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OPERATING ENVIRONMENT OF VOLTAGE GRADING CAPACITORS APPLIED TO HIGH VOLTAGE CIRCUIT-BREAKERS

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1 Introduction

1.1 Grading capacitor designs and technologies

Voltage grading capacitors are accessories for high-voltage circuit-breakers used to control the voltage distribution across each breaking unit / interrupting chamber of multi-unit circuit-breakers, both when the circuit-breaker is in open position and during making and breaking operations. Grading capacitors, if fitted, are always mounted in parallel with each chamber. Figure 1 shows a modern two unit 300 kV air insulated switchgear (AIS) circuit-breaker with the grading capacitors in separate porcelain housings next to the bigger porcelain housings containing the SF_6 filled interrupting chambers.

Figure 1 - Two unit circuit-breaker with grading capacitors

Several technologies and designs for grading capacitors exist, both with regard to dielectric material being used in the capacitive elements, electric insulation system, internal pressure system, and housing. Figure 2 shows a schematic drawing of the most common design: Stacked foil wound capacitor elements impregnated with oil and placed inside a porcelain housing with gas filled pressure bellows.

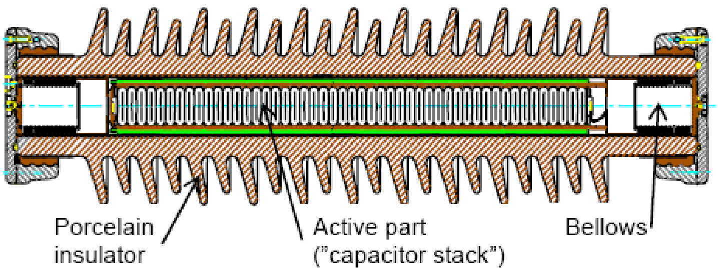

Figure 2 - Cross section of porcelain insulated grading capacitor for AIS circuit-breakers (schematic)

The capacitor elements are made by first winding foils of dielectric and aluminium on a circular mandrel. This round assembly is then flattened, and the elements are stacked on top of each other. Electrical interconnection is established either with a metal tab installed within the winding or simply by applying pressure on the mechanical connection between the aluminium foils. Up to few hundred capacitor elements are connected in series. Typical capacitance values are in the range 300 - 2500 pF.

In foil capacitors manufactured until around 1990, paper was used as the solid dielectric ("all-paper"), giving a tanδ (loss factor) of 40 - 50$\times10^{-4}$ (0,4 – 0,5 %). Newer designs use polypropylene films with a tanδ of 1 - 10$\times10^{-4}$, or a combination of polypropylene and paper films, so-called mixed dielectric, with tanδ typically below 30$\times10^{-4}$, depending on the paper to polypropylene ratio. Thin aluminium foils are used as electrodes.

The capacitor stack is impregnated with oil. Capacitors manufactured up to around 1990 contain mineral oil. Later synthetic oils became increasingly popular due to their better dielectric performance, especially at low temperatures. Furthermore, synthetic oils have around 10 % higher permittivity compared to mineral oil. SF_6 insulated grading capacitors also exist, but are rare.

Oil filled capacitors usually contain a system for compensation of the thermal expansion of the oil and/or keeping the internal pressure somewhat elevated and fairly constant across a specified temperature range. Some designs apply one or two large metal bellows filled with Nitrogen at 0,2 – 0,3 MPa overpressure (see Figure 2), whereas others use many, up to around 100, smaller diaphragm cells. A slight overpressure increases the dielectric strength compared to what it would have been at atmospheric pressure, and also avoids pressure variations introduced by fluctuations in the ambient temperature.

Open bellows solutions are also used, in particular for grading capacitors installed in gas insulated switchgear (GIS). The bellows then equalize the internal pressure of the grading capacitor with that of the surrounding SF_6.

SF_6 filled capacitors usually have a higher internal pressure than oil filled, and no bellows.

The stack of capacitor elements is mounted in an insulator housing with metal terminals at both ends. The housing is made in porcelain or composite with silicone sheds for AIS breakers, or in reinforced epoxy for GIS circuit-breakers.

Typical dimensions for grading capacitors used in GIS are lengths of 50 – 75 cm and diameters of 10 - 12 cm. AIS grading capacitors can be substantially larger, with lengths up to two metres or more.

Figure 3 shows a capacitor stack, Nitrogen filled metal bellows and two complete GIS capacitors.

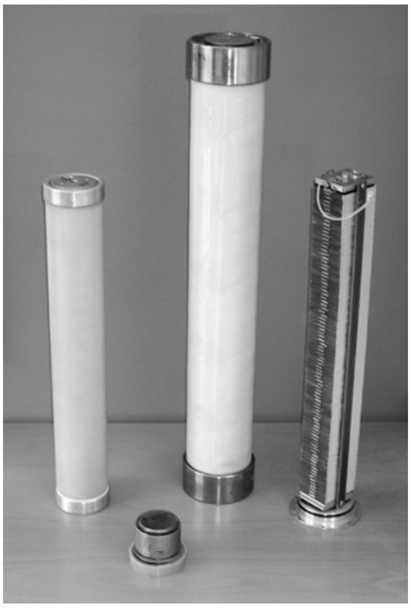

Figure 3 - Voltage grading capacitors for GIS circuit-breakers. Metal bellows (front) and capacitor element stack (right)

Grading capacitors based on using bulk ceramic dielectrics in the active parts also exist, see Figure 4.

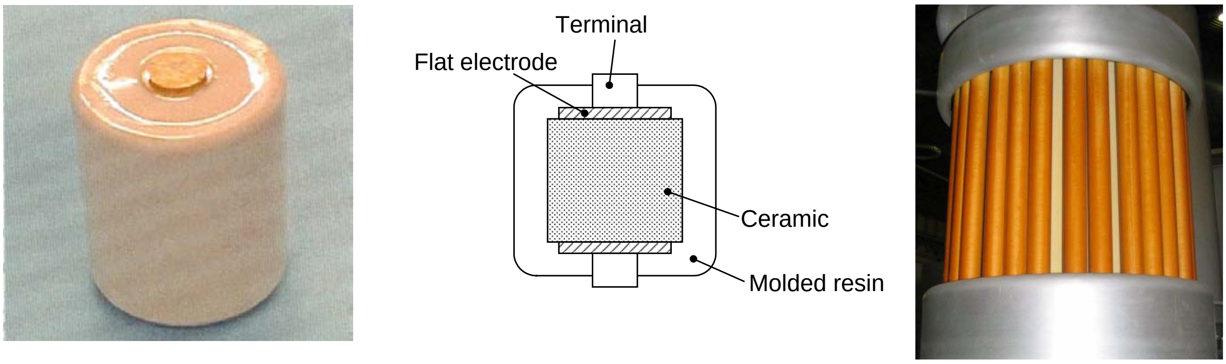

Figure 4 - Ceramic capacitor element (left and middle) and complete grading capacitor assembly installed on a GIS circuit-breaker (right)

Each capacitor element consists of a cylinder made from a ceramic material with a high dielectric constant, to which flat metal electrodes and terminals are attached at both ends and the assembly encapsulated in resin. Several such elements are mounted in series within a SF_6 insulated cylindrical housing to form a unit, and several such units in parallel are mounted across the interrupting chamber of the circuit-breaker, see right hand photo of Figure 4.

Ceramic capacitors are very common in GIS circuit-breakers manufactured in the Far East, and some are also in use in the North America. In Europe they hardly exist.

The big advantage is that there is no oil insulation involved, and thus no leak problems. A major drawback, and probably also one reason for the limited usage, is that many capacitor elements in series and in parallel are required, due to the limited voltage and capacitance per element.

1.2 Purpose of work and structure of report

A number of rather disturbing incidents in recent years have brought attention to issues related to reliability, service environment and test procedures of voltage grading capacitors, at least from some utilities.

Concerning service experience, it was found that very little precise information exists. The voltage grading capacitors are in many respects considered an integral part of the circuit-breaker, not as a separate component. Hence, in circuit-breaker reliability surveys the grading capacitors have played a rather anonymous role, sometimes not even listed among the possible alternatives on the “failed sub-component” list of the enquiry [1] [1].

In order to obtain some information about failures and flaws experienced on grading capacitors information has been collected by interviewing twenty utilities from nine countries. The objective was to get a general and qualitative overview of what types of problems that occur, which parts of the grading capacitors that fail, what the predominant failure modes are, and what the consequences are. The outcome of this investigation is presented in Chapter 2.

Chapter 3 deals with the mechanical stresses grading capacitors are subjected to, in particular during switching operations. The investigation was initiated by discoveries of mechanical fatigue in the metal bands connecting the capacitor elements in a few rather old capacitors. It became evident that robustness of these parts could be an important issue. Consequently, it was considered important to determine what mechanical stresses (acceleration amplitude and frequencies) the grading capacitors will experience in service and to clarify to what extent the various observed frequencies / g-levels are harmful. By using accelerometers the mechanical stresses / shocks / vibrations have been measured directly on the grading capacitors of circuit-breakers of different technologies during switching operations.

A number of cases where grading capacitors installed on shunt reactor circuit-breakers have failed violently (exploded) immediately after opening operations have occurred in several countries. It is thus speculated that reactive current switching under certain conditions may cause over-voltage or over-current stresses on the grading capacitors of a large and unforeseen type.

Chapter 4 deals with electrical stresses such as nominal voltage, power frequency, lightning impulse and switching impulse and defines a set of nominal voltages for grading capacitors.

Chapter 5 reports on comprehensive simulations of transient currents and voltages during shunt reactor switching, and possible explanations for the failures are put forward and discussed.

At present no internationally accepted standard for testing of grading capacitor exits. Chapter 6 gives, with basis in the findings reported in the previous chapters, recommendations for test procedures for grading capacitors. Mechanical, environmental and electrical tests are proposed, most of them to a large extent based on manufacturer test procedures being applied at present. The recommendations are meant as background material for ongoing and future work by standardizing bodies such as the IEC.

A number of other topics associated with grading capacitors exist. These include overvoltages associated with ferroresonance, trapped charges, effect on transient recovery voltages, etc. However, these and other issues addressing relationships with the entire transmission system or other types of equipment are considered to be beyond the scope of the present work.

1.3 References

[1] “Final report of the second international enquiry on high voltage circuit-breaker failures and defects in service”, CIGRÉ Technical Brochure no. 83, 1994

[1] Numbers in square brackets refer to the references at the end of each chapter.

2 Service experience with voltage grading capacitors

2.1 Introduction

Service problems and failures of grading capacitors do not seem to have been a matter of great concern for most utilities when considering the overall service experience of their circuit-breakers. However, exceptions exist. A few utilities have in recent years reported about substantial problems, including leaks, disruptive dielectric failures and mechanical fatigue problems [1].

The reported malfunctions were not limited to specific designs or equipment provided by certain manufacturers. It appeared that the majority of grading capacitor manufacturers and most circuit-breaker vendors were involved, signifying that this might be a broader and more general problem.

But again, the reported problems were limited to a few utilities. For obtaining a wider perspective on grading capacitor service experience, information should be collected from a broader basis. With this objective utility representatives from around the world have been contacted and interviewed about service experience and failure history of their grading capacitors. More than twenty utilities from nine countries around the world have contributed.

This chapter summarizes the outcome of this mini-survey and provides a general, descriptive and qualitative overview of what type of problems that have occurred. It is believed that even such limited and qualitative knowledge about grading capacitor service experience is of value for both manufacturers and for the electric utilities. It helps the manufacturers improve their products, and serves as inputs for the utilities when analysing flaws and failures, and in planning diagnostics testing, maintenance and replacement programs. Furthermore, when preparing international standards experience from service should be taken into account.

For quantitative failure statistics the reader is referred to the very comprehensive CIGRÉ survey on reliability of high-voltage equipment that is under way [2].

2.2 Problems experienced in service

2.2.1 Corrosion and leaks

The vast majority of the service problems reported concern leaks and corrosion. Leaks were most widely reported as oil leaking from grading capacitors in AIS. A significant number of cases of SF_6 leaking into GIS grading capacitors were reported, although these were confined to a few utilities. In some cases, oil leaks from GIS capacitors had been observed. Moisture ingress into AIS grading capacitors was reported in a significant number of cases.

There was no correlation with the number of operations or switching duty, but a clear correlation with age. Leaks were most common for older grading capacitors. Most of the affected capacitors had been in service for 20 years or more. A very few cases were reported where the grading capacitors had been in service for between 5 to 10 years.

In some cases, a significant proportion of the grading capacitor population of a certain type of design was affected. Some utilities reported leaks affecting more than 100 grading capacitors, one large utility estimated that more than 5 000 out of its total grading capacitor population of approximately 25 000 had been replaced due to leaks.

Figure 5 shows a typical appearance of a leak from the flange of an AIS grading capacitor and a common flange design.

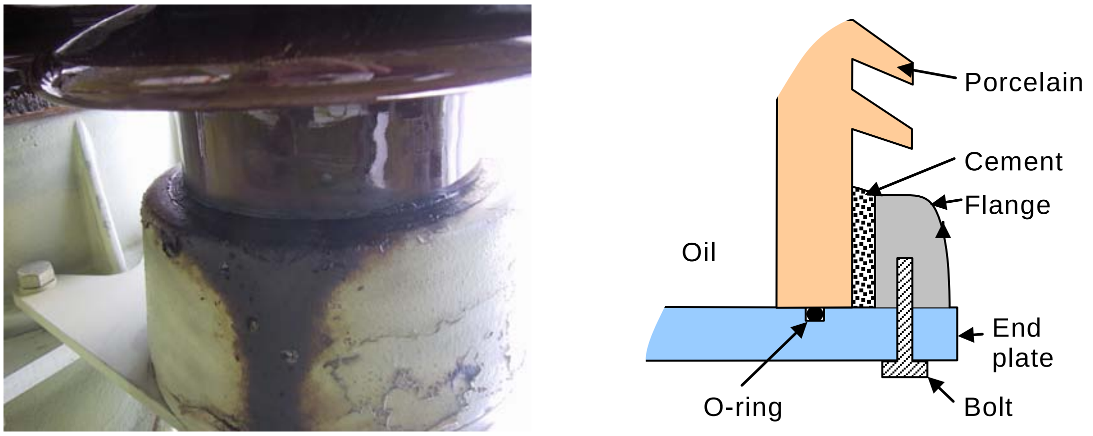

Figure 5 - Typical example of an oil leak from an old AIS grading capacitor (left), and a schematic drawing of a typical flange and sealing arrangement (right)

The end-plate is attached to the flange with the bolt and exerts a certain pressure on the o-ring and thus prevents the oil from leaking out. The flange in turn, is fixed to the porcelain insulator by a cement joint. There are three well-known causes of leaks and moisture ingress in such a configuration:

- Crevice corrosion at flange-end plate interface;
- Incompatibility between o-ring material and the end plate metal causing pitting corrosion in the O-ring groove;
- Cracking of cement causing movement of flange and loss of pressure on the O-ring.

Consequently, mechanisms causing leaks for AIS grading capacitors were reported as seal failures, corrosion and cracked porcelain. In some cases, seal failure and corrosion were quoted jointly as the cause of failure.

Leaks for GIS grading capacitors were reported to have been caused by poor workmanship and quality control during assembly. In particular, poor surface finish and spilt solder on sealing surfaces were quoted.

Moisture ingress was often associated with leaks in AIS grading capacitors. In some cases, leaks had lead to disruptive dielectric failure. However, the number of disruptive failures was very small compared with the large number of leaks reported. Tests on GIS grading capacitors showed that SF_6 leaks into the oil filled capacitors had not necessarily reduced the strength of the insulation.

In most cases, leaking grading capacitors were replaced. In some cases, all capacitors of a type had been replaced. Some utilities had repaired leaking capacitors, particularly where seal replacement was required.

2.2.2 Dielectric breakdown

Some instances of disruptive dielectric failure of grading capacitors were reported. The number of cases, a few dozens, was small compared to the total number of circuit-breakers covered in the survey. The failures had occurred on both GIS and AIS circuit-breakers. Most had occurred within less than 15 years service.

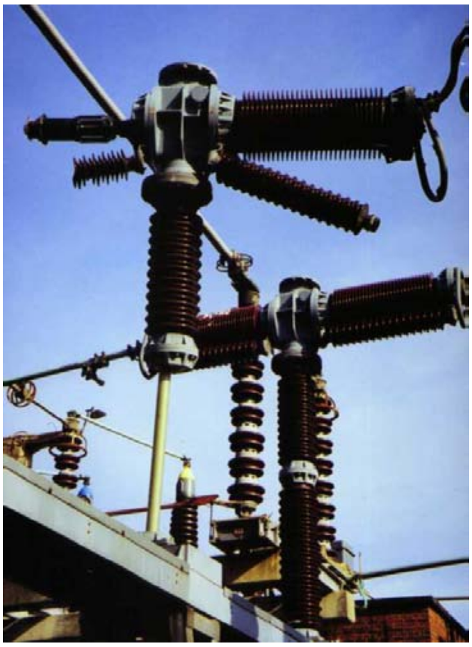

Figure 6 - Example of circuit-breaker grading capacitor following disruptive discharge

A dielectric disruptive failure is a highly disturbing event, usually causing major damages to the rest of the circuit-breaker (see Figure 6) and in some cases also affecting neighbouring equipment.

In most cases where failure had occurred, the remaining grading capacitors on the affected circuit-breaker were removed for examination. Some of these were found to exhibit various degrees of dielectric failure. Dielectric testing revealed increased capacitance and loss angle and the presence of partial discharge activity. In some cases the capacitors were then opened for visual inspection, and internal short-circuits were discovered, as shown in Figure 7.

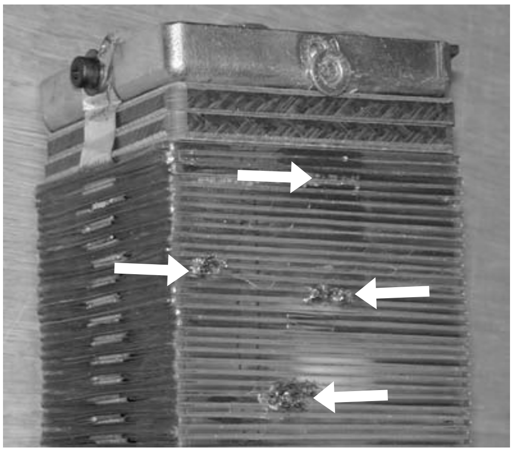

Figure 7 - Short-circuited capacitor elements

In general there was a clear correlation between disruptive dielectric failures and switching duty. Most of the circuit-breakers concerned had been switching low inductive currents and failure usually occurred on or shortly after an opening operation. (Although the internal damage may of course have been created during the previous closing operation.) Most of these were shunt reactor circuits applications.

The occurrence of failure was apparently not related to the number of operations, although shunt reactor circuit-breakers are usually operated frequently. The number of operations was typically thousands. At least one of the failures occurred on a circuit-breaker with controlled switching units installed; although most were without. The cause of the failures has not been fully explained.

One utility reported a number of cases where a change in capacitance value was detected. Some capacitors were apparently suffering from punctured elements and some from a complete insulation breakdown. In this case, the failures were not correlated with switching duty.

Examination of one of the partially failed capacitors, see Figure 8, suggests the following failure development: Dielectric breakdown apparently occurred first at the folded edge of one of the wound elements, but without causing a complete short-circuit. It is possible that pressing from a circular to a flat element during manufacture may produce weak areas at the folded edges. Discharge activity caused gas bubbles to form. The high relative permittivity of the oil and lower dielectric strength of the gas caused further discharge activity and gas formation under normal service voltage. The gas bubbles migrated along the interface between the capacitor stack and its pressboard support. Further discharges occurred, causing carbonisation of the pressboard and the paper insulation. When an element fails to a short-circuit, the electric stress on the remaining elements increases and more elements fail.

Figure 8 - Carbonisation and arc tracks along the stack (left) and in the supporting pressboard (right) of a partly short-circuited oil insulated grading capacitor

It appears, therefore, that failure in a single element is sufficient to initiate the failure process, which can develop under normal service voltage over time. But again, the reason for the initial element failure is not clear.

Following a dielectric failure, all capacitors of the affected circuit-breaker were usually replaced. Some utilities install controlled switching on shunt reactor circuit-breakers in order to eliminate re-ignition overvoltages. In some utilities, it is practice to open a sequential disconnector following opening of the shunt reactor circuit-breaker. Sequential disconnection reduces the period of time during which the grading capacitors are stressed by the system voltage from hours to minutes and reduces the rate of degradation of any failing capacitors accordingly.

2.2.3 Damaged internal conductors

Capacitance values indicating an open circuit inside the grading capacitor have in some cases been measured. Some utilities do capacitance measurements on a regular basis as a diagnostic test, whereas in other cases such measurements are motivated by a faint arcing noise, leaks or other types of suspicious or irregular behaviour of the grading capacitor.

Open circuit obviously means that the conductors that connect the individual capacitor elements or the electric connections from the capacitor stack to the terminals are broken or have loosened. When voltage is applied this of course leads to internal discharges and arcing and the insulation system of the grading capacitor quickly deteriorates.

When detecting an open circuit grading capacitor the common procedure among most utilities appears to be to simply replace it immediately without doing any further examinations. However, occasionally more careful investigations have been carried out in order to elucidate on the failure mechanisms.

Such examinations on grading capacitors installed on GIS circuit-breakers [1] revealed that on a few designs put into service in the 1980s the aluminium foils or bands used as conductors are potentially weak points, especially the part connecting the top and bottom of the capacitor stack to the terminals of the capacitor. Figure 9 shows a dismantled grading capacitor with the foil conductor partly broken in this area. The oil has here been drained off, and parts of the epoxy housing has been cut off and removed.

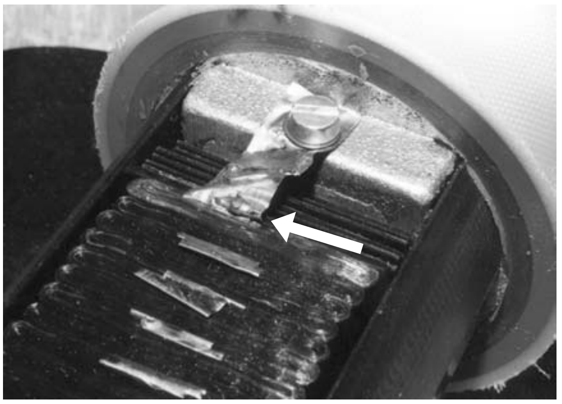

Figure 9 - Opened grading capacitor with partly broken foil conductor (see arrow).

Scanning electron microscopy (SEM) investigations clearly demonstrated that the damage was caused by mechanical fatigue. The foil conductors are in this case as thin as 0,05 mm (50 μm), and apparently not sufficiently mechanical robust to over time withstand the mechanical stresses and shocks generated during circuit-breaker operations. Of this particular grading capacitor design a substantial fraction the investigated objects (5 out of 12) had incipient fatigue damage, or partly or completely broken foil conductors.

