FAILURES OF VOLTAGE GRADING CAPACITORS IN GIS CIRCUIT BREAKERS

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Abstract: Voltage grading capacitors have over a five-year period been responsible for several serious Norwegian GIS circuit breakers failures. Five grading capacitors have exploded, hundreds leaked oil and/or SF6, and several cases of severe mechanical fatigue in the metal foils connecting the capacitor elements have been found. Apparently, the lifetime for grading capacitors installed in the 1970s and 1980s is shorter than for the rest of the GIS. Test procedures and standards that take into account the stresses grading capacitors are exposed to in service, particularly during circuit breaker operations, need to be developed.

Keywords: Circuit breaker – Voltage grading capacitor – Failure mechanism – Reliability

1. INTRODUCTION

Circuit breakers with several arcing chambers in series usually have capacitors mounted in parallel with each chamber. Their task is to equalize the voltage distribution across the individual chambers, both when the circuit breaker is in open position and during making and breaking operations.

In the second half of the 1990s voltage grading capacitors were responsible for several dramatic and serious failures in circuit breakers in gas insulated substations (GIS) in the Norwegian 300 and 420 kV grids. The incidents include five grading capacitor explosions causing major damages and time-consuming and expensive repairs. Furthermore, during the same period of time hundreds of grading capacitors were found to leak out oil and/or leak in SF6.

Only 36 GIS are in service at these voltage levels in Norway, so these problems significantly impaired the overall reliability record of this equipment. In fact, nearly all the major and minor failures occurring in GIS in this period originated in the grading capacitors. Furthermore, the malfunctions were not limited to equipment provided by certain manufacturers. All the major grading capacitors manufacturers and all GIS vendors were involved, signifying that this was a broader and consequently, more severe problem.

The present paper describes the failures in some detail and reports on the outcome of the investigations that were carried out to determine what caused them. Initially, some characteristics of the equipment populations considered in the present context, i.e. GIS circuit breakers with more than one arcing chamber, and their associated grading capacitors, are given.

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2. GIS CIRCUIT BREAKER AND GRADING CAPACITOR POPULATIONS

Fig. 1 shows the development of the Norwegian GIS circuit breaker population containing grading capacitors. Most of the equipment was put into service between 1975 and 1990, and by the turn of the century there were 216 GIS circuit breakers installed; equally divided between the 300 kV and 420 kV grids. Their average age was at that time almost 19 years.

The GIS were supplied by five different manufacturers. The circuit breakers have two or three arcing chambers in series; each chamber equipped with one, or in some cases, two voltage grading capacitors in parallel.

The GIS or circuit breaker vendors did not manufacture the grading capacitors themselves, but acquired them from subcontractors. As the reliability problems gradually became evident, the utilities involved were anxious to find out which capacitor brands and technologies that were installed in the various GIS. However, in most cases such information turned out to be difficult to obtain. The documents that followed the GIS usually contained nothing about this. Inquiries were sent to the GIS manufacturers, but at best it took many months and several reminders before any information was returned. Furthermore, it appeared that in some cases grading capacitors from different manufacturers were installed in the same GIS, with no record of what were put where.

In a few cases the utilities opened each and every circuit breaker of a GIS with the sole purpose of identifying the grading capacitor make. However, some capacitors turned out to be without any form of identification label or nameplate, and this made it rather difficult to determine their origin.

Nevertheless, with considerable efforts a reasonable good overview of the grading capacitor population was eventually established. Table I shows the best existing information with regard to which capacitor subcontractors (labelled A - E) the various GIS manufacturers (labelled I - V) have used.

In one GIS, put in service as late as 1992, the manufacturer of the 36 grading capacitors has not been positively identified, but it is assumed that the capacitors are either of make A or D.

