given to verifying a chopped wave lightning impulse withstand level on closed CBs. Open CBs in standard operation are protected by the open disconnector switch. Nonetheless, chopped wave tests on open GCBs must be successfully passed to prevent any potentially hazardous situations for the CB itself. In contrast, open VCBs have an intrinsic self-protection against impulse flashover.

The use of VCBs in a substation should take into account the following:

1. In state-of-the-art substations, MOV arresters are applied at line and transformer terminals, so that the chopped wave situation is not necessary.

2. In the case of open VCBs, the standard IEEE C37.04 recommends “special consideration”.
   Taking the described physical behavior of the open VCBs into account, the suppliers of medium and high-voltage VCBs follow the common practice:

   - the withstand for standard 1.2/50 µs-LI-wave as relevant and required, and
   - the withstand for 2 µs chopped wave as not relevant and, as such, not required.

In conclusion, even if an open VCB does not fully meet the chopped wave test requirements, it fully complies with the standards. In the case of VCBs in closed position, the CB chopped wave withstand capability of the overall circuit breaker insulation is to be tested according to standards.

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