On another design from the same period a grading capacitor explosion inside a GIS triggered investigations of internal parts of the remaining 11 capacitors of the circuit-breaker [1]. Also in this case the aluminium foil between the capacitor stack and the terminals attracted attention. Although no signs of fatigue or fractures were found, the investigators were not entirely convinced by the quality of the manufacturing process of the capacitors. It seemed like they were assembled in a rather hasty and careless way, and in several cases the foil conductor was very sharply bent, thereby greatly increasing the risk of developing fatigue damage.

Mechanical fatigue is of course not the only possible process that can lead to open circuits in grading capacitors. For example, conductor solderings, bondings or terminations may overheat and melt or fail mechanically, and cause an open circuit. However, there are no indications in the information provided by utilities that such failures are common. On the other hand, the replace-without-investigation procedure most utilities apply on open circuit capacitors does not allow for assessments of the underlying failure mechanisms.

Another type of flaw related to the internal electrical connections has also been discovered during dismantling and inspection of grading capacitors. The electric leads between the bellows and the end plate have in some cases been found to have become discoloured and brittle, see Figure 10.

Investigations made it clear that this was caused by electric discharges. The conductor loop is associated with a certain inductance, and during nearby disconnector switching the resulting high frequency travelling waves induce voltages of sufficiently large magnitude to give discharges from the leads. Over time the leads became brittle.

The problem was solved simply by replacing the bare leads with insulated ones.

Figure 10 - Discolouration of the electric leads between bellows and end plate caused by discharge activity during disconnector switching operations

2.2.4 Ceramic grading capacitors

The information presented in the previous sections concerns foil grading capacitors. With regard to ceramic grading capacitors far less little information about service experience have been available, presumably since this technology is not much used by the contributing utilities.

One utility reported major problems with cracking of the ceramic elements, tracking problems in cases where the circuit-breaker was in open position for prolonged periods of time, and also comprehensive difficulties with capacitance or dissipation factors out of range. As a result of this, the utility states that it often needs to replace the grading capacitors, and they are not buying new circuit-breakers equipped with ceramic grading capacitors.

In contrast, one major circuit-breaker manufacturer claims an excellent service record for the ceramic grading capacitors installed on their breakers. In a population of 7 000 capacitors with more than 150 000 service years only one failure has occurred.

2.3 Diagnostic testing of grading capacitors - methods and practices

2.3.1 Test methods

A standard method for assessing the condition of a grading capacitor in the field is to measure capacitance and tanδ. For this purpose there is a large variety of instruments available on the market, from low-voltage bridges to high-voltage instruments. The latter usually measure at a voltage of at least 10 kV.

Capacitor manufacturers usually state tolerances on capacitance and tanδ. Measurement of capacitor parameters in the factory is normally done at 10 % and 100 % of the nominal voltage of the capacitor. For that reason a measuring instrument that measures at least 10 kV is preferable to low-voltage bridges.

Measurement should be done on a clean capacitor, under dry weather conditions. Proximity of live equipment should be avoided; induction in the leads may result in incorrect readings. Care should always be taken to avoid unnecessary loops in the measuring cables.

If a value outside the acceptable range is measured, it needs to be assessed if this is due to a measuring error or other circumstances (insulator not clean, induction from nearby equipment, humid weather, etc.). This can be done by removing the capacitor, cleaning it and repeating the measurement on ground level. If both measurements give the same result, the capacitor should be checked at nominal voltage.

In particular, if a capacitor is energized to its full rated voltage between two 10 kV range measurements, the second one may show a much lower tanδ value than the first. This lack of reproducibility is attributed to the so-called “Garton effect”, which relates to motion of ions in an alternating field in the presence of solid boundaries [3]. The effect is observed on modern capacitors with high electric fields. For old grading capacitor designs ("all-paper") with rated voltage up to 80 – 100 kV, the effect is far less pronounced and reproducible tanδ measurements can usually be obtained.

Generally speaking, 10 kV range measurements can be a good and quick check for severe failures, but minor flaws can be overlooked. Measurements at the nominal voltage of the capacitor are more reliable, but are impractical in the field.

2.3.2 Utility practices

Some utilities report doing periodic measurements of tanδ and capacitance, typically at an interval of a few years, and claim that this had effectively detected moisture ingress. Some utilities performed an insulation resistance check across the circuit-breaker interrupter heads during routine maintenance. This had also been effective in detecting grading capacitor moisture ingress. Many utilities reported a routine visual inspection including a check for grading capacitor oil leaks. This had evidently been effective on account of the large number of leaks that were detected before failure.

At least one utility monitors the grading capacitors of shunt reactor circuit-breakers using thermal imaging. The circuit-breaker is left open for three hours while energised before the image is acquired. Care must be taken to rule out the effects of heating or thermal radiation from other sources, such as the sun. When comparing the images of the capacitors of the three phases, one having a higher temperature than the others will be clearly visible. This usually points to an internal problem in the capacitor. Figure 11 shows the thermal image of a grading capacitor with severe internal dielectric failures.

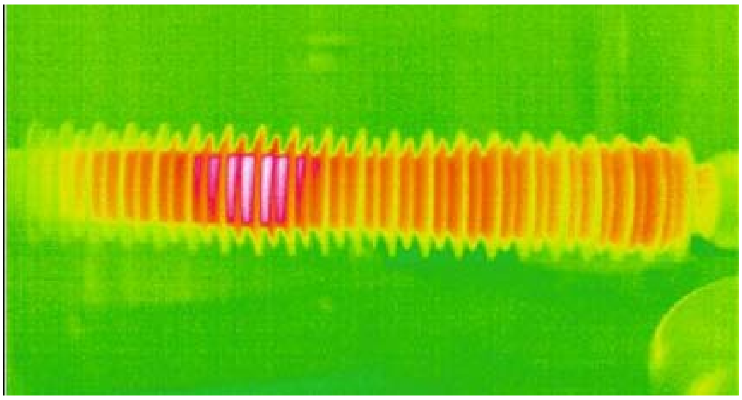

Figure 11 - Thermal image showing heating due to internal discharges in energized grading capacitor

2.4 Discussion and conclusion

It is evident from this simple and relatively limited utility survey that corrosion and leaks on old grading capacitors are quite common. Fortunately only very few disruptive failures are attributed to this, but still the costs associated with the leaks are far from negligible.

Largely due to these problems, it appears that the lifetime of many of the old grading capacitor designs is substantially less than the lifetime of the circuit-breaker itself. The latter may stay in service for 30 - 50 years. Hence, an increasing number of incidents with leaking old grading capacitors may be expected in the future if no precautions are taken. Some utilities have fully recognized this issue and have decided to replace all grading capacitors as a part of a mid-life revision of their circuit-breakers.

Fortunately, newer grading capacitor designs appear to have better technical solutions with regard to sealing and corrosion protection, and are also more mechanically robust. It may thus be reason to believe that the lifetime of capacitors manufactured in recent years is considerably longer.

A detailed and convincing explanation for the disruptive capacitor failures occurring during switching of small inductive currents has not yet been found. Examinations of partly damaged reactor breaker capacitors suggest that the failure originates in dielectric stresses of an unforeseen nature and magnitude. This is an unsatisfactory situation, as understanding the phenomena of course is essential for finding remedies against these very severe incidents. The fact that such failures have occurred also on circuit-breakers equipped with controlled switching units further increases the general uneasiness about this.

2.5 References

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[2] C-E. Sölver, “First results from on-going CIGRÉ enquiry on reliability on high voltage equipment”, paper no. 101, CIGRÉ SC A3&B3 Joint Colloquium, Tokyo, 2005.

[3] G.C. Garton, “Dielectric loss in thin films of insulation liquids”, JIEE, vol. 88, no. 23, pp. 23-40. 1941.

3 Mechanical stress on grading capacitors

3.1 Introduction

The present chapter is concerned with the mechanical stresses imposed on circuit-breaker grading capacitors. The mechanical stresses arising throughout the whole lifetime of the capacitor, including transport, commissioning and service life, are considered as a basis for test requirements to be proposed in Chapter 6.

Mechanical stresses arise from transportation, seismic activity on site and from operation of the circuit-breaker. Test requirements addressing transport and seismic activity can be derived from experience with components or equipment of similar size and weight and are covered by existing standards.

Concerning mechanical stresses due to operation of the circuit-breaker, no common requirements are known. The individual behaviour of each type of circuit-breaker influences the mechanical impact on the grading capacitors. In order to analyze the stresses caused by operation of the circuit-breaker, several measurements have been collected and are presented in the chapter. The standard requirements covering transportation and seismic activity are also described.

3.2 Mechanical stress during circuit-breaker operation

To evaluate and interpret the mechanical stresses on grading capacitors acceleration measurements have been carried out under different circumstances (on site and in laboratories) with different types of equipment and with different processing of the recorded data.

3.2.1 Background to acceleration measurement and data processing

A force F applied to a body of mass m produces an acceleration a, such that:

$$F = m \times a \text{ or } a = F/m \quad (1)$$

The acceleration is a measurable quantity that can be used to study the mechanical stressing of an object.

The mechanical stresses on a body are usually studied using accelerometers. The accelerometer is a piezoelectric device that provides an output signal proportional to acceleration. Since acceleration is the rate of change of velocity, the velocity may be determined by integrating the accelerometer output signal with respect to time. Similarly, since velocity is the rate of change of displacement, the displacement may be determined by integrating the accelerometer output signal twice with respect to time.

In the general case where the acceleration varies with time, the recorded data is integrated numerically to obtain the velocity and displacement. An example taken from an earthquake measurement in which acceleration data have been processed to obtain velocity and displacement in three dimensions is shown in Figure 12.

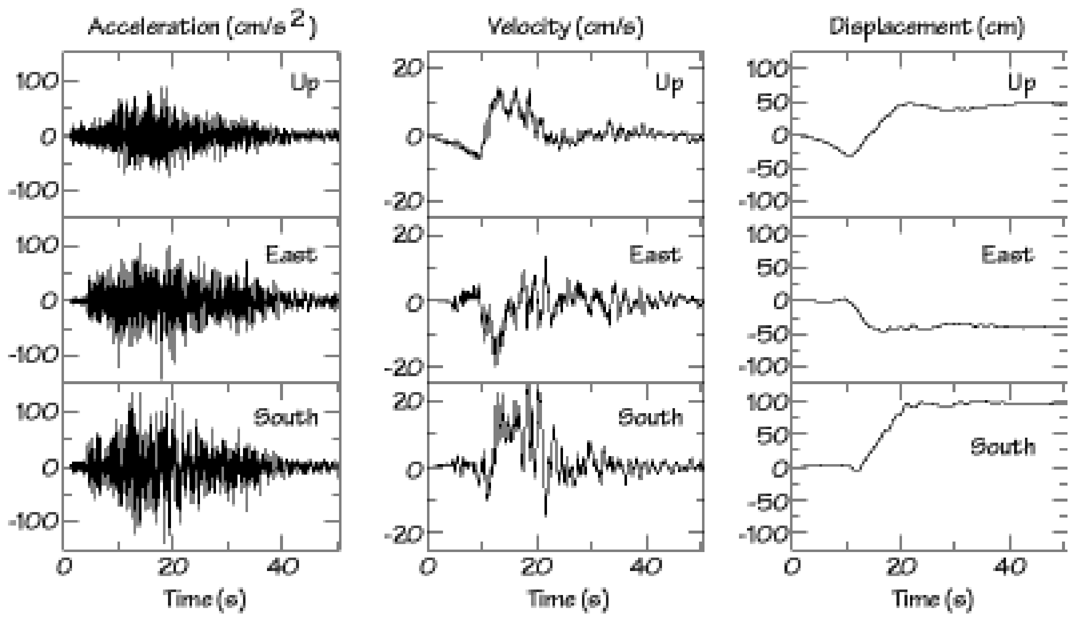


Figure 12 - General example of acceleration measurement and data processing to velocity and displacement in three directions during an earthquake

In order to determine the possible mechanical stresses on the object, the mass, acceleration and displacement must be known.

In addition to the amplitudes of the accelerations, the frequencies must also be considered. The recorded accelerations in Figure 13, as well as in Figure 12 show high amplitudes that were typical of those found in the collected measurements of grading capacitor stresses. Figure 13 shows the acceleration against time measured on a Transient Recovery Voltage (TRV) control capacitor mounted on a dead tank circuit-breaker during a Close-Open (CO) operation.

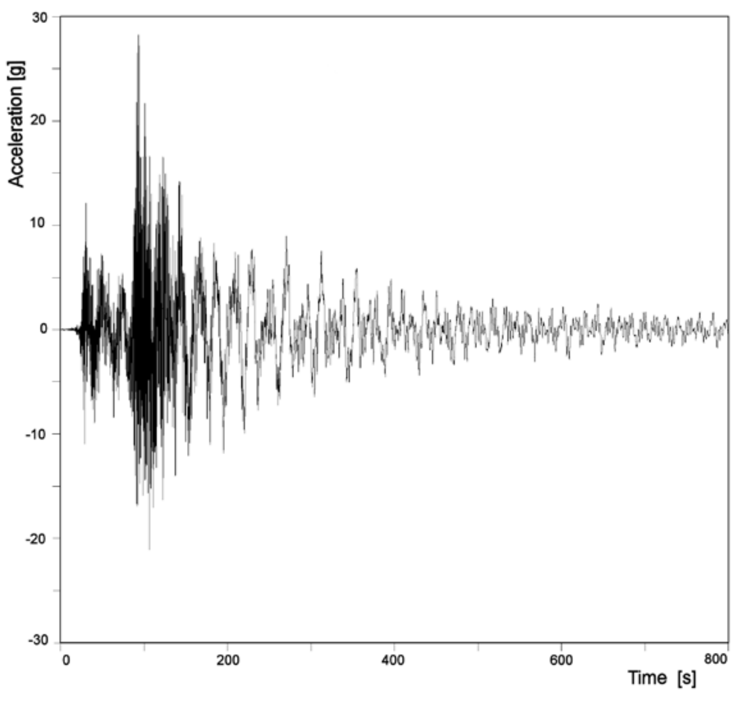


Figure 13 - Acceleration with respect to time, measured on a TRV control capacitor, mounted to a dead tank circuit-breaker during a CO-operation

The acceleration may be determined as a function of frequency by means of the Fourier Transform, in which a time varying function is expressed as a series of harmonic terms, each of the form:

$$a(\omega) = \mathrm{B}\sin(\omega t + \varphi_\mathrm{B}) \quad (2)$$

where

a is the acceleration (m/s^2)

B is a constant (m/s^2)

ω is de angular frequency (rad/s)

φ_B is a phase angle (rad)

Due to the mathematical basis of the Fourier Transform, the lowest possible frequency that may be covered by an analysis is equal to $1/T_0$, where T_0 is the length of the analysed time window. Figure 15 shows the acceleration as a function of frequency for the measurement of Figure 14 with a time window from 27 to 227 ms.

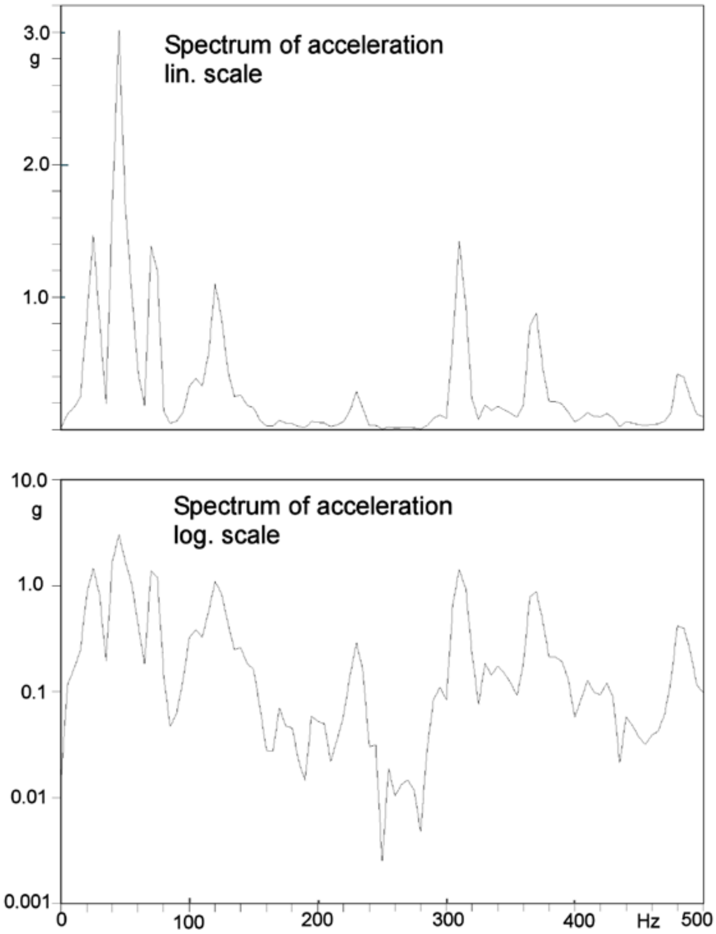


Figure 14 - Acceleration with respect to frequency based on measurement shown in Figure 13

By integrating the acceleration terms twice with respect to time, the displacement (x) may be expressed as a series of harmonic terms, each of the form:

$$x(\omega) = -(\mathrm{B}/\omega^2) \times \sin(\omega t + \varphi_\mathrm{B}) \quad (3)$$

Consequently, at higher frequencies the effect of acceleration on the displacement becomes smaller. This is illustrated by Figure 15, which shows the displacement as a function of frequency for the measurement of Figure 13.

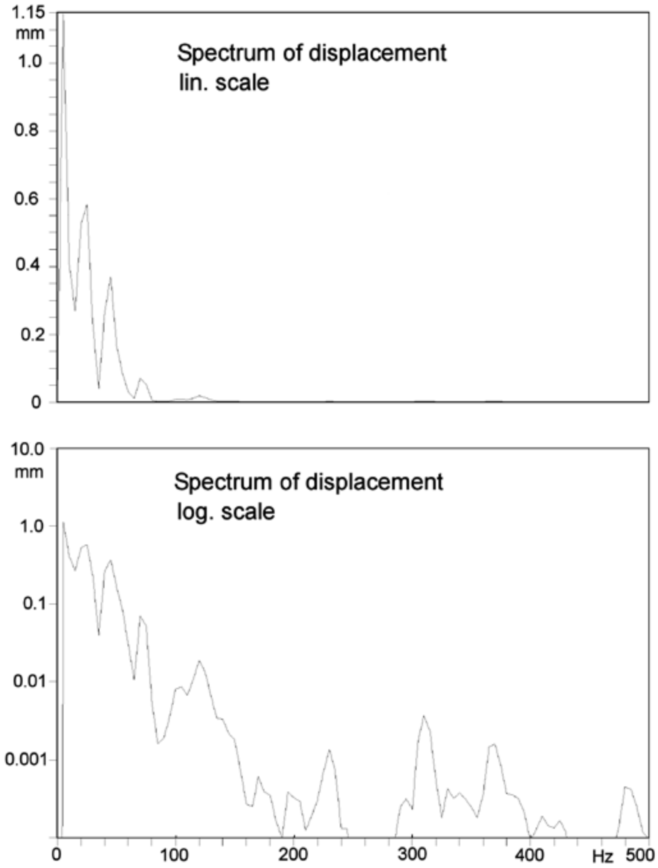


Figure 15 - Displacement with respect to frequency based on measurement shown in Figure 13

Damage is caused where the displacement results in cracks or delaminating, etc. Excluding resonances the displacement of parts due to a mechanical shock can only be less than or equal to the displacement measured on the outside surface.

In Figure 15, frequencies of more than 200 Hz only have values of displacement in the range of micrometers. Assuming that such displacements do not harm objects like a grading capacitor in any way, it is possible to neglect such frequencies. This will be true for short lived excitations such as the mechanical shock associated with circuit-breaker operation.

Where it is possible to neglect the higher frequency components, they may be removed from the recorded signals by means of low-pass filtering. Figure 16 shows the original curve from Figure 14 together with curves obtained by low-pass filtering with cut-off frequencies of 400 Hz, 200 Hz and 120 Hz. It may be seen that the high measured acceleration values of nearly 30*g* are associated with high frequencies and consequently only generate small values of displacement. At frequencies below 400 Hz, the acceleration does not exceed a level of 10*g* in the example shown.

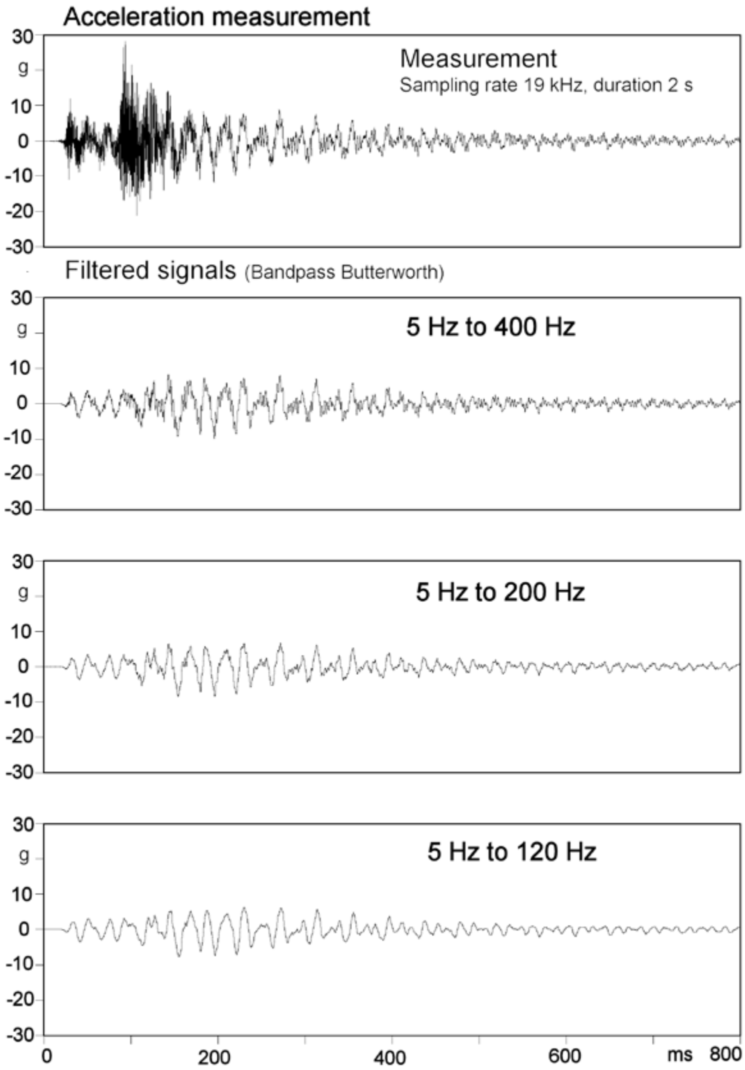


Figure 16 - Acceleration (*y*-axis) with respect to time (*x*-axis), measured at a TRV control capacitor, mounted to a dead tank circuit-breaker during CO-operation, original measuring signal and signal after low-pass filtering

In contrast to the mechanical shock, the more harmful case is a sustained oscillating stress that can excite mechanical parts to vibrate with their mechanical resonant frequency. Such an oscillating stress can occur during transport or as a result of the power frequency (50 Hz/100 Hz or 60 Hz/120 z).