Totally 1746 grading capacitors are installed in this GIS population. 234 of these employ SF\textsubscript{6} as fluid insulation whereas the remaining are oil filled. As can be seen from Table I, around 97% of the grading capacitors are supplied by four manufacturers and installed in GIS from the four dominating GIS vendors of this population.

3. GRADING CAPACITOR DESIGNS

Voltage grading capacitors are made up of a large number (hundreds) of stacked capacitor elements connected in series by metal foil conductors. The dielectric is paper, polymer film or a combination of paper and film (so-called mixed dielectric). The capacitor stack is impregnated with mineral oil, synthetic oil or SF\textsubscript{6} gas and placed inside a sealed epoxy tube with metal terminals at both ends. Synthetic oil was probably not used in the capacitors considered here, but has become increasingly popular in newer designs.

In oil filled capacitors a metal bellow filled with nitrogen at a few bars pressure is put inside the tube to keep the internal pressure

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<th>Table I. Number of grading capacitors installed in Norwegian GIS circuit breakers sorted after capacitor and GIS vendors.</th>
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* SF\textsubscript{6} insulated
somewhat elevated and fairly constant. This 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. Gas filled capacitors usually have a higher internal pressure, typically 6 bars, and no bellow.

Fig. 2 shows a capacitor stack, a metal bellow and two complete GIS capacitors. Typical dimensions for grading capacitors used in GIS circuit breakers are lengths of 50 - 70 cm and diameters of 10 - 12 cm.

4. OBSERVED FLAWS AND FAILURES

4.1 Leaks in capacitors from manufacturer D

During repair work on a circuit breaker it was by coincidence discovered that a grading capacitor contained a large gas bubble in its insulation oil volume. The gas was directly observable from the outside because the epoxy tube housing of the capacitor was partly transparent and because the gas volume was large (hundreds of cubic centimetres). When taking out the capacitor and turning it upside down, the characteristic sound of gas bubbling through a liquid was heard.

Later on, gas bubbles were discovered in many grading capacitors of the other circuit breakers in this GIS. As a result, also other GIS with grading capacitors from manufacturer D were opened for inspection. Among the more than 200 capacitors now being checked, around half contained gas volumes. Furthermore, when lowering the SF$_6$ pressure before opening the GIS several capacitors started leaking out oil.

A gas sample was taken from one of these capacitors. Chromatographic analysis showed that the gas was SF$_6$, with no signs of hydrocarbons from discharges or nitrogen from the bellow.

The oil was then tapped off and the capacitor was opened for inspection. The interface between the metallic end sections and the glass fibre reinforced epoxy tube of the capacitor housing is in this design gas sealed by using two o-rings. The o-rings are placed in tracks in the metallic parts and pressed against the inner wall of the epoxy tube. Close examination revealed that the surface finish of these latter surfaces was insufficient. The roughness caused by the glass fibre fabric was not machined away or in other ways smoothened out at the sealing surfaces. Hence, the reason for the leaks appeared, at least in the capacitor examined, to originate in poor workmanship during manufacturing and assembly of the capacitor.

The bellow was intact, so as gas leaked in from the 7.5 bar SF$_6$ ambient of the circuit breaker the internal pressure increased above the original 2 bar level, and the bellow was compressed accordingly. The sizes of the gas volumes observed indicate that the pressure in some cases was approaching the 7.5 bar of the surroundings.

In order to assess whether SF$_6$ bubbles inside an oil insulated capacitor is detrimental to its dielectric integrity, capacitors with and without gas bubbles were taken out and subjected to discharge measurements. These were carried out with the capacitors in vertical position with the metallic bellow at the upper end. The entire gas bubble was then above the capacitor stack. (When placing the capacitor with the bellow end down, the gas volume caused some of the capacitor elements to be surrounded by SF$_6$ instead of oil.)