3.2.2 Examples of acceleration measurements

Only a few measurements of acceleration on grading capacitors are available from circuit-breaker manufacturers and independent institutes. The measurements cannot be assumed as being representative for all circumstances, but will be used as examples and may give an idea of the mechanical stresses.

The different investigations have been carried out under different focus of evaluation and are therefore not always comparable. Only limited information is available concerning the measurement techniques for the recorded data. For interpretation of the recorded signals only general statements can be made here.

With regard to factors influencing acceleration measurements, the method of fixing the sensors to the capacitor is assumed to be the same or at least similar for all the collected examples. The sensors were fixed in a rigid, solid way directly to the end fittings or flange of the capacitor in axial and radial directions. Measurements at other points on the circuit-breaker are of no use for obtaining information on the stresses on the capacitor itself.

Factors that can be investigated from the available measurements are the following:

- Individual design of circuit-breaker including
  - structure of the circuit-breaker to ground;
  - type of operating mechanism (spring, hydraulic, pneumatic);
  - generally the length and design of the mechanical chain from operating mechanism to breaking unit.
- Direction of measurements in three dimensions
- Position of measurement: End of capacitor; near the terminal at the outer end of the interrupter; near to the drive side of the interrupter
- Type of operation (Open (O), Close (C) and combinations) and velocity of operation mechanism

3.2.2.1 On-site measurement at three types of live tank circuit-breakers

The mechanical behaviour of the grading capacitors of three different 300 kV live tank circuit-breakers was measured during operation.

Two of the investigated circuit-breakers are double-break SF_6 circuit-breakers. Circuit-breaker A (Figure 17) is single-pole, spring operated. Circuit-breaker B (Figure 18) has a hydraulic drive mechanism for all three poles on a common structure. Both circuit-breakers have grading capacitors manufactured by the same manufacturer with capacitances of 1600 pF and 500 pF, respectively. Circuit-breaker C (Figure 19) is a spring operated minimum oil circuit-breaker with 6 interrupters per pole, each pole on a single frame. Its grading capacitors have a value of 1000 pF. The measurements were performed with the circuit-breakers disconnected from the grid. The manufacturing years of the breakers A, B and C were 1987, 1976 and 1971 respectively.

Figure 17 - One pole of circuit-breaker A

Figure 18 - Circuit-breaker B, three poles on a common structure

Figure 19 – Circuit-breaker C with six units per pole

Measurements were performed with accelerometers attached directly to the capacitors, as shown in Figure 20. In most cases, the measurements were performed with four accelerometers attached to a capacitor during one circuit-breaker operation. Two accelerometers were attached at either end of the capacitor, one in the axial direction and the other in a direction perpendicular to it.

The recorded signals were low-pass-filtered with a cut-off frequency at 16 kHz. The background noise was recorded several times and a Fast Fourier-Transform (FFT) of the background noise signal was used as a basis for the digital filters used during post processing.

Signals were recorded and analysed for circuit-breakers A, B and C in a systematic investigation. Some examples will be shown here to give an impression of the variety of results.

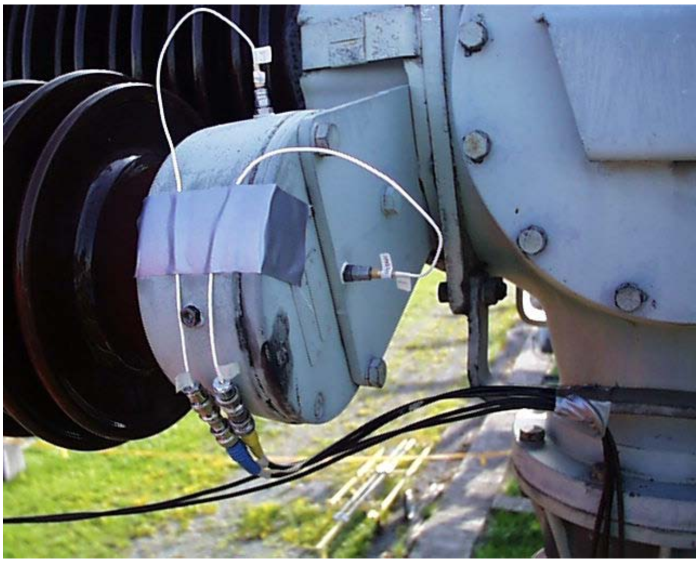
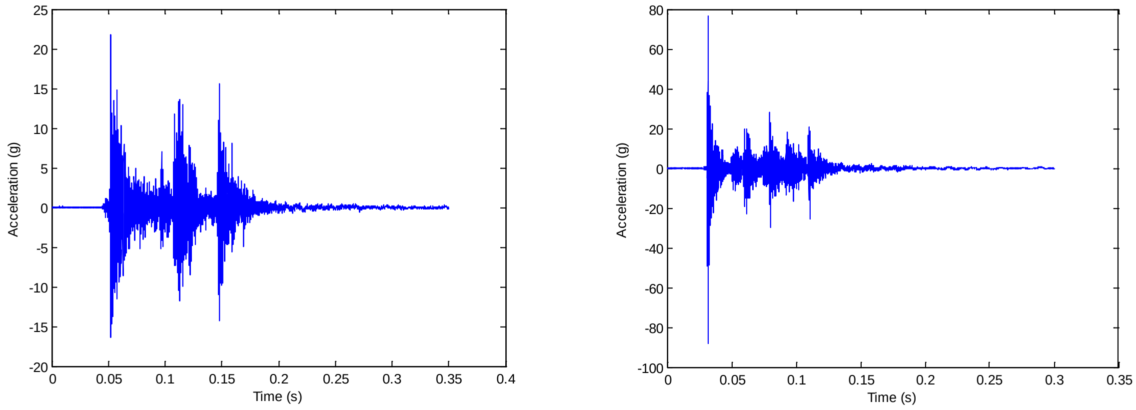


Figure 20 - Attaching the accelerometers to the capacitor

3.2.2.1.1 Effect of operating cycle

Figure 21 shows the difference in recorded signals during C and O operations. Some distinct amplitude maxima occur during the operations. The highest amplitudes occur when the contacts are opened. The maximum values recorded here are ± 80*g*. The maximum amplitudes for the other circuit-breakers are less extreme but were also in the range of several tens of *g*'s.



a) Closing operation

b) Opening operation

Figure 21 - Acceleration measurements on circuit-breaker B in axial direction on the driving side

3.2.2.1.2 Direction of acceleration

Figure 22 shows the pattern recorded simultaneously by the four accelerometers. Accelerometers 1 and 4 are in the axial direction of the grading capacitor with number 1 near the drive side of the interrupter. Accelerometers 2 and 3 are in a perpendicular direction.

The highest amplitude was measured by accelerometer number 1, corresponding to the axial direction and nearer the drive side. The acceleration in the radial direction is substantially smaller.

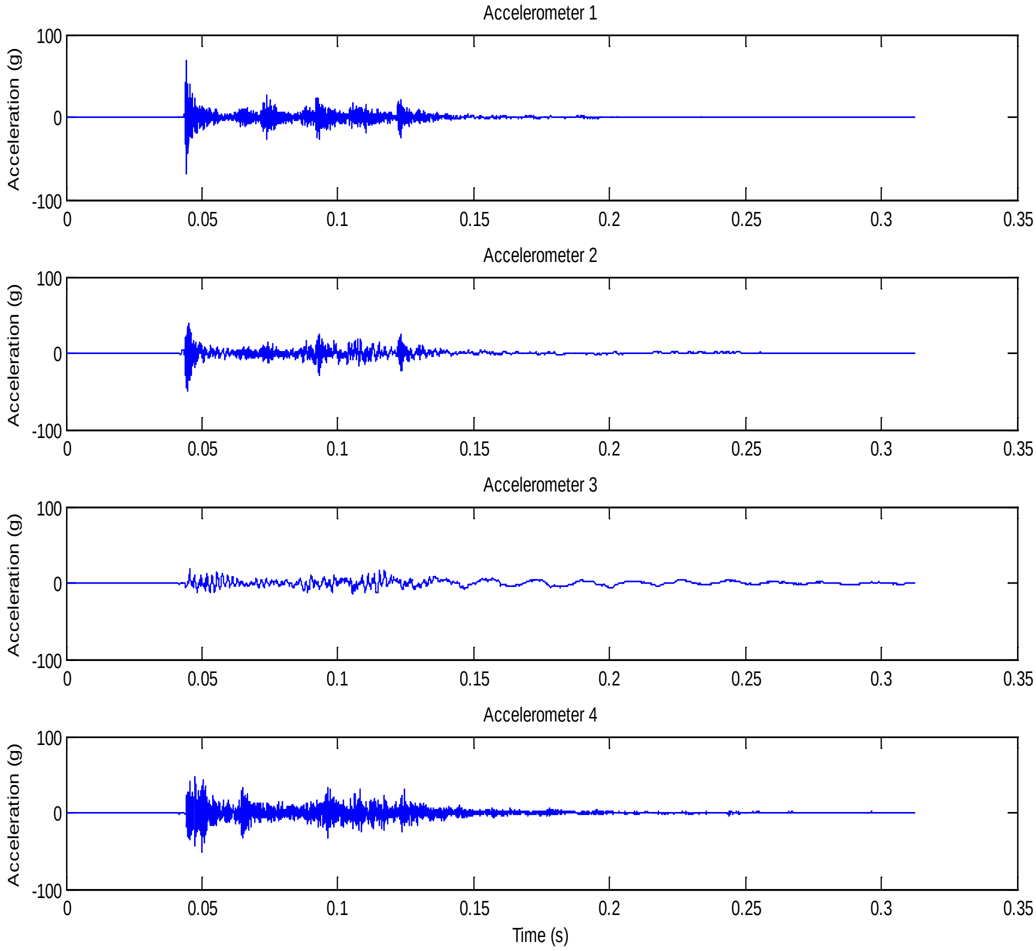


Figure 22 - Acceleration versus time during opening operation measured by four accelerometers simultaneously

3.2.2.1.3 Post-processing

Taking into account that the extreme acceleration values are dominated by high frequencies which may have a negligible impact on the test object because of the very low displacement, the recorded signals have been post-processed by integrating twice. The resulting curves of velocity and displacement are shown below the acceleration over the recorded time window in Figure 23. The calculated displacement in this example is less than 0,5 mm.

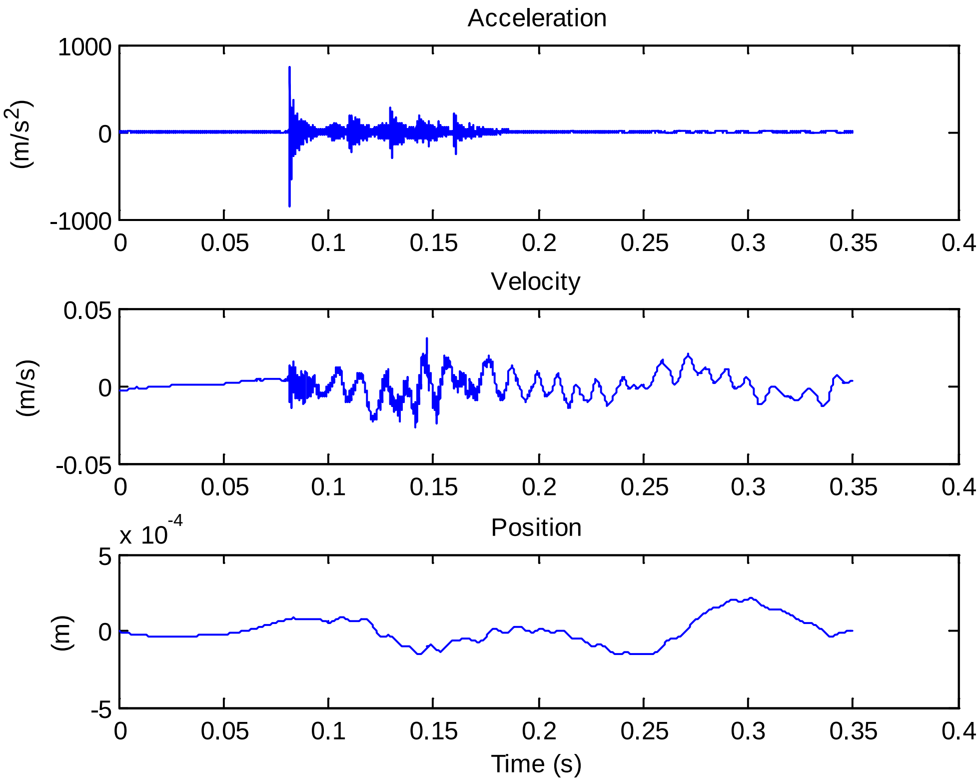


Figure 23 - Acceleration, velocity and displacement of opening operation

3.2.2.2 Further aspects of acceleration measurements

3.2.2.2.1 GIS circuit-breaker

Measurements were performed on the grading capacitors of two different, double-break 300 kV GIS circuit-breakers from two manufacturers: Circuit-breaker D was put into service in 1980 with hydraulic operating mechanism and vertical interrupters and circuit-breaker E was put into service in 1981, with a pneumatic operating mechanism and horizontal interrupters.

The recorded signals were unfiltered. The signals recorded during C and O operations for the two circuit-breaker types show the same characteristics as the live tank circuit-breakers: of the highest acceleration was in the axial direction, generally with amplitudes of 20 to 40g and single peaks up to 60g in the time domain. Since the signals were unfiltered, the results give little information about the real stresses on the grading capacitors.

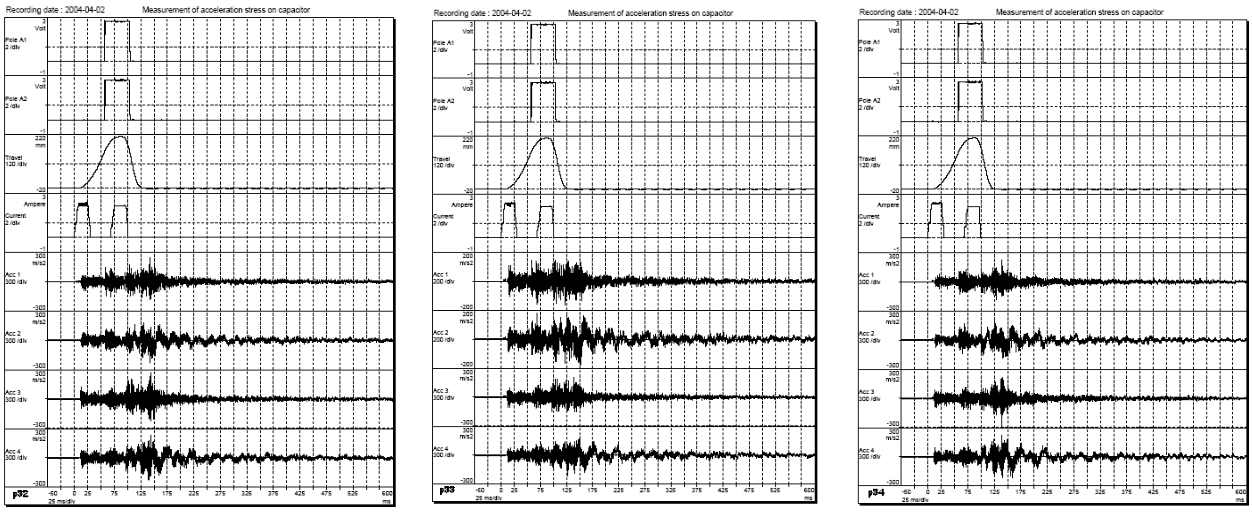
3.2.2.2.2 Repeatability of measurement

Differences between measurements under identical conditions have also to be considered. This is illustrated in Figure 24, which shows acceleration measurements for circuit-breaker F, a modern 550 kV double-break SF_6 live tank circuit-breaker.

During the measurements, for each switching condition and for identical measuring points five measurements were recorded for calculation of mean values. For measurements obtained under identical conditions, visual comparison shows large differences in the traces of the acceleration, with the peak values differing by more than 50 %. See, for example, the three measurements in Figure 24. In addition to the acceleration patterns, the position of main contacts, puffer travel and coil current were recorded.

Due to the large scatter in the measured values, only tendencies can be derived from these results. The acceleration values are smallest during C operations due to the lower velocity of contact movement. Acceleration values during O and CO operations are similar and generally higher than those during C operations, reaching values of nearly 300 m/s^2 or around 30g. Here, the acceleration in the axial direction of the capacitor (z-direction) has the lowest values.

The large scatter between the measured records may also originate from the measuring technique. Acceleration sensors measuring very low levels are very sensitive to changes in the connection leads and this can influence the measured values. It is not possible to distinguish between changes in the recorded signal due to the measurement technique and those due to variation in the measured signal. Consequently, the results have to be interpreted with care.



Traces from the top: Position of main contacts, puffer travel, coil current and signals from four accelerometers

Figure 24 - Measurements carried out during circuit-breaker operations (CO) under identical conditions

3.2.2.2.3 Filtering and post-processing

In addition to unfiltered recording of acceleration signals, filtering and post-processing have been applied to results from circuit-breaker G, a 420 kV double break SF_6 live tank circuit-breaker.

All of the unfiltered measurements show acceleration values in the range of up to 30*g* or even more in some cases. No systematic differences due to the different measurement positions or directions can be distinguished.

Only when the signal bandwidth is limited to a lower frequency (200 Hz in this case) do differences in the stressing become obvious. This is illustrated in Figure 25. The values recorded in the axial direction of the capacitors are small in comparison with those recorded in the radial direction. The radial acceleration values are generally some *g*, in all cases below 10*g*.

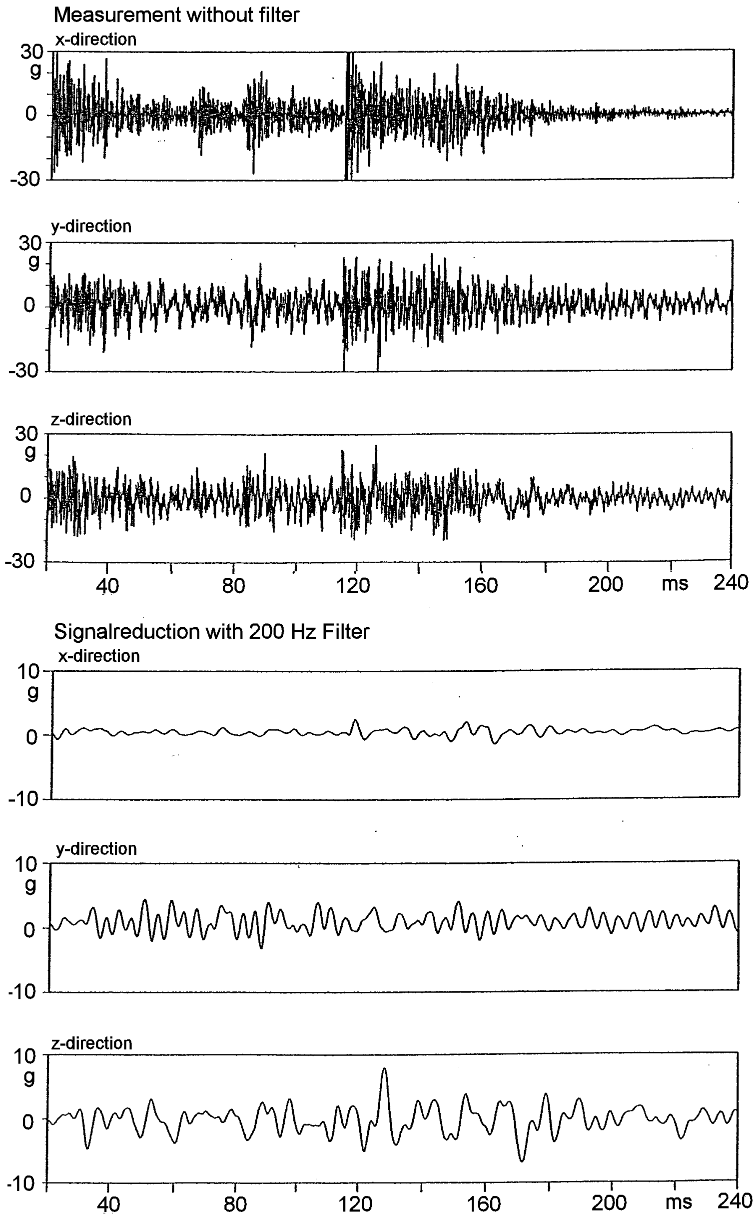


Figure 25 - Acceleration in the x-, y- and z-directions during CO operation without filter and with 200 Hz filter (x = axial direction)

The unfiltered signals were post-processed to obtain the displacement as a function of frequency. The results are shown in Figure 26. The displacement values are in the range of a millimetre at low frequencies, decreasing rapidly with increased frequency to the micrometre-range at some hundred Hertz. At frequencies above 300 Hz all displacement values are below 1 µm.

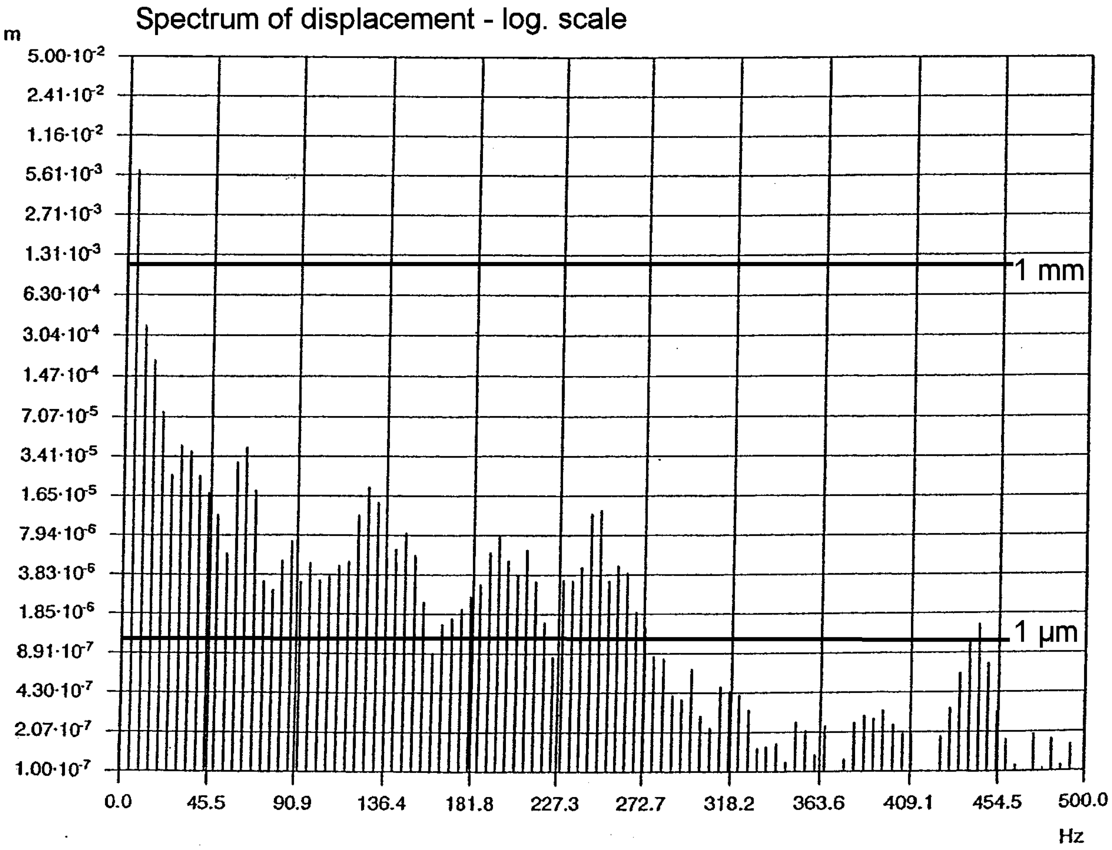


Figure 26 – Displacement in *y*-direction in log-scale vs. frequency without filtering

Since an exact limit between the values of displacement that are harmless and those that are harmful cannot be given, a frequency limit can be proposed as an alternative in order to achieve comparable measurements and test procedures.

Displacements that can result in cracks, delamination, contact problems, etc are important since these cause damage to the grading capacitor. The displacement of parts inside the capacitor is normally the same as or smaller than the displacement measured on the outside surface, as long as mechanical resonances do not occur. A frequency of around 200 Hz may be defined as a limit above which frequencies have no significant influence on displacements and are not considered destructive. In the evaluation of acceleration measurements, signals should be limited to this frequency by low-pass filtering or by post-processing. The result is that the mechanical stress from operation of the circuit-breaker is apparently below 10g as seen from Figure 16 and Figure 25.

A more harmful case of mechanical stress is an oscillating stress that can stimulate mechanical parts to vibrate at their mechanical resonance frequency. Such an oscillating stress may occur during transport. A circuit-breaker switching operation is more similar to a mechanical shock or a random vibration that only influences the capacitor momentarily. Therefore, for switching operations, the resonance will not be sustained.

3.3 Mechanical stress during transport

An exact description of the mechanical stresses during transport and handling of grading capacitors cannot be given due to the diversity of the factors involved. The way in which the capacitors are packaged is one of the most important factors. The grading capacitors can be shipped as separate parts, packaged singly or in as a set, or as an integral part of the circuit-breaker assembly when they are already fitted in the factory. In all cases the packaging method will influence the mechanical stresses on the grading capacitor and its internal parts along a mechanical chain from the transport system to the grading capacitor itself.

A German rule for packaging states that an acceleration of 4g has to be considered for stress due to single shocks. This value corresponds to the maximum assumed acceleration due to a shunting shock on railways. For any kind of transport, many more parameters have to be considered. In general, these should be covered by IEC standards.

Transportation as part of the environmental conditions has been described in IEC documents concerning classification and severity (IEC 60721-3-2 [1], IEC TR 60721-4-2 [2]) and environmental testing (IEC 60068-2-27 [3]). The documents include transports by road, rail, water, air and vertical transport such as cranes and lifts. The specified environmental conditions apply to the package containing the product, if it is packed.

The severities of stresses specified in IEC 60721-3-2 are those which will have a low probability of being exceeded. All specified values may be reached, but they do not occur permanently. Special values and frequency of occurrence have to be additionally be specified, if applicable.

The mechanical conditions have been classified with their environmental parameters as follows:

- Sinusoidal and random stationary vibrations;
- Non-stationary vibration including shock;
- Free fall;
- Others not relevant to grading capacitors.

For each parameter a classification of severity is given. An idea of the stress values and corresponding tests is given below. The values given correspond to the highest severity class 2M3:

- Stationary vibration sinusoidal:
  - Displacement amplitude: 7,5 mm for 2-8 Hz;
  - Acceleration amplitude: 20 m/s^2 for 8-200 Hz;
  - Acceleration amplitude: 40 m/s^2 for 200-500 Hz.

NOTE The frequency range may be limited to 200 Hz for transportation on parts of the vehicle with high internal damping.

- Non-stationary vibration including shock:
  - Shock response spectrum type I: 300 m/s^2;
  - Shock response spectrum type II: 1000 m/s^2.

  (The response spectra are dependant on the duration of the impacting half-sine pulse: type I with 11 ms and type II with 6 ms half sine wave. The concept of shock response spectrum is described in detail in Appendix B of IEC 60068-2-27 [3]).
- Free fall:
  - Mass of 20 kg to 100 kg: 1,2 m height;
  - Mass more than 100 kg: 0,5 m height.

All possibilities concerning the mechanical stress due to transport should be considered as far as possible: Transportation by truck, railway or ship; packaging method and handling requirements. Shock indicators can be used to record the stresses during transport from factory to site. However, not all types of stresses can be covered and analyzed by this method. Experience has shown that damage to equipment during transport cannot always be explained. The experience from transports of grading capacitors or similar goods will give an indication for selection of the severity of the mechanical test conditions. Generally applicable guidance for a transport test cannot be given in this report.

Considering the way in which the grading capacitors are transported, fitted to the circuit-breaker or packed separately, the values mentioned above seem to be too high and are not recommended for capacitor testing. In particular, the acceleration values of the non-stationary vibrations including shock, as well as the free fall tests are outside the ranges normally considered by capacitor and circuit-breaker manufacturers for transport.

3.4 Mechanical stress due to seismic activity

Mechanical stresses due to seismic activity have to be considered, since these are often a basic requirement for circuit-breakers. The requirements for circuit-breakers are covered by standards, which describe the method of qualification, e.g. by testing or calculation.

According to the rules for testing, the maximum acceleration response of the test object is proven using a defined frequency range. In this way the response of the test object to an acceleration applied at ground level and covering all relevant frequencies is obtained, including the condition causing maximum stress at the circuit-breaker head. These acceleration values will also be experienced by the grading capacitors.

The maximum acceleration response value in IEC standards is 0,8g and in IEEE standards 1,2g is stated. The maximum frequency relevant for seismic testing is 35 Hz only.

3.5 Conclusions

As sources of the mechanical stresses on grading capacitors, the operation of the circuit-breaker, transport and seismic activities on site have been considered. For transportation and seismic activity, relevant standards can been used to cover the requirements. For the mechanical stresses during circuit-breaker operations, measurements of acceleration have been collected and evaluated.

There are only a few measurements of mechanical stresses due to circuit-breaker operation available. Each of these was conducted under different and special circumstances. The measurements indicate only certain tendencies in the different parameters. From consideration of the measured acceleration as a function of frequency and the corresponding values of displacement, the conclusion can be drawn that the measurements are not sufficient for a comprehensive analysis of the stresses but can give a hint concerning the stress values.

All measurements show high acceleration values in the range of some tens of g. These high values are probably harmless since they only occur at high frequencies for which the associated values of displacement become very low.

Assuming that frequencies above 200 Hz have no significant influence on displacement and are therefore harmless, the evaluation of acceleration measurements should be limited to this frequency by low-pass filtering or by post-processing. The result is that the mechanical stress from operation of the circuit-breaker is apparently below 10g.

The effects of resonances generated during circuit-breaker operation can be excluded since damping makes the vibrations decay within a few hundred milliseconds and the resonance condition is not sustained. Hence a switching operation is more similar to a mechanical shock or a random vibration that only influences the capacitor momentarily.

Mechanical stresses due to transport are well covered by standard test procedures. By defining the transport class, the ability of a capacitor to withstand mechanical stresses of the relevant severity can be proven by test, including vibration, shocks and resonances.

Assuming that the mechanical stresses on circuit-breakers due to seismic activity are covered by the relevant standards, the stressing of the grading capacitors is low in comparison to transport or operation stressing.

3.6 References

[1] IEC 60721-3-2: Classification of environmental conditions – Part 3: Classification of groups of environmental parameters and their severities – Section 2: Transportation

[2] IEC 60721-4-2: Classification of environmental conditions – Part 4-2: Guidance for the correlation and transformation of environmental condition classes of IEC 60721-3 to the environmental tests of IEC 60068-Transportation

[3] IEC 60068-2-27: Basic environmental testing procedures – Part 2: Tests – Test Ea and guidance: Shock

3.7 Bibliography

IEC 62271-300: High-voltage alternating current circuit-breakers – Part 300: Seismic qualification of alternating current circuit-breakers

IEC 60068-3-3: Environmental testing – Part 3: Background information. Seismic test methods for equipment.

4 Electrical stresses and nominal voltage

4.1 Introduction

Circuit-breaker voltage grading capacitors are subjected to a range of electrical stresses that occur when the circuit-breaker is in the open position and that arise during switching operations. When considering the electrical stresses that are imposed on the grading capacitors and the consequent insulation levels required of the capacitors, the following factors should be taken into account:

a) Voltage sharing across interrupters

The sharing of voltage across the interrupters of an open circuit-breaker is largely determined by the values of the grading capacitors, but is also affected by stray capacitances, particularly from the interrupters to earth, and by capacitor tolerances. The stray capacitances of the interrupters in the open position are also significant. Consequently, grading capacitors may be stressed by voltages higher than those that would occur under equal sharing of voltage across the circuit-breaker pole.

b) Rated withstand voltages required across the open circuit-breaker

The dielectric requirements for the grading capacitor can only be based on the requirements for the circuit-breaker. These requirements are specified in the relevant equipment standards (circuit-breaker standard, GIS standard) of IEC and ANSI/IEEE. Special requirements of circuit-breaker customers have to be considered in addition.

The rated withstand voltage values of the circuit-breaker normally cover all overvoltages in service. Therefore, special insulation coordination aspects e.g. overvoltage protection or substation configuration aspects do not need to be considered. Some special operating practices, such as leaving the circuit-breaker in the open position for a prolonged time under phase-opposition conditions, impose stresses that are particularly arduous for grading capacitors and need to be considered separately.

c) Stresses arising out of switching duties

Grading capacitors are subjected to a range of transient electrical stresses that occur as a result of switching operations. Some of these have significant implications for the grading capacitors and must be adequately considered.

d) Coordination of withstand voltages between circuit-breaker interrupter and grading capacitor

Withstand voltage values for grading capacitors should be coordinated with those of the circuit-breaker so as to avoid grading capacitor internal failures.

The above factors will be discussed in the following sections.

4.2 Voltage sharing

The effects of stray capacitance and capacitor tolerances on voltage sharing can be illustrated for a circuit-breaker with two interrupters per pole using the equivalent circuit of Figure 27.

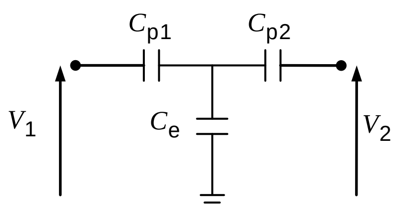


Figure 27 - Equivalent circuit for voltage sharing, circuit-breaker with 2 interrupters per pole

In Figure 27, C_e represents the stray capacitance to earth and C_{p1} and C_{p2} represent the total capacitances across the interrupters comprising the grading capacitor and stray capacitance of the open interrupter.

The most unequal voltage sharing occurs when one terminal of the open circuit-breaker is energised, the other terminal is at earth potential, the grading capacitor on the energised side has a value at the lower end of the tolerance range and the capacitor on the opposite side has a value at the higher end of the tolerance range. The voltage across the more highly stressed capacitor is

$$V_{p1} = V_1 \frac{(C_{p2} + C_e)}{(C_{p1} + C_{p2} + C_e)} \qquad (4)$$

Expressing the increased voltage V_{p1} across the capacitor as a ratio compared to the value $V_1/2$ under equal sharing gives

$$\frac{V_{p1}}{V_1/2} = \frac{2(C_{p2} + C_e)}{(C_{p1} + C_{p2} + C_e)} \qquad (5)$$

If the nominal capacitance of the grading capacitor C shunted by the stray capacitance C_s of an interrupter in the open position is represented by C_p and the range of capacitor tolerance by $\pm\Delta C_p$, then

$$C_p = C + C_s \qquad (6)$$

$$C_{p1} = C_p - \Delta C_p \qquad (7)$$

and

$$C_{p2} = C_p + \Delta C_p \qquad (8)$$

For a circuit-breaker with four interrupters per pole, the effects of stray capacitance and capacitor tolerances on voltage sharing can be illustrated using the equivalent circuit of Figure 28.

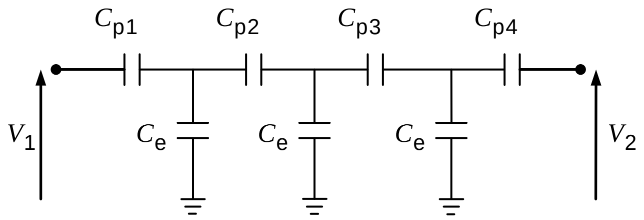


Figure 28 - Equivalent circuit for voltage sharing, circuit-breaker with 4 interrupters per pole

The capacitance to earth C_e at the centre of the circuit-breaker may be less than at the other two positions if no support column is present, but in the present work it will be assumed to be the same as this is a worst case. The most unequal voltage sharing occurs when one terminal of the open circuit-breaker is energised, the other terminal is at earth potential, the grading capacitor nearest the energised terminal has a value at the lower end of the tolerance range and the remaining capacitors have a value at the higher end of the tolerance range. The voltage across the most highly stressed capacitor is

$$V_{p1} = V_1 \frac{A}{B} \qquad (9)$$

where

$$A = C_{p2}C_{p3}C_{p4} + C_e(3C_{p2}C_{p3} + 2C_{p2}C_{p4} + C_{p3}C_{p4}) + C_e^2(2C_{p2} + 2C_{p3} + C_{p4}) + C_e^3 \qquad (10)$$

and

$$\begin{aligned} B = {} & C_{p1}C_{p2}C_{p3} + C_{p1}C_{p2}C_{p4} + C_{p1}C_{p3}C_{p4} + C_{p2}C_{p3}C_{p4} + \\ & C_e(C_{p1}C_{p2} + 2C_{p1}C_{p3} + C_{p1}C_{p4} + 3C_{p2}C_{p3} + 2C_{p2}C_{p4} + C_{p3}C_{p4}) + \\ & C_e^2(C_{p1} + 2C_{p2} + 2C_{p3} + C_{p4}) + C_e^3 \end{aligned} \qquad (11)$$

Expressing the increased voltage V_{p1} across the capacitor as a ratio compared to the value $V_1/4$ under equal sharing gives

$$\frac{V_{p1}}{V_1/4} = \frac{4A}{B} \qquad (12)$$

C_{p1} is given by Equation 7 in the previous case,

and

$$C_{p2} = C_{p3} = C_{p4} = C_p + \Delta C_p \qquad (13)$$

Values for the factor by which the voltage across a grading capacitor is increased due to unequal voltage sharing compared with the value under equal voltage sharing are given in Table 1 for AIS circuit-breakers and Table 2 for GIS circuit-breakers.

Stray capacitances are strongly dependent on the design of the circuit-breaker. The stray capacitance to earth is dependent on the geometry of the interrupters, stress shields, etc and may vary in a wide range. Values in the range 20 to 50 pF for AIS circuit-breakers and 100 to 400 pF for GIS circuit-breakers have been taken. The stray capacitance across the interrupter in the open position has a minor effect and tends to improve the voltage sharing. In order not to overestimate its effect therefore, a modest value of 12 pF has been assumed. This value has been used for both AIS and GIS circuit-breakers.

Values for the capacitor tolerance ΔC_p of ±5 % for AIS circuit-breakers and ±3 % for GIS circuit-breakers have been taken.

Table 1 - Factor by which voltage is increased compared with an equal voltage sharing, AIS circuit-breakers

Nominal capacitance (pF)	**Number of interrupters per pole**							
	2				**4**			
	Capacitance to earth C_e (pF)				**Capacitance to earth** C_e (pF)			
	20	30	40	50	20	30	40	50
500	1,067	1,076	1,085	1,093	1,204	1,263	1,320	1,373
1000	1,059	1,063	1,068	1,072	1,143	1,175	1,206	1,237
1500	1,056	1,059	1,062	1,065	1,122	1,144	1,165	1,186
2000	1,054	1,057	1,059	1,061	1,111	1,127	1,144	1,160

Table 2 - Factor by which voltage is increased compared with an equal voltage sharing, GIS circuit-breakers

Nominal capacitance (pF)	**Number of interrupters per pole**							
	2				**4**			
	Capacitance to earth C_e (pF)				**Capacitance to earth C_e** (pF)			
	100	200	300	400	100	200	300	400
500	1,116	1,188	1,249	1,302	1,575	1,918	2,163	2,349
1000	1,075	1,117	1,155	1,190	1,347	1,581	1,770	1,926
1500	1,061	1,090	1,117	1,143	1,256	1,432	1,583	1,713
2000	1,053	1,076	1,097	1,118	1,207	1,348	1,473	1,584

The voltage sharing becomes more unequal as the stray capacitance to earth C_e increases. GIS circuit-breakers have higher stray capacitances to earth than AIS circuit-breakers and hence exhibit the more unequal voltage sharing. The unequal voltage sharing is significantly greater for a circuit-breaker with 4 interrupters per pole than for a circuit-breaker with two interrupters per pole. As the capacitance value of the grading capacitors is increased, the influence of the stray capacitance to earth reduces and the unequal voltage sharing becomes determined largely by capacitor tolerance. Thus, in the case of an AIS circuit-breaker with two interrupters per pole, for example, the factor by which the voltage is increased tends towards a minimum value of 1,05, corresponding to the capacitor tolerance of 5 %.

It is common practice for circuit-breaker manufacturers to specify a grading factor, F, which is chosen so as to take into account the possible increase in voltage across a grading capacitor due to unequal sharing.

From the values shown in Table 1, a grading factor of 1,1 would cover all cases considered for an AIS circuit-breaker with 2 interrupters per pole. A grading factor of 1,2 would cover cases considered for an AIS circuit-breaker with 4 interrupters per pole where the grading capacitors have a value of 1500 pF or more.

From the values shown in Table 2, a grading factor of 1,2 would cover cases considered for a GIS circuit-breaker with 2 interrupters per pole where the grading capacitors have a value of 1000 pF or more. A grading factor of 1,1 would cover some cases where the capacitance of the grading capacitors is higher and the capacitance to earth is lower. For a GIS circuit-breaker with 4 interrupters per pole, the voltage unbalance is greater, with the voltage in some cases exceeding twice that under equal sharing. Extreme values merit special attention. Higher values of grading factor may be specified for these cases or, alternatively, different values of grading capacitor may be selected to achieve a more equal voltage sharing across the circuit-breaker pole.

4.3 Nominal voltage

Currently, the nominal voltages for grading capacitors vary over a wide range with no definition and no clear relation to the standardised highest voltages for equipment U_m (for switchgear, the term "rated voltage U_r" is used, in accordance with IEC 62271-1 [1]; standards of all other committees use the term "highest voltage for equipment U_m").

For a unique designation and furthermore for description of test recommendations, e.g. service lifetime requirements, a nominal voltage U_N will be defined for grading capacitors. The value of U_N implies that this voltage will be the guaranteed maximum voltage stress that the capacitor can withstand for its whole lifetime. The proposed nominal voltage is higher by a factor equal to the grading factor than the linear voltage distribution for phase to earth voltage across the circuit-breaker, thus:

$$U_N = \frac{F}{N}\left(\frac{U_r}{\sqrt{3}}\right) \tag{14}$$

where N is the number of interrupters per pole and U_r is the rated voltage of the circuit-breaker.

Values of nominal voltage for grading capacitors are given in Table 3 for circuit-breakers with 2 and 4 interrupters per pole for grading factors of 1,1 and 1,2.

Table 3 - Rated voltages of circuit-breakers and nominal voltages of grading capacitors

Circuit-breaker		**Grading capacitor**		
Rated voltage U_r kV (r.m.s.value)	**Phase-to-earth voltage** $U_r/\sqrt{3}$ kV (r.m.s. value)	**Grading capacitor nominal voltage** U_N kV (r.m.s. value)		
		N **= 2**		N **= 4**
		F **= 1,1**	F **= 1,2**	F **= 1,2**
300	173	95	104	52
362	209	115	125	63
420	242	133	145	73
550	318	175	191	95
800	462	254	277	139

4.4 Rated insulation level

Minimum values of insulation levels for grading capacitors may be derived from the rated insulation levels of the circuit-breaker with which they are to be used, taking into account the number of interrupters and unequal voltage sharing. The dielectric performance of the grading capacitors should not be less than that of the circuit-breaker.

In the following sections, minimum values of withstand voltage for grading capacitors are derived from the withstand voltages for circuit-breakers specified in IEC standards. The requirements of other standards such as ANSI/IEEE and special customer requirements may not be covered by the examples given. However, the same methodology can be applied using values specified in other standards.

Where values specified in the standards are in the form of a combined voltage, i.e. an impulse applied to one terminal of the open circuit-breaker and a power-frequency voltage applied to the opposite terminal, the sum of both components of the combined voltage has been used as the basis for calculation and application to the grading capacitors.

4.4.1 Short-duration power-frequency withstand voltage

Values of rated short-duration power-frequency withstand voltage are given in IEC 62271-1 [1] for AIS circuit-breakers and IEC 62271-203 [2] for GIS circuit-breakers. Minimum values of rated short-duration power-frequency withstand voltage U_d for grading capacitors can be determined from the values for the circuit-breaker given in the standards according to the following equation.

$$U_d = \frac{F}{N} \times U_{dCB} \qquad (15)$$

Values derived from the above are given in

Table 4 for AIS circuit-breakers and Table 5 for GIS circuit-breakers.

Table 4 - Minimum short-duration power-frequency withstand voltage for grading capacitors, AIS circuit-breakers (IEC 62271-1 [1])

Circuit-breaker		Grading capacitor		
Rated voltage U_r kV (r.m.s. value)	**Rated short-duration power-frequency withstand voltage** U_d kV (r.m.s. value)	**Short-duration power-frequency withstand voltage** U_d kV (r.m.s. value)		
	Across open switching device	N **= 2**		N **= 4**
		F **= 1,1**	F **= 1,2**	F **= 1,2**
300	435	239	261	131
362	520	286	312	156
420	610	336	366	183
550	800	440	480	240
800	1 150	633	690	345

Table 5 - Minimum short-duration power-frequency withstand voltage for grading capacitors, GIS circuit-breakers (IEC 62271-203 [2])

Circuit-breaker		Grading capacitor		
Rated voltage U_r kV (r.m.s. value)	**Rated short-duration power-frequency withstand voltage** U_d kV (r.m.s. value)	**Short-duration power-frequency withstand voltage** U_d kV (r.m.s. value)		
	Across open switching device	N **= 2**		N **= 4**
		F **= 1,1**	F **= 1,2**	F **= 1,2**
300	595	327	357	179
362	675	371	405	203
420	815	448	489	245
550	925	509	555	278
800	1 270	699	762	381

4.4.2 Switching impulse withstand voltage

Values of rated switching impulse withstand level for AIS circuit-breakers are given in IEC 62271-1 [1]. A choice of two values is given for the rated switching impulse withstand voltage across the open switching device for each rated voltage in range II (300 to 800 kV). In addition, values specified for rated switching impulse withstand voltage across the isolating distance are also applicable to some circuit-breakers, as specified in IEC 62271-100 [3].

Values for rated switching impulse withstand level for GIS circuit-breakers are specified in IEC 62271-203 [2]. Single values for rated switching impulse withstand voltage across the open switching device are given for each rated voltage in range II. As for AIS circuit-breakers, values specified for rated switching impulse withstand voltage across the isolating distance are also applicable to some circuit-breakers, as specified in IEC 62271-203 [2].

Minimum values of grading capacitor switching impulse withstand voltage U_s have been calculated according to

$$U_{\mathrm{S}} = \frac{F}{N} \times U_{\mathrm{sCB}} \tag{16}$$

Values derived from the above are given in Table 6 for AIS circuit-breakers and Table 7 for GIS circuit-breakers.

Table 6 - Minimum switching impulse withstand voltage for grading capacitors, AIS circuit-breakers (IEC 62271-1 [1])

Circuit-breaker			Grading capacitor					
Rated voltage U_r kV (r.m.s. value)	**Rated switching impulse withstand voltage** U_s kV (peak value)		**Switching impulse withstand voltage** U_s kV (peak value)					
	Across open switching device	**Across isolating distance**	**Across open switching device**			**Across isolating distance**		
			N = 2		**N = 4**	**N = 2**		**N = 4**
			F = 1,1	**F = 1,2**	**F = 1,2**	**F = 1,1**	**F = 1,2**	**F = 1,2**
300	750	700 (+245)	413	450	225	520	567	284
	850		468	510	255			
362	850	800 (+295)	468	510	255	602	657	329
	950		523	570	285			
420	950	900 (+345)	523	570	285	685	747	374
	1 050		578	630	315			
550	1 050	900 (+450)	578	630	315	743	810	405
	1 175		646	705	353			
800	1 425	1 175 (+650)	784	855	428	1 004	1 095	548
	1 550		853	930	465			

Table 7 - Minimum switching impulse withstand voltage for grading capacitors, GIS circuit-breakers (IEC 62271-203 [2])

Circuit-breaker			Grading capacitor					
Rated voltage U_r kV (r.m.s. value)	**Rated switching impulse withstand voltage** U_s kV (peak value)		**Switching impulse withstand voltage** U_s kV (peak value)					
	Across open switching device	**Across isolating distance**	**Across open switching device**			**Across isolating distance**		
			N = 2		N = 4	N = 2		N = 4
			F = 1,1	F = 1,2	F = 1,2	F = 1,1	F = 1,2	F = 1,2
300	850	700 (+245)	468	510	255	520	567	284
362	950	800 (+295)	523	570	285	602	657	329
420	1 050	900 (+345)	578	630	315	685	747	374
550	1 175	900 (+450)	646	705	353	743	810	405
800	1 425	1 100 (+650)	784	855	428	963	1 050	525

4.4.3 Lightning impulse withstand voltage

Values of rated lightning impulse withstand voltage are given in IEC 62271-1 [1] for AIS circuit-breakers, where a choice of two values is given for each rated voltage in range II, and in IEC 62271-203 [2] for GIS circuit-breakers.

Minimum values of grading capacitor lightning impulse withstand voltage have been calculated according to

$$U_{\mathrm{p}} = \frac{F}{N} \times U_{\mathrm{pCB}} \qquad (17)$$

Values derived from the above are given in Table 8 for AIS circuit-breakers and Table 9 for GIS circuit-breakers.

Table 8 - Minimum lightning impulse withstand voltage for grading capacitors, AIS circuit-breakers (IEC 62271-1 [1])

Circuit-breaker		Grading capacitor		
Rated voltage U_r kV (r.m.s. value)	Rated lightning impulse withstand voltage U_p kV (peak value)	Lightning impulse withstand voltage U_p kV (peak value)		
	Across open switching device	N = 2		N = 4
		F = 1,1	F = 1,2	F = 1,2
300	950 (+170)	616	672	336
	1 050 (+170)	671	732	366
362	1 050 (+205)	690	753	377
	1 175 (+205)	759	828	414
420	1 300 (+240)	847	924	462
	1 425 (+240)	916	999	500
550	1 425 (+315)	957	1 044	522
	1 550 (+315)	1 026	1 119	560
800	1 800 (+455)	1 240	1 353	677
	2 100 (+455)	1 405	1 533	767

Table 9 - Minimum lightning impulse withstand voltage for grading capacitors, GIS circuit-breakers (IEC 62271-203 [2])

Circuit-breaker		Grading capacitor		
Rated voltage U_r kV (r.m.s. value)	Rated lightning impulse withstand voltage U_p kV (peak value)	Lightning impulse withstand voltage U_p kV (peak value)		
	Across open switching device	N = 2		N = 4
		F = 1,1	F = 1,2	F = 1,2
300	1 050 (+170)	671	732	366
362	1 175 (+205)	759	828	414
420	1 425 (+240)	916	999	500
550	1 550 (+315)	1 026	1 119	560
800	2 100 (+455)	1 405	1 533	767

4.4.4 Insulation level and nominal voltage

Table 4 through Table 9 highlight that for each rated voltage for the circuit-breaker there are a number of sets of withstand voltage values for the grading capacitors, depending on the grading factor and number of interrupters. If the requirements of additional standards, such as ANSI/IEEE, had also been considered, then the number of sets of withstand voltage would have increased further. It makes sense to seek a smaller number of standardised values that will cover the broadest range of applications.

4.5 Stresses arising out of switching duties

In most cases, the electrical stresses to which grading capacitors are subjected during switching operations are less severe than those associated with the withstand voltages described above. However, some switching operations give rise to stresses that have significant implications for the grading capacitors. In particular, a number of dielectric failures of grading capacitors have occurred during switching of low inductive currents associated with shunt reactors, as reported in Chapter 2. The electrical stresses to which grading capacitors are subjected during shunt reactor switching will be described in detail in the next chapter.

4.6 Coordination of withstand voltages between circuit-breaker interrupter and grading capacitor

The standard impulse withstand test procedures are based on a flashover probability of 10 %. To prevent an internal failure of the grading capacitor during the test of a circuit-breaker, the withstand voltage value should be chosen to be somewhat higher for the grading capacitor compared to the interrupter. The rationale for this is that the internal flashovers in grading capacitors are non-self restoring.

The short-duration power frequency test has no statistical background since testing is normally without flashover. Nevertheless, to prevent an internal failure of the grading capacitor during the test of a circuit-breaker, the withstand voltage value should be chosen to be somewhat higher for the grading capacitor compared to the interrupter.

4.7 Conclusions

The factors which determine the electrical stresses on circuit-breaker voltage grading capacitors in service have been described and a methodology for deriving the insulation levels required of the grading capacitors has been demonstrated. Recommended withstand voltages based on the above will be given in Chapter 6.

4.8 References

[1] IEC 62271-1: High-voltage switchgear and controlgear – Part 1: Common specifications

[2] IEC 62271-203: High-voltage switchgear and controlgear – Part 203: Gas-insulated metal-enclosed switchgear for rated voltages above 52 kV

[3] IEC 62271-100: High-voltage switchgear and controlgear – Part 100: Alternating current circuit-breakers

5 Electrical stresses during shunt reactor switching

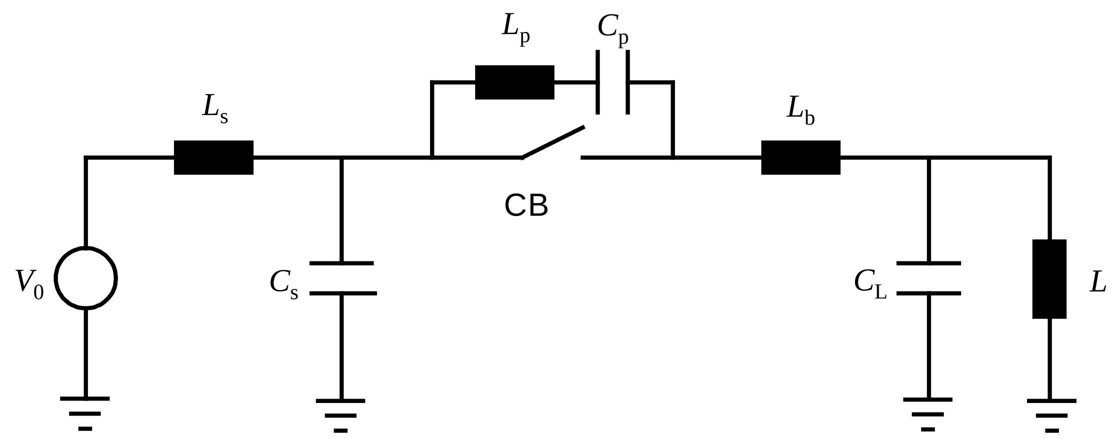
As described in Chapter 2, a number of disruptive dielectric failures of circuit-breaker grading capacitors have been reported. In general, there was a clear correlation between disruptive dielectric failures and switching duty. Most of the circuit-breakers concerned had been switching low inductive currents associated with shunt reactors and failure usually occurred on or shortly after a breaking operation. The cause of the failures has not been fully understood.

This chapter is concerned with the electrical stresses imposed on circuit-breaker voltage grading capacitors during shunt reactor switching. The relevant aspects of shunt reactor switching are summarised. The corresponding electrical stresses imposed on the grading capacitors are discussed and possible explanations for dielectric failures are proposed. Conclusions are drawn for specification and test requirements for grading capacitors for shunt reactor switching applications.

5.1 Background

Working Group 02 of Study Committee No. 13 (A3) has studied the interruption of small inductive currents. Its report was published in a CIGRE brochure [1], of which Chapters 1 and 2 present the general theory of small inductive current switching, while Chapter 4 deals specifically with reactor switching. Test requirements and an application guide for high-voltage circuit-breakers for shunt reactor switching are published in IEC 62271-110 [2]. More recently, CIGRÉ Working Group A3.11 have compiled an application guide for IEC 62271-100 and IEC 62271-1, which includes a detailed analysis of switching of inductive loads [3].

The salient phenomenon associated with shunt reactor switching may be illustrated using the basic equivalent circuit shown in Figure 29. The circuit can be extended as required to take into account neutral reactor grounding, interphase coupling or other features that may be applicable to the case under consideration.



Key

V_0	source voltage (peak value)	C_L	load capacitance
L_s	source inductance	L_b	stray inductance
L	load inductance	L_p	stray inductance in parallel with circuit-breaker
C_s	source capacitance	C_p	capacitance in parallel with circuit-breaker
CB	circuit-breaker		

Figure 29 - Simplified single phase equivalent circuit

5.1.1 Load side oscillation

As the circuit breaker opens, it will tend to interrupt as the current reaches current zero. Since, for a shunt reactor, the load is predominantly inductive at the power frequency, the current zero coincides with the peak of the voltage wave. When interruption occurs, therefore, the capacitive elements on the load side of the circuit-breaker are charged to a level corresponding to the voltage peak. The trapped energy discharges through the inductance of the shunt reactor, resulting in the load side oscillation. The frequency of the load side oscillation is largely determined by the capacitance C_L and inductance L of the load:

$$f_L = \frac{1}{2\pi\sqrt{LC_L}} \quad (18)$$

The frequency is typically in the range 0,5 – 5 kHz. The load side oscillation decays within a few tens or hundreds of milliseconds.

5.1.2 Current chopping

In practice, current chopping occurs as instability forces the arc current to zero, causing interruption to occur before the natural power frequency current zero. The power frequency current i_{ch} flowing through the inductance of the reactor at the moment of interruption then contributes to the trapped energy, increasing the amplitude of the load side oscillation above that of the power frequency voltage. The first peak of the oscillation is of the same polarity as the power frequency voltage at the moment of interruption and is referred to as the suppression peak. The second peak of the oscillation is referred to as the recovery voltage peak and usually corresponds to the maximum stress across the circuit-breaker.

Making the simplifying assumptions that interruption occurs close to the power frequency voltage peak, that the arc voltage drop may be neglected and that damping does not significantly affect the suppression peak, the amplitude V_m of the suppression peak (or chopping overvoltage) may be calculated from the trapped energy, thus:

$$V_m = \sqrt{\left[V_0{}^2 + (L/C_L)i_{ch}{}^2\right]} \quad (19)$$

Except in the case of vacuum circuit-breakers, the level of chopped current may be calculated using the ‘chopping number’, which is a characteristic of the circuit-breaker and is usually determined during testing. The level of chopped current is dependent on the chopping number λ for a single interrupter, the number N of interrupters in series per pole and the effective capacitance C_t in parallel with the circuit-breaker terminals:

$$i_{ch} = \lambda\sqrt{C_t} \quad (20)$$

Where

$$C_t = C_p + \frac{C_s \times C_L}{C_s + C_L}$$

The amplitude of the suppression peak therefore becomes:

$$V_m = \sqrt{[V_0{}^2 + NL\lambda^2(C_t/C_L)]} \quad (21)$$

From Equation 21 it will be appreciated that the chopping level of the circuit-breaker, the inductance of the shunt reactor and the capacitance of the grading capacitors all tend to increase the level of the suppression peak. For SF_6 puffer circuit-breakers, the chopping number generally increases with arcing time, while for oil circuit-breakers and some air-blast breakers it is fairly independent of arcing time [2].

The voltage waveform at the load side of the circuit-breaker and the resultant voltage across the circuit-breaker, or recovery voltage, are of the form shown in Figure 30.

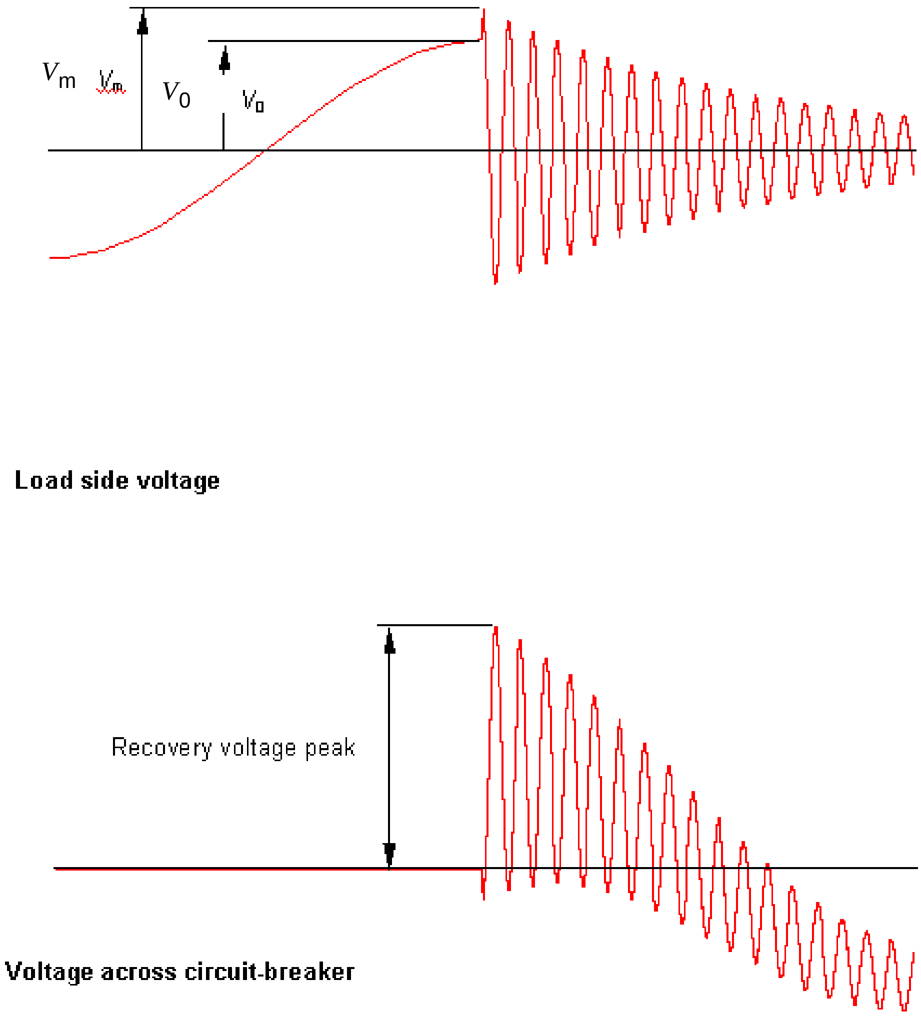


Figure 30 - Load side oscillation

5.1.3 Reignition

Following interruption, if the rising voltage across an interrupter exceeds the recovering dielectric strength of the contact gap at a given moment, the arc will reignite. When interrupting small inductive currents, the dielectric recovery of the circuit-breaker is given by its cold recovery characteristic [4, 5]. The likelihood of reignitions and the voltage magnitudes at which they occur are dependent on the type of circuit-breaker. Reignition may occur at any voltage up to the recovery voltage peak.

Reignition re-establishes a conducting path through the circuit-breaker and initiates three kinds of oscillations:

- the first parallel oscillation occurs as the capacitance C_p across the circuit-breaker, which includes the grading capacitors, is discharged through the circuit-breaker;
- the second parallel oscillation occurs as the capacitances C_S and C_L on either side of the circuit-breaker are equalised in voltage;
- the main circuit oscillation occurs as the voltage on C_S and C_L returns to a steady state value.

An example of the voltage waveform on the load side of the circuit-breaker during reignition is shown in Figure 31.

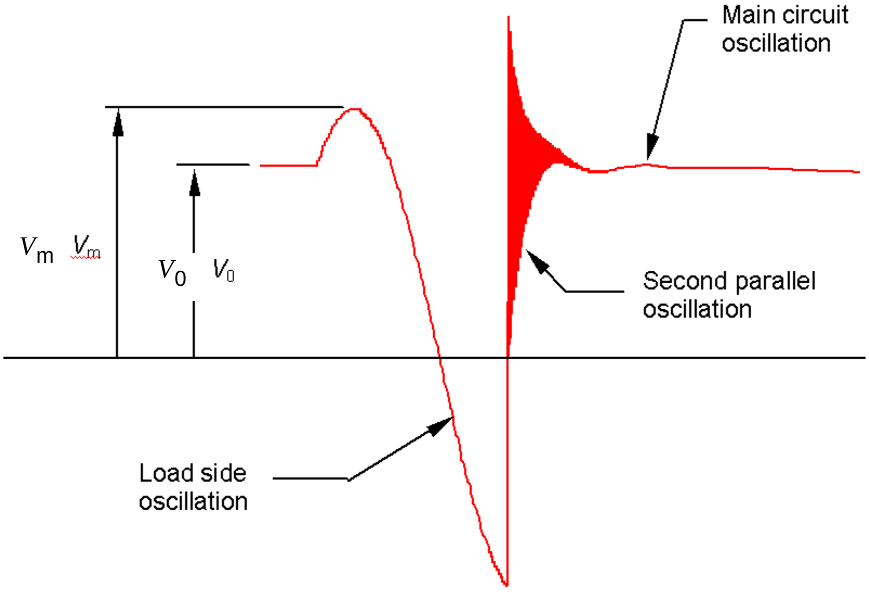


Figure 31 - Reignition

Following a reignition, the circuit-breaker will normally run in arc until interruption occurs at the next power frequency current zero. The load side voltage during reignition followed by interruption at the power frequency current zero is shown in Figure 32.

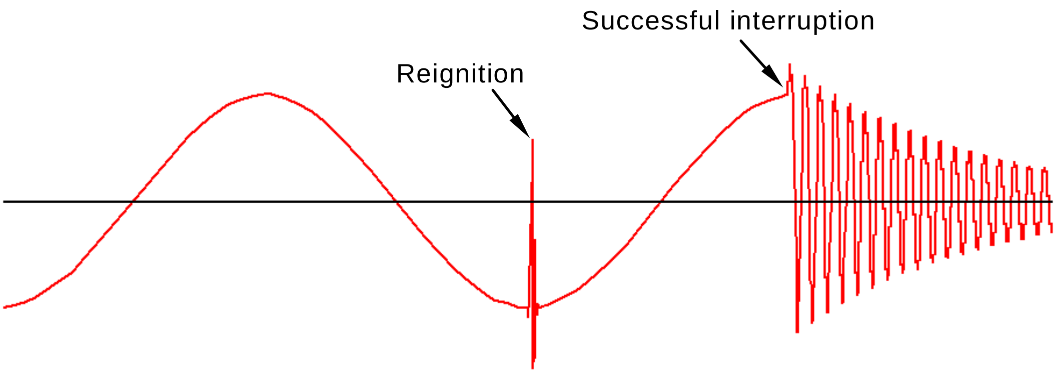


Figure 32 - Reignition followed by successful interruption

5.1.4 Multiple reignitions

Following a reignition, interruption may occur at a natural zero crossing of the current during the second parallel oscillation or the main circuit oscillation. Whether or not interruption occurs depends on the characteristics of the circuit-breaker and the rate of change of current with time at the zero crossing.

Where interruption following reignition does occur, conditions may be such that the trapped energy on the load side of the circuit-breaker is greater than it was just before the reignition. A new load side oscillation is therefore established with a greater prospective peak voltage and a further reignition may occur. Such a reignition is likely to occur at a higher voltage than the previous reignition due to the increased contact gap. In some cases, a condition is possible where multiple reignitions and interruptions give rise to voltage escalation.

Vacuum circuit-breakers are able to interrupt high frequency currents and may give rise to multiple reignition and voltage escalation. Other types of circuit-breaker are generally not able to interrupt high frequency currents and the risk of multiple reignitions is low.

5.1.5 Interaction between phases

Coupling between phases may occur due to stray capacitance and mutual inductance. The interruption behaviour in one phase may be influenced by events in other phases: Induced current chopping may occur where an induced current creates a current zero before the power frequency current zero; induced reignition may occur where an induced voltage causes a sufficient increase in voltage across an open circuit-breaker pole. In addition to induced transients, a transfer of energy between phases during the load side oscillation may occur after the interruption of at least two phases.

5.2 Electrical stresses imposed on grading capacitors

5.2.1 Circuit-breaker in closed position

While the circuit-breaker is in the closed position, the grading capacitors are not exposed to any dielectric stress other than that due to the surrounding electric field, which will be greatest at the edges. The electric field around the capacitor is significant and is an important consideration in circuit-breaker design.

5.2.2 Circuit-breaker opening operation

5.2.2.1 Recovery voltage

Following interruption, the grading capacitors are stressed by the recovery voltage as shown in Figure 30. The voltage waveform is the difference between the phase-to-earth power frequency voltage of the source and the load side oscillation. The maximum value of the recovery voltage occurs at the recovery peak. Assuming the source voltage does not change appreciably during the first half cycle of the load side oscillation and if damping is neglected, the recovery peak has a value of:

$$V_{\mathrm{R}} = V_0 + \sqrt{[V_0{}^2 + NL\lambda^2 (C_{\mathrm{t}} / C_{\mathrm{L}})]} \qquad (22)$$

The value of the recovery peak exceeds 2 times the peak value of the source voltage V_0 by an amount depending on the level of chopped current and hence the chopping number of the circuit-breaker and the characteristics of the circuit in which it is applied. It is therefore difficult to be precise about an upper limit to the value of the recovery peak. CIGRÉ Technical Brochure 50 [1] states that suppression peak overvoltages for reactors with earthed neutral are below 2 p.u. for normal reactor sizes if switched with a modern circuit-breaker. It seems unlikely, therefore, that the recovery peak will exceed 3 times the peak value of the source voltage for a modern circuit-breaker. However, for small reactors or reactors earthed through a reactance, the suppression peak overvoltage may exceed 2 p.u. and the recovery peak may therefore exceed 3 p.u.

5.2.2.2 Reignition

Where a reignition occurs, the voltage across the grading capacitors collapses within a fraction of a microsecond and the first parallel oscillation is established. The grading capacitors are discharged through the near-short circuit formed by the circuit-breaker interrupters and the reignited arc. The frequency of oscillation is dependent on the capacitance in parallel with the circuit-breaker and the inductance of the loop:

$$f_{\mathrm{p}} = \frac{1}{2\pi\sqrt{L_{\mathrm{p}} C_{\mathrm{p}}}} \qquad (23)$$

The frequency is typically in the range 1 – 10 MHz. The amplitude I_{p} of the current is dependent on the voltage V_{p} across the grading capacitors at the instant of reignition:

$$I_{\mathrm{p}} = V_{\mathrm{p}} \sqrt{C_{\mathrm{p}} / L_{\mathrm{p}}} \qquad (24)$$

The resulting current is of short duration but may reach a value of several kiloamperes.

The grading capacitors are not directly influenced by the second parallel oscillation or the main circuit oscillation, since the circuit-breaker is running in arc during these oscillations and the capacitors are effectively short-circuited.

Where multiple reignitions occur, the grading capacitors will be exposed to repeated cycles of stressing by the load side oscillation and discharging through the first parallel oscillation.

In some utilities, circuit-breakers switching shunt reactors are provided with controlled opening to reduce the likelihood of reignition.

5.2.3 Circuit-breaker in open position

Following successful interruption, the load side oscillation decays leaving the capacitors stressed by the phase-to-earth power frequency voltage of the source. In some utilities, it is practice to open a sequential disconnector in series with the shunt reactor circuit-breaker thus eliminating the stress on the grading capacitors while the circuit-breaker is in the open position. Elsewhere, the grading capacitors may remain stressed by the power frequency voltage until the next closing operation, typically a period of several hours or days.

5.2.4 Circuit-breaker closing operation

Prestriking during a making operation imposes similar stresses on the grading capacitors to those imposed by reignition, with a rapid voltage collapse, stressing of the inductive elements of the grading capacitor and high instantaneous currents associated with the first parallel oscillation.

The current is dependent on the voltage across the grading capacitors at the instant of prestrike, the maximum value of which corresponds to the peak of the power frequency voltage V_0. Although this is less than the maximum voltage across the capacitors that may occur at reignition, the current may still reach a value of a few kiloamperes.

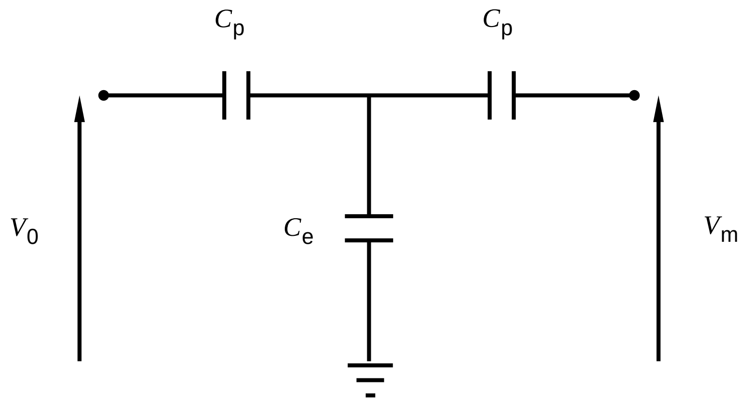
In some utilities, it is the practice to use controlled closing for shunt reactor circuit-breakers. The closing operation is timed to occur around the peak of the power frequency voltage in order to protect the shunt reactor from the effects of an excessive magnetic flux.

5.2.5 Unequal voltage sharing

5.2.5.1 Unequal voltage sharing under static conditions

The distribution of voltage across the open interrupters of a circuit-breaker pole is affected not only by the capacitance of the grading capacitors, but also by stray capacitances, particularly the capacitance to earth, and unequal sharing of voltage between the grading capacitors.

The effect of stray capacitance on voltage sharing can be illustrated in the case of a circuit-breaker with two interrupters per pole. When the circuit-breaker is in the open position, the impedances of the load and the source have negligible influence on the voltage distribution at low frequencies and the equivalent circuit can be simplified to that of Figure 33. C_p is the capacitance of the grading capacitors and C_e is the stray capacitance to earth of the circuit-breaker.



Key

V_0 source voltage

V_m load voltage

C_p capacitance of grading capacitor

C_e capacitance to earth of circuit-breaker

Figure 33 - Equivalent circuit for voltage sharing under static conditions

In general, the voltage on the source side capacitor is determined by

$$\frac{dV_{p1}}{dt} = \frac{\frac{dV_0}{dt}\left(C_e + C_p\right) - \frac{dV_m}{dt}C_p}{2C_p + C_e} \qquad (25)$$

and the voltage on the load side capacitor is determined by

$$\frac{dV_{p2}}{dt} = \frac{\frac{dV_0}{dt}C_p - \frac{dV_m}{dt}\left(C_e + C_p\right)}{2C_p + C_e} \qquad (26)$$

Under steady state conditions, V_m = 0 and the voltage on the source side capacitor becomes

$$V_{p1}(t) = V_0(t)\frac{C_p + C_e}{2C_p + C_e} \qquad (27)$$

and the voltage on the load side capacitor becomes

$$V_{p2}(t) = V_0(t)\frac{C_p}{2C_p + C_e} \qquad (28)$$

Thus, at steady state, the voltage is shared between the grading capacitors in the ratio

$$1 + C_e/C_p \qquad (29)$$

with the greater voltage across the source-side grading capacitor.

Under transient conditions, i.e. during the load side oscillation, the voltages on the source and load side grading capacitors may be determined from Equations (25) and (26) taking into account the changes ΔV_0 in V_0 and ΔV_m in V_m from the initial condition where the voltage on both capacitors is zero. The voltage on the source side capacitor becomes

$$V_{p1} = \frac{\Delta V_0(C_e + C_p) - \Delta V_m C_p}{2C_p + C_e} \qquad (30)$$

and the voltage on the load side capacitor becomes

$$V_{p2} = \frac{\Delta V_0 C_p - \Delta V_m (C_e + C_p)}{2C_p + C_e} \qquad (31)$$

Particularly during the first half cycle of the load side oscillation, the change ΔV_m in V_m will be larger than the change ΔV_0 in V_0 and hence the voltage across the load side grading capacitor will be greater.

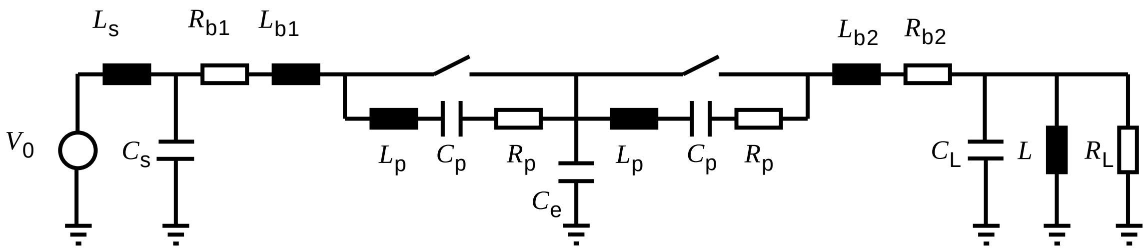
Both at steady state and during the load side oscillation, the inequality in voltage sharing is dependent on the value of the stray capacitance to earth compared to the capacitance of the grading capacitors. Since the stray capacitance is normally significantly less than the capacitance of the grading capacitors, the inequality in voltage sharing will be modest. If, for example, the stray capacitance has a value of 20 % of that of a grading capacitor, the voltage across the more stressed grading capacitor at steady state may be increased by about 9 % compared to an equal division. The increase in voltage across the more stressed capacitor during the early part of the load side oscillation is similar. The values given correspond to a rather extreme case of a GIS circuit-breaker with high stray capacitance and low value grading capacitors. The increase in voltage across a grading capacitor due to unequal sharing under static conditions will usually be less than this.

5.2.5.2 Unequal voltage sharing under dynamic conditions

Unequal voltage sharing may arise under dynamic conditions where reignition or prestriking does not occur simultaneously across all interrupters of a pole. In practice, this is likely to occur in all cases to a greater or lesser extent. When an interrupter reignites or prestrikes before the other interrupters of the pole, the collapse of voltage across the interrupter causes an instantaneous redistribution of voltage around the adjacent components. The voltage across the grading capacitors of the other interrupters will tend to increase until each interrupter reignites or prestrikes.

The redistribution of voltage and the subsequent transient response as each interrupter reignites or prestrikes is dependent on the stray impedances associated with the circuit-breaker and its connections. The resulting voltages will be difficult to calculate unless the stray impedances are known in detail. There is also little information available on the possible intervals between reignition or prestriking of the interrupters. Furthermore, WG A3.18 knows of no studies in which this phenomenon has been investigated. The following sections attempt to predict the stresses that might result due to unequal voltage sharing under dynamic conditions. Much of that which follows is speculative, since it has not been possible to confirm the predictions by measurement. Nevertheless, some general conclusions about the voltage sharing under dynamic conditions may be drawn.

The effects on the grading capacitor of a delay between closing of interrupters during prestriking or reignition are illustrated in the following example of a circuit-breaker with two interrupters per pole switching a 400 kV 200 MVA shunt reactor. The circuit is shown in Figure 34. The component values used in the example are given in the key to the figure.



Key

V_0	Source side voltage (peak value)	326,6 kVpeak
L_s	Source inductance	12 mH
C_s	Source capacitance	60 nF
R_{b1}	Damping, source side connections	2 Ω
L_{b1}	Inductance, source side connections	6 µH
L_p	Inductance, grading capacitor	840 nH
C_p	Capacitance, grading capacitor	750 pF
R_p	Resistance, grading capacitor	7,75 Ω
C_e	Capacitance to earth, circuit-breaker	130 pF
L_{b2}	Inductance, load side connections	6,4 µH
R_{b2}	Damping, load side connections	2 Ω
C_L	Load capacitance	2,6 nF
L	Load inductance	2,4 H
R_L	Load damping	1,0 MΩ

Figure 34 - Equivalent circuit for voltage sharing under dynamic conditions

Due to the short time window in which voltage sharing under dynamic conditions takes place, the events will be dominated by C_s, C_L and the components in the loop between them.

5.2.5.3 Prestriking

The voltage stress across grading capacitors during a circuit-breaker making operation where there is a delay between prestriking of interrupters is illustrated for the two cases where the source side interrupter prestrikes before the load side interrupter and where the load side interrupter prestrikes before the source side interrupter. In both cases, the voltages across the grading capacitors have been simulated for the circuit described above. The simulations represent the worst-case scenario where the prestrike occurs at the peak of the source voltage waveform.

When the source side interrupter prestrikes before the load side interrupter, the voltage across the load side capacitor rises from its initial value, as described by Equation 28, towards the instantaneous value of the source voltage and can be expected to overshoot, since the resistances around the circuit contribute little damping. The frequency of the initial transient is dominated by the capacitance of the grading capacitor C_p and the inductance $L_{b1} + L_p + L_{b2}$ and approximates to

$$f_p = \frac{1}{2\pi\sqrt{(L_{b1} + L_p + L_{b2})C_p}} \qquad (32)$$

The value of the source capacitance C_s is generally much larger than that of the grading capacitor, C_p, and its voltage tends not to vary during the timescale of the initial transient. The load side capacitance C_L shunted by the inductance L of the reactor does not respond significantly during this timescale and remains essentially at earth potential during the period of interest.

Figure 35 shows the transient rise in voltage across the load side grading capacitor when the source side interrupter prestrikes at time t = 0 as simulated for the circuit of Figure 34.

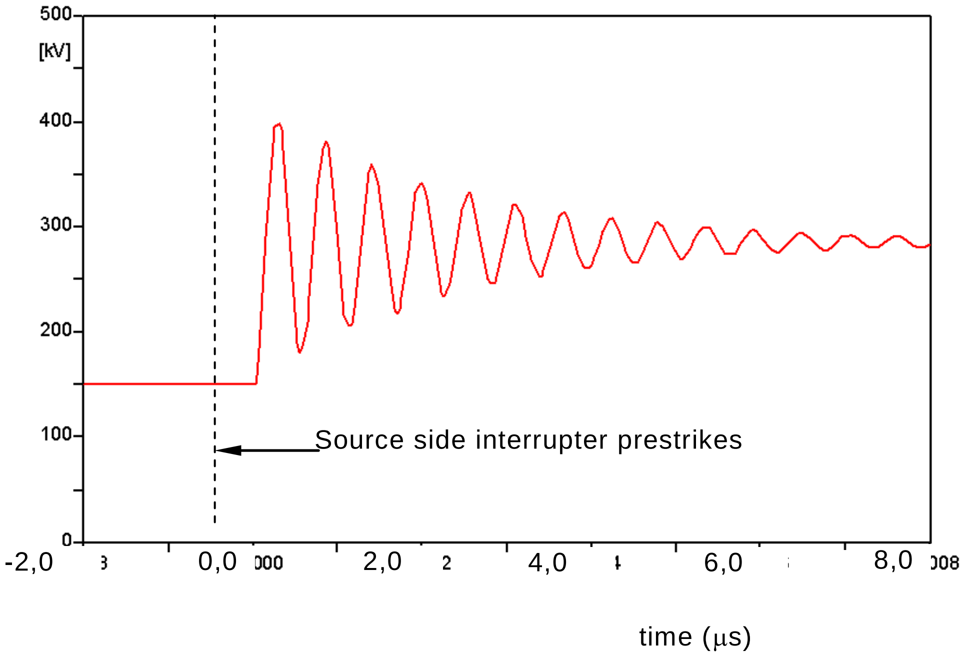


Figure 35 - Initial rise in voltage across load side grading capacitor when source side interrupter prestrikes

In the simulation, the initial voltage across the load side grading capacitor when the source side interrupter prestrikes is 150 kV. The frequency of the transient voltage across the capacitor following the prestrike is 1.8 MHz. The voltage reaches a peak value of 399 kV, equal to 1,22 times the peak value of the source voltage and occurring around 300 ns after the first prestrike.

When the load side interrupter prestrikes before the source side interrupter, the voltage across the source side capacitor increases from its initial value, as described by Equation 26, towards the instantaneous value of the source voltage and overshoots. The behaviour of the transient voltage is similar to that described above for the previous case.

In the simulation, the initial voltage across the source side grading capacitor when the load side interrupter prestrikes is 176 kV. The voltage reaches a peak value of 380 kV, equal to 1,16 times the peak value of the source voltage and occurring around 300 ns after the first prestrike.

When calculating the transient rise of voltage across the grading capacitors, the values of R_{b1} and R_{b2} will generally be difficult to determine. However, the effects of damping may be neglected from the calculation to obtain a worst-case result for either grading capacitor of approximately 1,5 times the peak value of the source voltage or 3 times the initial voltage across the capacitor.

5.2.5.4 Reignition

During a breaking operation, the voltage across the grading capacitors is zero until the circuit-breaker interrupts, following which the recovery voltage is shared between the source and the load side grading capacitors according to Equations 30 and 31. Where a reignition occurs, the redistribution of voltage shows similar behaviour to that when a prestrike occurs, except that the amplitude of the transient may be larger.

The voltages across grading capacitors have been simulated using the circuit of Figure 34 for the two cases where the source side interrupter reignites before the load side interrupter and where the load-side interrupter reignites before the source-side interrupter. The simulations represent the worst-case scenario where reignition occurs at the recovery voltage peak. Since reignitions occur when the contact gap is small, interruption at current zero has been assumed and the effect of current chopping has not been taken into account.

When the source side interrupter reignites before the load side interrupter, the voltage across the load side grading capacitor increases towards the instantaneous value of the recovery voltage and overshoots. In the simulation, the initial voltage across the load side grading capacitor when the first reignition occurs is 349 kV. The voltage across the capacitor reaches a peak value of 765 kV, equal to 2,34 times the peak value of the source voltage.

When the load side interrupter reignites before the source side interrupter, the voltage across the source side grading capacitor increases towards the instantaneous value of the recovery voltage and overshoots. In the simulation, the initial voltage across the source side grading capacitor when the first reignition occurs is 298 kV. The voltage across the capacitor reaches a peak value of 779 kV, equal to 2,39 times the peak value of the source voltage.

Where the effects of damping are neglected from the calculation, a worst-case result is obtained for either grading capacitor of approximately 3 times the peak value of the source voltage.

5.2.5.5 Discussion on unequal voltage sharing under dynamic conditions

From the above it will be seen that when one interrupter of a pair prestrikes or reignites before the other, the voltage across the second interrupter, and hence its associated grading capacitor, rises. The rate of rise of the voltage is rapid and largely determined by the capacitance of the grading capacitor, the inductance of the connections to the circuit-breaker and the associated resistive damping. Other components have little influence on the shape of the initial transient. The prospective amplitude of the transient is dependent on the voltage across the circuit-breaker pole when the first prestrike or reignition occurs. The level that the transient voltage may reach before the second interrupter prestrikes or reignites is dependent on the interval that elapses until the second prestrike or reignition occurs. If the interval is sufficient, the voltage across the grading capacitor may approach a value of up to 1,5 times the peak value of the source voltage in the case of a prestrike and up to 3 times the peak value of the source voltage in the case of a reignition.

An interval between prestriking or reignition of the interrupters of a pole may be caused by mechanical differences in operation of the interrupters and by the time lags affecting gas breakdown. The time lag between the application of a sufficiently high voltage to a gas gap and the subsequent breakdown comprises the statistical and formative time lags. The statistical time lag is the time that elapses until an electron capable of initiating breakdown appears in the gap, while the formative time lag is the time required for the breakdown to develop.

Boeck et al [6] studied the insulating behaviour of SF_6 in the presence of fast transients. Tests were performed in which a fast oscillating voltage with rise time of about 50 ns was applied to a coaxial gap in SF_6 at 0,3 MPa and the voltage at which breakdown occurred recorded. The results are shown in Figure 36 for positive polarity and in Figure 37 for negative polarity. Results obtained for double exponential impulse voltages 0,4/50 µs are also shown for comparison. The latter are shown as points within an envelope. For both polarities, the lowest measured breakdown voltage under impulse voltage is shown by a dotted line.

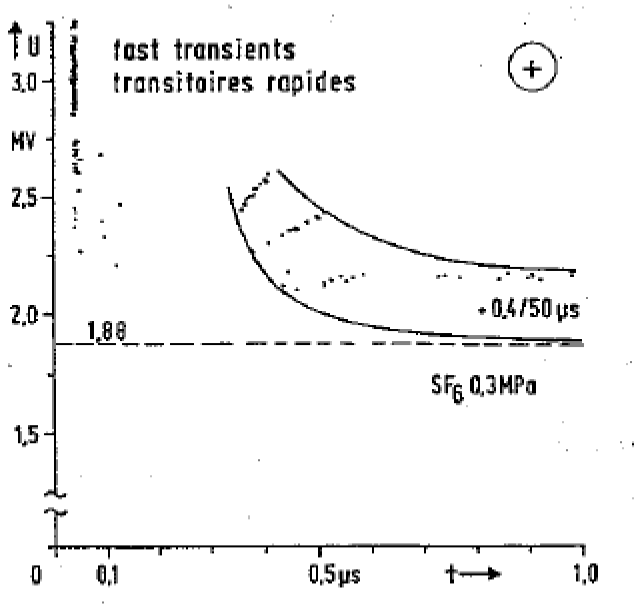


Figure 36 - *V-t* curve for coaxial gap in SF_6 (positive polarity) [6]

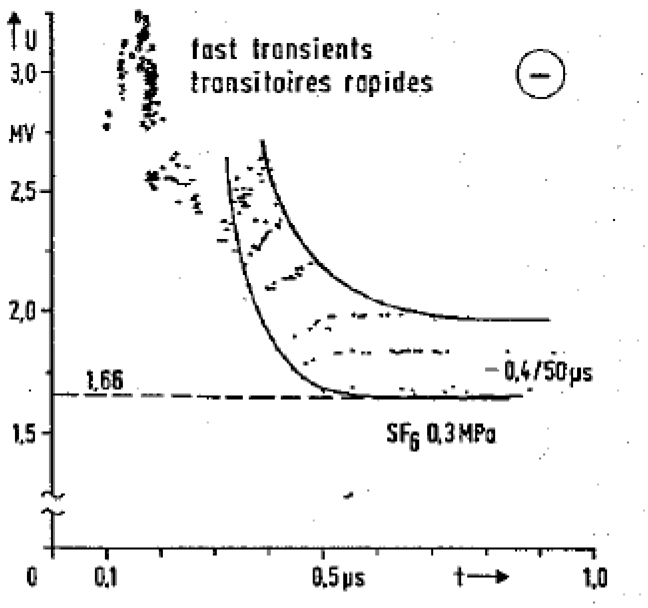


Figure 37 - *V-t* curve for coaxial gap in SF_6 (negative polarity) [6]

The results show that the voltage at which breakdown occurred was dependent on the rise time of the applied voltage. Results obtained for the fast oscillating voltage show considerable scatter, with some values of breakdown voltage significantly higher than those for the double exponential envelope. A distinct polarity effect can be seen, with breakdowns under the positive polarity fast oscillating voltage occurring predominantly at around 50 ns, while those for the negative polarity occurred predominantly in the range 100-200 ns.

The values of breakdown voltage and time to breakdown that were observed under fast oscillating voltages support the view that unequal voltage sharing under dynamic conditions may be significant. The investigations were performed under cold, steady state conditions and did not reproduce those of a circuit-breaker interrupter, where hot gases, ions and gas flow will have an influence. There is a clear need for further studies in this area.

5.2.6 Capacitor discharge current

A simulation of the current through a grading capacitor following a prestrike is shown in Figure 38. The example corresponds to the circuit of Figure 34, with the prestrike occurring at the voltage peak. The current reaches a peak value in excess of 4000 A. The frequency of oscillation is approximately 6 MHz.

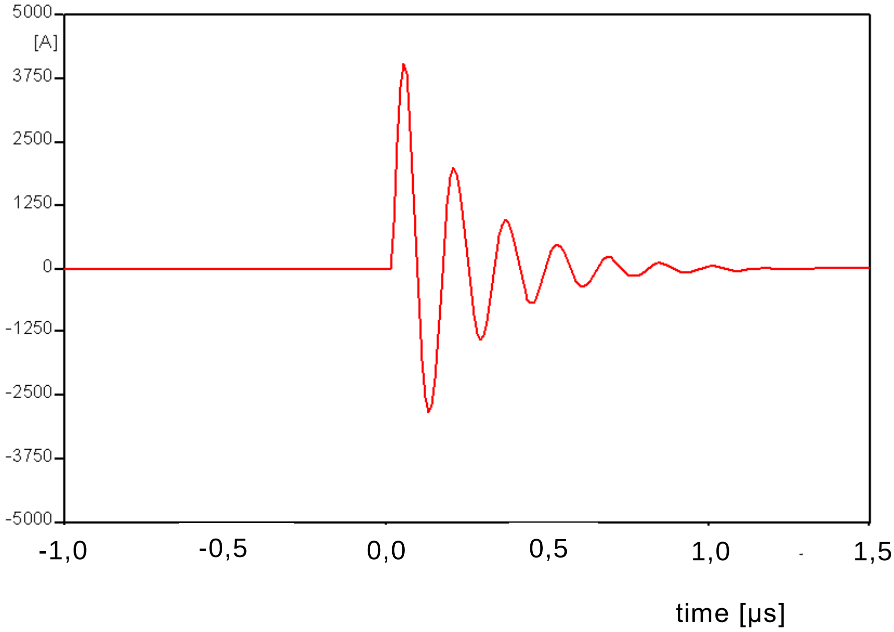


Figure 38 - Current through grading capacitor at prestrike

In the case of a reignition at the recovery voltage peak, if the interval between reignition of the two interrupters is such that the second interrupter reignites when the transient voltage across it is near its peak value, the peak value of the current would increase to around 19 000 A.

In general, the transient current that flows when a grading capacitor is discharged following a prestrike or reignition may be determined using the equivalent circuit for the capacitor and its associated interrupter shown in Figure 39.

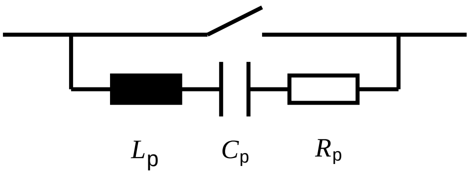


Figure 39 - Equivalent circuit for capacitor

If the capacitor is discharged from an initial voltage V_p, the transient current at time t from the discharge is

$$i = Ae^{-\alpha t}\sin\beta t \qquad (33)$$

where

$$\alpha = \frac{R_p}{2L_p},\ \beta = \sqrt{\omega_0{}^2 - \alpha^2},\ \omega_0{}^2 = \frac{1}{L_p C_p} \text{ and } A = \frac{V_p}{\beta L_p}$$

On account of the high resonant frequency of the loop formed by the grading capacitor and the associated interrupter, a test performed by discharging the capacitor through a rod-rod gap in air, as recommended in some standards, may not be able to fully excite the resonance. The current in such a test may therefore be less than that which occurs in service.

Since many shunt reactors are switched daily, the grading capacitors may be subjected to the stresses associated with prestrikes hundreds of times per year and the stresses associated with reignitions several tens of times per year.

5.3 Discussion on levels of electrical stresses

Grading capacitors experience electrical stresses during shunt reactor switching as follows:

Following successful interruption, the open circuit-breaker and hence the grading capacitors are stressed by a recovery voltage comprising the difference between the power frequency phase-to-earth voltage of the source and the load side oscillation. The load side oscillation has a frequency in the range 0,5 to 5 kHz and decays within a few tens or hundreds of milliseconds. The peak value of the load side oscillation exceeds the peak value of the source voltage by an amount depending on the level of chopped current and hence difficult to specify precisely. IEC 62271-110 specifies values of the prospective transient voltage of the load circuit to be used in circuit-breaker shunt reactor switching tests. The peak values of the prospective transient voltage specified in the standard have been used in the present work to determine maximum values of the recovery voltage across the circuit-breaker. The maximum values of the recovery voltage peak so derived are compared with the rated switching impulse withstand voltage across the open switching device of IEC 62271-1 [7] in Table 10.

Table 10 - Comparison between recovery voltage peak and rated switching impulse withstand voltage of IEC 62271-1

Rated voltage U_r kV (r.m.s. value)	Peak voltage of load circuit V_m kV	Recovery voltage peak V_R kV	Rated switching impulse withstand voltage across open switching device U_s kV (peak value)
300	465	710	750
			850
362	562	857	850
			950
420	652	997	950
			1 050
550	853	1303	1 050
			1 175
V_m corresponds to u_c as defined in 6.115.6 of IEC 62271-110.			

NOTE

The recovery voltage peak is assumed to be the sum of the source voltage peak and the peak voltage of the load circuit

$$V_R = U_r\sqrt{\frac{2}{3}} + V_m$$

The recovery voltage peak is comparable to and may exceed the rated switching impulse withstand voltage across the open switching device. Therefore, the recovery voltage must be taken into consideration and allowance made for current chopping when specifying grading capacitors for shunt reactor switching applications.

Following the decay of the load side oscillation, the open circuit-breaker and hence the grading capacitors remain stressed by the phase-to-earth power frequency voltage of the source. The stress persists typically for several hours or days until the circuit-breaker is closed, or for a few minutes where sequential disconnection is used. The maximum power-frequency voltage that may exist across the open circuit-breaker is well below the rated short-duration power-frequency withstand voltage across the open switching device. However, the long-term performance of the grading capacitors if stressed with the power-frequency voltage for long periods must be addressed.

The sharing of voltage between the grading capacitors of a pole is affected by stray capacitances. Under static conditions, a grading capacitor may be stressed by a few percent more than its nominal share of the voltage and this must be taken into account by the use of an appropriate factor when determining test levels for grading capacitor units.

Under dynamic conditions, where one interrupter of a pole prestrikes or reignites momentarily before the others, the stress across the grading capacitor of the other interrupters will begin to increase rapidly. Depending on the interval that elapses before an interrupter prestrikes or reignites, the increase in voltage across the interrupter and, consequently, across its grading capacitor may be significant. There is, however, very little information available on the possible intervals that may occur or the consequent levels of voltage across the grading capacitors.

For a circuit-breaker having two interrupters per pole, under worst-case conditions the stress across the grading capacitor may, in principle, reach a level of approximately 1,5 times the peak value of the source voltage in the case of a prestrike and 3 times the peak value of the source voltage in the case of a reignition, as given in Table 11. It should be emphasised that the values given are speculative worst-case values, since no experimental data is available on the actual stresses that might occur due to unequal voltage sharing under dynamic conditions.

Table 11 – Maximum voltage across one grading capacitor of a pair due to unequal sharing under dynamic conditions (speculative worst case)

Rated voltage U_r	**Maximum voltage across grading capacitor due to unequal sharing under dynamic conditions** kV (peak value)	
kV	**Prestrike**	**Reignition**
300	367	735
362	443	887
420	514	1028
550	674	1347

It is recommended that the stress due to unequal voltage sharing under dynamic conditions must therefore be taken into account when specifying grading capacitors for shunt reactor switching applications.

Following prestriking or reignition, a grading capacitor is discharged from its initial voltage through the low impedance loop closed by its interrupter. There are two ways in which the discharge might impose a stress on the grading capacitor:

a) Firstly, the rapid collapse of voltage causes an equal and opposite voltage to appear across the inductive elements of the grading capacitor. The distribution of this voltage is dependent on the geometry of the capacitor elements and the connections between them and may result in transient dielectric stresses appearing in regions not normally stressed under steady state conditions.

b) Secondly, the capacitor is discharged through minimal impedance and the current may reach a value of some kiloamperes. Where resistive contact is present within the grading capacitor assembly, the current may result in local heating.

The highest discharge currents are associated with reignition where the initial voltage across the capacitor may be greater. The ability of the capacitor to be discharged through a short circuit from such an initial voltage must therefore be taken into account when specifying grading capacitors for shunt reactor switching applications.

Shunt reactor switching is typically performed on a daily basis and the grading capacitors will, in general, be exposed to the associated stresses hundreds of times per year. The capacitors may be exposed to the stresses associated with reignitions during one in every few O operations or several tens of times per year.

5.4 Conclusions

Shunt reactor switching imposes significant stresses on circuit-breaker grading capacitors. It is necessary, therefore, to specify additional requirements and type tests for grading capacitors for shunt reactor switching in order to ensure their strength and capability for this application.

The additional requirements and type tests are required to cover the stresses associated with the recovery voltage, making allowance for the contribution of current chopping, and the stresses associated with unequal voltage sharing under dynamic conditions, particularly those that might arise during reignition. The ability of a capacitor to support continuous power frequency stressing must be addressed.

The specified ratings and test levels should make allowance for unequal voltage sharing under static conditions, which may cause the stress across a capacitor to be increased by a few percent from its nominal share of the voltage across the circuit-breaker.

Account needs to be taken of the ability of a capacitor to be discharged through the near short circuit loop closed by its associated interrupter, during prestriking and during reignition, due to the rapid rate of change of voltage and the high amplitude currents that will result. Due to the high resonant frequency of the short-circuited capacitor, a test using a rod-rod gap in air to discharge the capacitor is unlikely to be sufficient to excite resonance.

It has been shown that unequal voltage sharing under dynamic conditions is likely to have a significant effect on the electrical stresses experienced by grading capacitors. It has not been possible to quantify the levels of voltage and current that might result since experimental data is not presently available. There is a need for more research in this area.

5.5 References

[1] S. Berneryd et al – (CIGRE WG 13.02), Interruption of small inductive currents, CIGRE Technical Brochure 50, December 1995.

[2] IEC 62271-110, High-voltage switchgear and controlgear – Part 110: Inductive load switching

[3] CIGRE WG A3.11, Guide for application of IEC 62271-100 and IEC 62271-1: Part 2 – Making and breaking tests, CIGRE Technical Brochure 304, October 2006.

[4] I. Uglesic et al, Transients due to switching of 400 kV shunt reactor, Proceedings of International Conference on Power Systems Transients, Rio de Janeiro, Paper No. 45, 2001.

[5] Z. Ma et al, "An investigation of transient overvoltage generation when switching high voltage shunt reactors by SF_6 circuit breakers", IEEE Transactions on Power Delivery, Vol. 13, No. 2, April 1998.

[6] W Boeck et al, "Insulating behaviour of SF_6 with and without solid insulation in case of fast transients", Paper 15-07, CIGRE 1986 Session

[7] IEC 62271-1: High-voltage switchgear and controlgear – Part 1: Common specifications

6 Recommendations for test procedures

6.1 Introduction

As previously mentioned, no internationally accepted testing standards exist for grading capacitors. The lack of standards has been an obvious short-coming, both as seen from the point of view of manufacturers of grading capacitors, of circuit-breaker manufacturers, and of the end users in the electric utility sector. The objective with this chapter is to give recommendations with regard to standards for testing.

Considering the described service experiences discussed in Chapter 2 and the dielectric, mechanical and environmental stresses grading capacitors are subjected to, a set of test procedures has to be selected. The objective with the tests is to qualify a certain capacitor design, to prove the requirements in a type test and to check the manufacturing process. Consequently, electrical, mechanical and environmental qualification tests have to be selected for:

- **Design tests:** These are carried out on a sample or a full size capacitor. The results can be extended to a range of designs by modelling and extrapolation. Moreover, design tests can be carried out on a one-of-a-kind development stage device;
- **Type tests:** These carried out on a full sized capacitor manufactured in an industrial production line. In principle, the type tests are only valid for the capacitor type tested, but in practice the results are extended to types of similar technology, size and rating;
- **Routine tests:** These carried out on each capacitor before delivery and can be used as verification test after type tests;
- **Performance check:** These checks are carried out after the grading capacitor has been subjected to various types of stresses, to prove the condition.

It should be noted that the terms “design test” and “type test” are not very accurately defined. The most important difference is that type tests should be performed on a complete, full scale unit.

The tests should take into consideration that grading capacitors not only are purchased by circuit-breaker manufacturers. Utilities are also buying grading capacitors for replacement on their circuit-breaker during revisions or after failures. (It is however, recommended that utilities consult the manufacturer of the circuit-breaker before replacement is initiated.)

The tests described in this chapter are grouped into mechanical, environmental and dielectric tests. In each of these sections common practices are reviewed first. Then recommendations of the working group are given. The recommendations are based on current practices, assessments of stresses occurring during service, service experience and failures, and existing circuit-breaker test standards.

6.2 Mechanical tests

6.2.1 General

The properties to be checked are primarily the mechanical strength of the housing and the mechanical robustness of the internal parts, such as the capacitor stack, electrical connections, mechanical fixations etc. Stresses can originate from mechanical operation, transportation, handling etc., as discussed in Chapter 3.

The housing can be tested mechanically in three different ways:

- Bending;
- Pressure, if necessary (depends on design);
- Vibration;

Several types of housings are used as outlined in Chapter 1, and several types of internal pressures are used. The requirements for the housing are quite different for the different types, e.g. outdoor air insulated grading capacitors with porcelain or composite housing, and GIS grading capacitors installed inside a pressurized SF_6 ambient, and testing must take the application into consideration.

It is foreseeable that the capacitor occasionally might be subjected to its own weight when supported at one end only during, for example, removal. Such a procedure may be in violation of the manufacturer's recommended procedures.

The mechanical integrity of the internal parts is typically tested by mechanical vibration / mechanical shock tests.

The best way to qualify the overall mechanical behaviour of the grading capacitor is to test it on the circuit-breaker as specified in the mechanical endurance test of IEC 62271-100 [1] with 2 000 or 10 000 mechanical operations. However, in many contexts this is very impractical.

6.2.2 Design and Type Tests

6.2.2.1 Bending and pressure test on housing

6.2.2.1.1 Common practice

Because of different developments or switchgear manufacturer specification, the different grading capacitor manufacturers have introduced different test procedures, but these tests are not technically relevant, the grading capacitor being usually fixed on both sides.

GIS capacitors with epoxy housing are typically not subjected to static tests.

6.2.2.1.2 Recommendations of the WG

The service experience survey carried out (see Chapter 2) did not disclose any failures that were due to mechanical failure of the housing.

a) Bending test

   Grading capacitors usually do not see high bending stresses since they are fixed between the two ends. One of the highest bending stresses could be a 100 kg assembly crew worker standing in the middle of a 2 m long grading capacitor (not a recommended practice). Such load results in a bending moment of approximately 1 kNm. Considering this 1 kNm as bending load, IEC 62155 [2] requires a test with 2,1 times the routinely expected loads as type test value. This would result in a bending test with 2,2 kNm for long insulators.

b) Pressure test

   IEC 62155 specifies the tests for hollow pressurised and unpressurised ceramic and glass insulators. For pressure type test the IEC 62155 specifies the following:

   1) hollow insulators intended for general use

      "The insulator shall withstand a test pressure which is higher than the design pressure for 5 min without failure. The test pressure is dependent on equipment."

   2) hollow insulators intended for use with permanent gas pressure

      "The type test withstand pressure is dependent on equipment design. The insulator shall withstand 4,25 times the design pressure for 5 min without failure. The design pressure shall be determined by the equipment manufacturer."

The WG recommends to follow IEC 62155 regarding pressure tests.

6.2.2.2 Mechanical vibration test

6.2.2.2.1 Common practice

Two types of vibration tests are currently in practice.

a) A frequency sweep vibration test in which the capacitor is subjected to frequency sweeps in the range of 8 to 80 Hz or 10 to150 Hz with 100 sweeps at 10 octave/min. The amplitude (d) is 1,6 mm in the radial direction test and 0,6 mm in axial direction test with an acceleration limited at 25g. This corresponds to accelerations (a) in the range 1,5 – 25g ($a = \omega^2 \times d$, where $\omega = 2\pi f$ is the radial frequency);

b) A half cycle sinus impulse "shock" per axis. Among the shock durations being used are 5 - 7 ms or 14 ms (corresponding to frequencies of approximately 30 - 100 Hz). The accelerations being applied are up to 15g in radial direction and 30g (15g for GIS) in axial direction. Typically 500 to 1 000 shocks are applied in each direction.

The pass criteria include the performance of an extended frequency sweep to determine the mechanical resonance frequency before and after the test. No significant changes should be seen. A second criterion is doing tightness tests before and after the vibration tests. The third criterion is to carry out the dielectric tests and a performance check (see 6.4.6) after the vibration test.

Another procedure that is used is performing vibration tests on a complete circuit-breaker pole, i.e. during a mechanical endurance test.

The seismic test according to IEC 62271-300 [3] is less demanding for the grading capacitor and only rarely applied on the grading capacitor itself. The transportation tests described in 3.3 are not considered adequate and are not generally used.

6.2.2.2.2 WG recommendations

As described in Chapter 3, the most severe mechanical vibration stresses are those originating from the operation of the circuit-breaker and the frequencies of interest are those below around 200 Hz. Accelerations up to around 15*g* in all directions are assumed to cover the stresses that may occur on the grading capacitors.

The mechanical impulse test using a shaking table on a complete capacitor assembly is recommended. Impulses should be made in all three directions.

Prior to the impulse tests, the lowest mechanical resonance frequency should be determined by performing a frequency sweep. Typical resonance frequencies are in the range of 50 - 80 Hz. Half sine shocks should be applied with an amplitude of 15*g*. The duration of the half sine should be as long as 1 cycle of the lowest mechanical resonance frequency (corresponding to a frequency of 0,5 times the resonance frequency), but not longer than 20 ms. The reason for the choice of 0,5 times the resonance frequency is that the maximum displacement is generated between external components and internal components when the duration is 1 cycle. If the test with the duration of 1 cycle is impractical, the test should be done with a duration that is as long as possible. The number of impulses should be 1 000 in each direction. While this number is lower than that corresponding to the mechanical endurance class M2, experience shows that any failure will have occurred within the recommended number of impulses. Moreover, the test stress level is greater than the stress under normal service conditions.

The acceptance criteria should be based on checking if the lowest mechanical resonance frequency has changed, followed by the tightness test (see 6.3.2.2) and the electrical performance test (see 6.4.6). Visual inspection of the internal parts should also be carried out.

6.2.3 Routine test

6.2.3.1 Common practice

The routine test performed is a check of dimension of the housing. No other tests are presently carried out.

6.2.3.2 WG recommendations

No routine tests regarding the mechanical properties are recommended by the WG.

6.2.4 Performance check

6.2.4.1 Common practice

No tests are presently being applied, just a visual inspection.

6.2.4.2 WG recommendations

No performance checks are recommended by the WG.

6.3 Environmental tests

6.3.1 General

The environmental tests comprise tests that verify the resistance against corrosion and tightness tests.

Corrosion tests for AIS grading capacitors should consider the usual environmental stresses that all outdoor equipment is subjected to. Grading capacitors in GIS have to withstand SF_6 by-products.

Tightness tests should take account of oil and gas tightness both when the external pressure is higher than the internal pressure of the grading capacitor, and vice versa. See the description in Chapter 1 of the various pressure systems being used.

As described in Chapter 2 oil leaks were by far the most common problem. However, most of the leaks were found on rather old capacitors. It appears that the improvements with regard to corrosion protection, sealing designs and quality assurance have made this a lesser problem on newer designs.

6.3.2 Design tests

6.3.2.1 Corrosion tests

6.3.2.1.1 Common practice

One circuit-breaker manufacturer specifies salt fog tests and Sulfur Dioxide (SO_2) tests for grading capacitors used in AIS. The test is made on representative samples which are put into climatic chamber.

- Typically the salt fog test consists of 500 hours in a NaCl (50 g/l) atmosphere at 35 °C (IEC 60068-2-11 [4]);
- The SO_2 test may comprise 20 cycles each with 8 h at 40 °C under normal humidity with SO_2 for 16 h at 23 °C and with relative humidity of 75 % (IEC 60068-2-42 [5]).

For grading capacitors to be installed in GIS no corrosion test is done.

Generally speaking, unless some materials or combinations of materials that have not been used previously in such application, no particular corrosion tests are performed.

The acceptance criteria are that the samples pass the tightness test after the corrosion test and that the contact surfaces between flanges and covers have no significant traces of corrosion.

6.3.2.1.2 WG recommendations

For grading capacitors used in AIS it is recommended to perform a corrosion tests according to IEC 60068-2-11 or IEC 60068-2-52 [6] and IEC 60068-2-42. It is however, recognized that it may be difficult to find a laboratory that is willing (or still has an installation) to perform the test with SO_2.

The acceptance criteria are that the samples pass the tightness test after the corrosion test and that the contact surfaces between flanges and covers have no significant traces of corrosion.

When introducing new materials for GIS grading capacitors their ability to withstand SF_6 by-products have to be verified; No standard test is available, the one way to check the compatibility against SF_6 by-products is to store a test sample in an atmosphere of used gas including a certain amount of SF_6 by-products for a suitable long time.

The stressed materials have to be qualified after that by visual inspection, measurement of surface resistivity or similar measures.

6.3.2.2 Tightness test

6.3.2.2.1 Common practice

Tightness is normally checked by subjecting a grading capacitor or a smaller (shorter) model with the same flange design to elevated temperatures and/or by thermal cycling, with visual leakage control during the thermal cycling, the routine leakage test is applied before and after the thermal cycling. The temperature range for the cycles is the same as the operating temperature range, typically from -40 °C up to 90 °C for GIS and from -55 °C up to 75 °C for grading capacitors used in AIS. The number of cycles is typically around 10.

For oil filled capacitors leakage tests are done by visual inspection, i.e. looking for oil coming out. For SF_6 impregnated capacitors, SF_6 or Helium (He) leakage detection systems are typically used. When SF_6 leakage detection is performed, the filled capacitor is placed in a plastic bag and the SF_6 concentration is checked at the beginning and after a suitable time and the leakage range is calculated. When He leakage detection is applied He is sprayed around the capacitor seals while the capacitor is evacuated and a He detector is connected to the vacuum pump.

6.3.2.2.2 WG recommendations

The cycle test with min 10 cycles at minimum temperature (10 h) – ambient temperature (2h) - maximum temperature (10 h) according to the graph in Figure 40 should be applied.

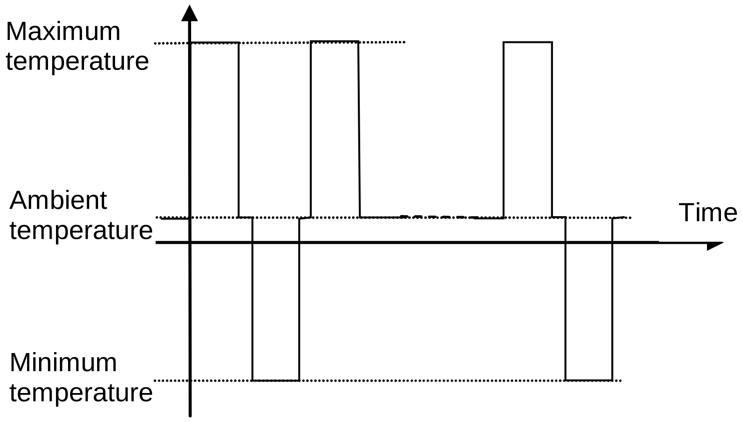


Figure 40 – Temperature cycle test

The acceptance criteria are that the sample passes the tightness test according routine test paragraph hereunder after this program.

6.3.2.3 Gas tightness test for oil impregnated capacitors used in GIS circuit-breakers

6.3.2.3.1 Common practice

One circuit-breaker manufacturer specifies to check tightness by installing a grading capacitor in an SF_6 environment at elevated temperature and pressure (maximum values of the rated ranges), typically at 90 °C / 0,9 MPa abs (based on a filling pressure of 0,7 MPa abs at 20 °C). After 40 days, a dissolved gas analysis is performed.

The acceptance criterion is that the maximum SF_6 content of the oil shall not exceed a level corresponding to a leakage rate of 10^{-6} cm^3/s at 100 kPa for 1 dm^3 oil.

This test is considered as design test, and it is made on one capacitor which will cover the complete range of grading capacitors.

6.3.2.3.2 WG recommendations

Apply, as design test, the common practice to all oil impregnated capacitors for GIS application.

6.3.2.4 Type test

6.3.2.4.1 Common practice

As the sealing system is tested in full size during design testing, no type test is necessary.

6.3.2.4.2 WG recommendations

The WG does not recommend any environmental test as type test.

6.3.2.5 Routine test

6.3.2.5.1 Common practice

The tightness of oil filled capacitors is routine tested with a pressure of the liquid above the operating pressure, depending on the type of the expansion device for the capacitor units for 24 h. A visual check with powder or paper is made when the capacitor is removed from the oven and repeated after 24 or 48 hours at ambient temperature and atmospheric pressure. A Helium test before the impregnation has also proved very good results.

For capacitors used in GIS, both vacuum (1 Pa) and air pressure (0,8 MPa) is applied during the routine test at the highest temperature of its application range, typically 90 °C. The reason for this test is that capacitor is subjected to vacuum (by the circuit-breaker manufacturer before the SF_6 filling) and SF_6 pressure in service.

The acceptance criteria for Helium test is a leakage rate of 10^{-4} Pa×l/s at ambient temperature. For the pressure test, when the grading capacitor is removed from the oven an absorbent is applied to the flanges. No trace of oil is allowed on the absorbent immediately after the grading capacitor has been removed from the oven or 24 or 48 hours after.

For SF_6 impregnated capacitors SF_6 or He leakage detection systems are typically used. When SF_6 leakage detection is performed, the filled capacitor is placed in a plastic bag and the SF_6 concentration is checked at the beginning and after a suitable time and the leakage range is calculated. When He leakage detection is applied He is sprayed around the capacitor seals while the capacitor is evacuated and a He detector is connected to the vacuum pump.

6.3.2.5.2 WG recommendations

The WG recommends applying the common practice.

6.3.2.6 Performance check

6.3.2.6.1 Common practice

The repetition of the routine test is made currently to check the tightness of the capacitor.

6.3.2.6.2 WG recommendations

The WG recommends applying the common practice.

6.4 Electric tests

6.4.1 General

The aim of the electric tests is mainly to cover the dielectric requirements of the active parts of the capacitor, i.e. the internal performance. The external insulation is normally not the subject of qualification, because the circuit-breaker design determines the external behavior and the capacitor is only an integral part of the circuit-breaker.

6.4.2 Nominal voltage of grading capacitors

6.4.2.1 Current practice

As discussed in Chapter 4, the nominal voltages (U_N) for grading capacitors are varying in a wide range without any definition and no clear relation to the standardized highest voltages for equipment U_m. The common practice of circuit-breaker manufacturers is to specify a grading factor between 1,05 to 1,3 (e.g. a voltage of 170 – 210 kV for a two break 550 kV circuit-breaker), sometimes up to 1,75 (280 kV) but with different relations to the test voltages.

6.4.2.2 WG recommendation

The value of U_N is the maximum voltage the capacitor should be capable of withstanding during its entire lifetime. Based on the considerations given in Chapter 4, the WG recommends, a nominal voltage of 20 % above the linear voltage distribution for the line-to-ground voltage across the circuit-breaker.

$$U_N = 1{,}2 \times (U_r / \sqrt{3}) / N$$

with N = the number of series connected breaking units per phase and U_r = rated voltage of the circuit-breaker. The factor 1,2 covers most unbalanced voltage distributions and is a simple and general approach of handling the large number of possible cases.

It should be noted that the grading factor 1,2 does not necessarily apply to the test voltages. The reason for this is that the test voltages are derived from the requirements given in IEC 62271-1 applying a voltage grading factor of 1,2. The calculated values are rounded to the nearest standardized voltage for the particular waveshape.

Table 12 - Rated voltages of circuit-breaker vs. nominal voltages of grading capacitors

Circuit-breaker		Grading capacitor	
Rated voltage U_r kV	Phase-to-earth voltage $U_r/\sqrt{3}$ kV	Circuit-breaker with 2 breaking units/pole U_N kV	Circuit-breaker with 4 breaking units/pole U_N kV
300	173	105	50
362	209	125	65
420	242	145	75
550	318	190	95
800	462	280	140

6.4.3 Design tests

6.4.3.1 Ageing test – Life time test

The ageing of the dielectric of the capacitor is following Arrhenius' rule. By means of an accelerated ageing test using increased voltage, temperature and/or frequency manufacturers determine the lifetime of a sample of the grading capacitor.

6.4.3.1.1 Common practice

Common practice is an accelerated ageing test as described above.

6.4.3.1.2 WG recommendation

A sample capacitor should be tested at $2{,}3 \times U_N$ during 500 hours and $2{,}0 \times U_N$ during 10 000 hours in an oven such that the dielectric is maintained at a temperature of 90 °C (maximum ambient temperature including self-heating of the capacitor).

The 500 and 10 000 hours test represent the life time of 100 000 to 1 000 000 hours, respectively at nominal voltage. This rule applies to capacitors based on "mixed dielectric" and "polypropylene film" technology.

6.4.3.2 Discharge test

This test covers the daily duty of the circuit-breaker when switching capacitive loads. The switching of disconnectors near to the circuit-breaker is also covered by this test.

6.4.3.2.1 Common practice

Some manufacturers perform discharge tests on capacitor samples during development. When such a test is performed, common practice is to charge the capacitor and discharge it through an air gap a large number of times. Such a test would demonstrate the long term reliability of the dielectric material and internal connections of the capacitor.

6.4.3.2.2 WG recommendation

For the verification of the reliability of the dielectric material and internal connections, the WG recommends discharge testing using for example the following procedure. A capacitor is charged with a DC voltage and it is discharged through a air gap. 10 000 discharges are applied on a sample at $U_{DC} = 1{,}5 \times U_N\sqrt{2}$ at an interval of 3 s. It is sufficient to perform the test with one polarity only. The inductance in the discharge loop should be as small as possible. The factor 1,5 is considered to also cover the application of a line circuit-breaker closing on a trapped charge, as the probability that the voltage during closing is at its maximum (2 p.u.) is considered low. The routine test should be repeated after the discharge test and there should be no change in capacitance.

For this test a sample capacitor can be used to verify the design of a capacitor type. Figure 41 shows a suggested test set-up.

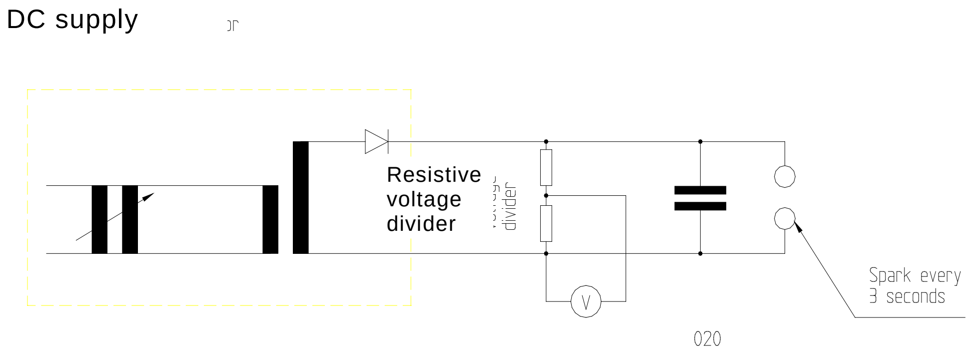


Figure 41 - Discharge test set-up

6.4.4 Type tests

6.4.4.1 Withstand voltage tests

6.4.4.1.1 Common practice

The withstand voltages for the grading capacitors vary in a wide range for the same or similar applications. It depends on the requirements of the purchaser who, in most cases is the circuit-breaker manufacturer, but who also can be an end user. Table 13 shows an example of the range in requirements for grading capacitors for 550 kV circuit-breakers having two breaking units. The data have been derived from data obtained from capacitor manufacturers.

Table 13 - Range of requirements for grading capacitors for 550 kV circuit-breakers with two breaking units

Type of voltage	Levels
Lightning impulse	970 kV -1500 kV
Chopped wave	1350 kV – 2000 kV
Switching impulse	700 kV – 850 kV
Short duration power frequency up to 5 min	460 kV – 720 kV

6.4.4.1.2 WG recommendation

The choice of withstand voltages for a grading capacitor is based on the considerations given in Chapter 4. An example of selected values for 550 kV is given in Table 14. The calculated values have been rounded to the standardized values given in IEC 60071-1.

Table 14 - Recommended withstand test voltages for grading capacitors for 550 kV circuit-breakers with two breaking units

Type of voltage	Withstand voltage test levels for grading capacitors kV	
	General purpose	Special purpose
Lightning impulse	1050	1175, 1300, (1425)
Chopped wave	1300	1425, 1550
Switching impulse	750	850, 950, (1050)
Short duration power frequency	460	510, 570, (630)
NOTE The values in brackets are to be considered only for exceptionally high requirements across the		

open circuit-breaker

The lowest values cover the dielectric withstand requirements of the open circuit-breaker given in IEC 62271-1. The highest values have been derived from the shunt reactor switching stresses corresponds to the highest requirements. Values in between have to be chosen according to the special requirements of each application.

For the impulse tests 15 impulses with both polarities should be applied. For the power frequency type test a voltage application of 5 minutes is recommended.

6.4.4.2 Flashover test

During dielectric testing of circuit-breakers flashovers cannot be avoided. With flashovers the stressing of these sudden discharge or charge reversals of the capacitors shall be simulated here. Also the current carrying capability of switching operation discharge processes in service are covered with this. Furthermore, a flashover along the outside of the capacitor should not harm the porcelain or composite housing.

6.4.4.2.1 Common practice

Some manufacturers perform a special test comprising 20 flashovers with a 50 Hz test voltage prior to the withstand voltage tests to check the insulation coordination of the capacitor. After these 20 flashovers and the withstand test the capacitor has to be partial discharge (PD) free, and no capacitance change and no perforation is permitted.

6.4.4.2.2 WG recommendation

The common practice should be followed, i.e. a flashover test on the complete grading capacitor, but not necessarily with power frequency voltage, impulse voltage is also suitable.

6.4.4.3 Long duration power-frequency voltage withstand test

Concerning the power-frequency application in service two situations have to be considered. First for the circuit-breaker in open position (with one terminal at service voltage and the other one earthed) the line-to-ground voltage is stressing the open circuit-breaker. The second situation is the out-of-phase condition which periodically appears with 2 times the line-to-ground voltage across the open circuit-breaker. The out-of-phase condition during an automatic synchronising operation in the grid normally last some seconds or minutes only, but special requirements based on operation practice or other ideas lead to prolonged time requirements in some specifications of the end user of the circuit-breaker. Requirements of out-of-phase durations up to the whole lifetime of the circuit-breaker are known, but are considered as not realistic service application.

6.4.4.3.1 Common practice

Common practice is to verify the increased service voltage by the short duration power-frequency voltage test (1 or 5 minutes) or by application of defined voltage values for long time periods (8 or 24 hours) covering the out-of-phase conditions.

6.4.4.3.2 WG recommendation

The aim during the type test is to prove the thermal stability of the complete grading capacitor.

To cover out-of-phase condition a long time power-frequency voltage withstand test is recommended with 2 times the nominal voltage of the grading capacitor ($2{,}0 \times U_N$) in a type test. The time duration has to be chosen according the requirements. Eight hours is the recommended test duration. Special applications may lead to longer testing time requirements.

Special attention has to be paid to “old” capacitors of the “all paper” design with high $\tan\delta$ values. These capacitors tend to have increased self-heating due to the relatively high losses.

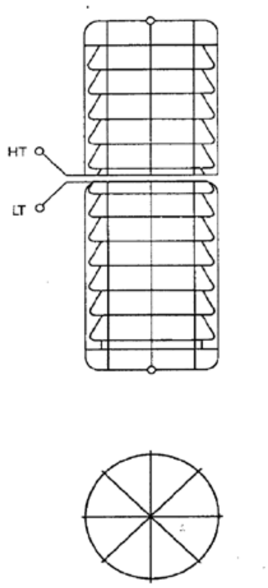
6.4.4.4 Resonance frequency measurement

6.4.4.4.1 WG recommendation

The resonance frequency has to be higher than 700 kHz, so that the capacitor is still effective with a front time up to 0,5 µs (500 kHz - transient voltage).

The measurement can be made either using analysis of the discharge current, or a measurement of the high frequency capacitance as given in IEC 60358 [8], the measured values of the capacitance between the line and low-voltage terminals shall not deviate by more than –20 % to +50 % from the rated capacitance.

When measuring the resonant frequency of the grading capacitor, it is essential to keep the stray inductance of the connecting leads to a minimum in order not to influence the resonant frequency significantly. In the test arrangement of Figure 42 a number of parallel leads have been distributed around the circumference of the grading capacitor and arranged as close to its axis as possible.



Key

HT Line terminal

LT Low voltage terminal

Figure 42 - Wiring diagram of the measuring circuit for the high frequency capacitance of a capacitor

6.4.5 Routine test

6.4.5.1 Short duration power-frequency withstand voltage test

This test should eliminate every risk of breakdown coming in the beginning of the lifetime of a capacitor.

6.4.5.1.1 Common practice

The voltage is specified at values between 1,25 and 1,8 × $U_{50Hz\text{-}CB}$/N. The duration is 60 seconds, historically the capacitors are tested during 72 s at 50 Hz so that the capacitor sees the same number of oscillations as 60 s at 60 Hz (which is not specified in IEC 60060 [9]).

Two very often used test values are either 1,35 or 1,6 × $U_{50Hz\text{-}CB}$/N.

6.4.5.1.2 WG recommendation

For routine tests the same power frequency voltage test values can be chosen as for the type tests With this the recommended short-duration power frequency withstand test voltages for grading capacitors intended to be used on 550 kV circuit-breakers with two breaking units are 460 kV, 510 kV, 570 kV and 630 kV.

The capacitor is considered having passed the test when the subsequent measurement of capacitance, tanδ and PD measurements do not deviate significantly from those measured before the test.

6.4.5.2 Capacitance measurement

The measurement of the capacitance is to check that its value lies in the specified tolerance. The tolerance of the capacitance is depending on the design of the housing and the capacitor stack..

6.4.5.2.1 Common practice

The used values of tolerance for AIS capacitors are in the range of $^{+6}_{-0}$ % up to ±5 % and for GIS capacitors ±2 % up to ±5 %.

The measurement of capacitance is normally specified at a nominal voltage. The capacitor manufacturers propose to measure first at 10 % of the nominal voltage to check that no breakdown occurs or has occurred during the first application of voltage.

6.4.5.2.2 WG recommendations

The measurement of capacitance should be done at least at the voltage levels 0,1 × U_N and 1,0 × U_N and again at 1,0 × U_N after to the power-frequency test.

The recommended maximum tolerances are for

- AIS grading capacitors ±5 %
- GIS grading capacitors ±3 %.

6.4.5.3 Loss factor measurement (tanδ)

The loss factor measurement will confirm a good impregnation and that all contacts are correct. The value of tanδ is dependent on the used technology of the capacitor elements.

The values of tanδ measured are depending on the capacitor technology and are as follows (at nominal voltage):

- Oil impregnated paper: tanδ < 50 × 10^{-4}
- Oil impregnated mixed dielectric: tanδ < 30 × 10^{-4}
- Oil impregnated Polypropylene: tanδ < 10 × 10^{-4} (see IEC 60044 [10])

6.4.5.3.1 Common practice

The tanδ measurement is performed at nominal voltage by the capacitor manufacturers.

Some utilities perform a tanδ measurement on site at 10 kV. The results of such a test should be approached with caution, as the measurement is not repeatable. This is due to the low voltage stress (an accepted capacitor at the exit of the factory can be refused 2 months later due to the "Garton effect", see Chapter 2).

6.4.5.3.2 WG recommendations

The loss factor should be measured at a voltage level of at least 1,0 × U_N.

The capacitance as well as tanδ, measured and documented during the routine test, are important values to check the integrity of the grading capacitor after any kind of stressing by repeating these measurements.

6.4.5.4 Partial discharge measurement

The Partial Discharge (PD) measurement will detect any flaw in a capacitor element (like crack in the aluminium foil, bad contact between 2 elements, conductive parts in the capacitor, etc.). The measurement is specified in 60270 [11].

For PD measurement of grading capacitors the following matters have to be considered:

a) The quality check of the capacitor itself after the manufacturing process or after a certain stressing to check the capacitor performance;

b) The PD test procedure of the complete GIS circuit-breaker or of GIS compartments including the circuit-breaker. There the power frequency voltage test has to be performed before the PD test as a pre-stress or as withstand test. During this time PD monitoring can be done for failure detection in the tested GIS section. A similar situation is the on-site testing including PD monitoring. No PD noise from anywhere is allowed during this time. Therefore concerning the grading capacitors the extinction voltage is generally of high importance.

c) For AIS circuit-breakers there should be no PD which could disturb the required radio interference voltage test.

6.4.5.4.1 Common practice

Sometimes the inception and extinction voltage are specified, but usually the capacitor manufacturers measure the PD at a fixed voltage value before and after the power frequency voltage test.

The voltage level for PD measurement is varying between one and two times the linear fraction of line-to-ground voltage of the circuit-breaker. The permissible maximum PD values are between 3 pC and 10 pC for GIS and AIS grading capacitors.

For comparison the standard maximum permissible partial discharge level for GIS is 5 pC at $1{,}2 \times U_m/\sqrt{3}$ after pre-stress with the power frequency withstand voltage.

6.4.5.4.2 WG recommendation

The proposed test voltage for partial discharge measurement for GIS-capacitors should be $2{,}0 \times U_N$ with a maximum permissible level of 3 pC and recording of the inception and extinction voltages. For AIS capacitors $1{,}5 \times U_N$ is considered sufficient.

Special for type tests only: Additionally, it may be useful to know the behaviour of the capacitor when exposed to different voltages. Therefore, the PD-values should be recorded during the voltage up and down for inception/extinction to check the behaviour of the capacitor when the circuit-breaker test is exceeding the 2 p.u. level.

A further aspect is that for GIS the PD test is required to be performed after all withstand voltage tests (impulse and power-frequency). Therefore, this test should be done directly after a series of dielectric tests (important for type tests). For example if switching impulse, lightning impulse and chopped wave tests have been performed in one day, than the PD test should be done at the end on the same day, but only once at the end, not between each impulse test.

6.4.6 Performance check

These measurements give the possibility to check the capacitor after any kind of stressing and provide acceptance criteria or control criteria concerning the performance of the grading capacitor by comparison with the first measurements (normally routine test).

Three measurements are recommended (at nominal voltage):

- capacitance [2];
- $\tan\delta$;
- partial discharge.

If possible a power-frequency voltage test can be added. Generally a maximum voltage of 80 % of that of the routine test voltage is applied.

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2 Generally, the capacitance measured at 10 kV has a good repeatability, in contradiction to the $\tan\delta$ measurement at 10 kV.

6.5 Conclusions

Based on assessments of the operating environment as well as the utility service experience with voltage grading capacitors, the following recommendations with regard to test procedures are given.

6.5.1 Environmental tests

AIS grading capacitors should be subjected to the same corrosion tests as specified by the IEC for other outdoor components. Similarly, GIS grading capacitors should be tested for their ability to withstand SF_6 by-products in the same way as other GIS components are.

To check the tightness of the capacitor housing the design test should include thermal cycling across the entire specified service temperature range. For routine tests grading capacitors should at its maximum operating temperature be pressurized to a level above the maximum operating pressure. GIS grading capacitors should also be tested in vacuum. In all cases the results should be qualified with leakage tests.

6.5.2 Mechanical tests

Mechanical design and type testing of capacitors should be carried out using a shaking table and subject the capacitor to half sine mechanical shocks with a duration corresponding to a frequency lower than the mechanical resonance frequency, as determined by a frequency sweep recording.

In addition, to verify the mechanical strength and integrity of the capacitor housing, it is recommended to carry out bending tests and pressure tests according to the IEC standard for hollow ceramic or glass insulators.

6.5.3 Electrical tests

The dielectric tests level and procedures should be based on those applied for circuit-breakers, but by taking the voltage sharing between the grading capacitors into account. The voltage sharing differs substantially for different circuit-breaker designs and applications as it is determined by the values of the capacitors, the tolerances and stray capacitances.

Grading capacitors used on circuit-breakers applied for shunt reactor switching deserve special consideration. Increased dielectric requirements are recommended.

6.6 References

[1] IEC 62271-100: High-voltage switchgear and controlgear – Part 100: Alternating current circuit-breakers

[2] IEC 62155: Hollow pressurized and unpressurized ceramic and glass insulators for use in electrical equipment with rated voltages greater than 1 000 V

[3] IEC 62271-300: High-voltage switchgear and controlgear – Part 300: Seismic qualification of alternating current circuit-breakers

[4] IEC 60068-2-11: Environmental testing - Part 2: Tests. Test Ka: Salt mist

[5] IEC 60068-2-42: Environmental testing - Part 2-42: Tests - Test Kc: Sulphur dioxide test for contacts and connections

[6] IEC 60068-2-52: Environmental testing - Part 2: Tests - Test Kb: Salt mist, cyclic (sodium, chloride solution)

[7] IEC 62271-1: High-voltage switchgear and controlgear – Part 1: Common specifications

[8] IEC 60358: Coupling capacitors and capacitor dividers

[9] IEC 60060: High-voltage test techniques (all parts)

[10] IEC 60044: Instrument transformers (all parts)

[11] IEC 60270: High-voltage test techniques - Partial discharge measurements