At the rated voltage of 150 kV and at 200 kV no discharges exceeding the noise level of a few picocoulombs were measured in the two capacitors. This indicates that the SF$_6$ volume does not
necessarily impair the quality of the insulation severely, at least as long as the gas remains in the low field region around the metal bellow. However, the oil will after some time become saturated with SF$_6$, and if the temperature falls abruptly small SF$_6$ bubbles may form, also in high-field regions, and possibly result in discharges. On the other hand, the dielectric strength of SF$_6$ is high, and as long as the gas pressure is high and the bubbles small, it is not obvious that problems will arise.

4.2 Leaks in capacitors from manufacturer A

One vintage of capacitors from manufacturer A also leaked. When opening a GIS for its 20-year revision, oil leaks were observed at several capacitors. In a few cases oil was actually seen dripping off the capacitors after the external overpressure was relieved.

Measurements revealed that the internal pressure in these capacitors was several bars higher than it was supposed to be, indication that SF$_6$ had leaked in over the years. All 66 capacitors in this GIS were visually inspected and around 70% had signs of oil leaks.

Also in this case the cause for the leaks appeared to be related to poor workmanship and insufficient quality control. During assembly the capacitor elements were soldered together and excess solder metal appeared to have been spilt on the sealing surfaces, causing small leaks.

The leaks in capacitors from manufacturers D and A have not resulted in any spark-overs or other major breakdowns. Nevertheless, the utilities considered these findings highly disturbing and, as will be described later, replacement programs were initiated.

4.3 Fatigue damages in foil conductor in capacitors from manufacturer B

An operator that visited a normally unattended GIS noticed a clearly audible noise from one of the circuit breakers. The breaker was in open position, as was the disconnector next to it, but due to capacitive charging a substantial fraction of the system voltage remained across the circuit breaker.

The breaker was immediately taken out of service, dismantled and the capacitances of the two grading capacitors were measured with a hand held instrument. One capacitor showed a value close to the 800 pF of the nameplate, whereas the capacitance of the other was so low that it signified an internal open circuit.

The latter capacitor was then retrieved for further examinations. Discharge measurements showed discharge ignition at 35 kV. The oil being tapped off afterwards was black and contained large amounts of soot particles. Opening the capacitor revealed clear signs of internal arcing near the lower end of the capacitor stack, probably between the last capacitor element and the end terminals of the capacitor. The metal foil that connects these parts electrically was partly melted away creating an open circuit, and insulating materials in this region were heavily burnt.

As it was suspected that the arcing might have been a result of a mechanical fracture of this foil conductor, the other end of the capacitor stack where the same type of arrangement is used, was carefully examined. Fig. 3 shows the uppermost capacitor element after it has been taken out by unscrewing the bolt attaching it to the end terminals.

The aluminium foil was partly broken off. Scanning Electron Microscopy (SEM) analyses of the fracture zone (the area indicated with the arrow in Fig. 3) revealed the very characteristic appearance of a fatigue fracture, see Fig. 4.
The horizontal stripes are clearly fatigue striations representing the successive positions for the propagation front of the fracture; one stripe per mechanical load/unload cycle.

From this it is evident that this partial fracture is caused by mechanical fatigue. It is also reasonable to assume that the arcing at the opposite end of the capacitor stack was initiated as the foil conductor broke off due to mechanical fatigue. The mechanical stresses are probably generated during circuit breaker operations. The grading capacitors are mounted very close to the arcing chambers and are thus exposed to the substantial mechanical shocks and vibrations associated with operation of large circuit breakers. Apparently, the applied aluminium foil conductors, having a thickness of only 0.05 mm (50 µm) are not sufficiently mechanical robust to withstand such stresses.

These findings spurred further investigations on grading capacitors of this type. Totally 12 have been opened, and in three of them the foil conductor was partially fractured in the same manner as described above. One example is displayed in Fig. 5. In two more cases incipient fatigue damage was observed.

Even though the mechanical fatigue phenomena discovered in grading capacitors from manufacturer B did not cause any major circuit breaker failures, it was rather obvious to the utilities that these capacitors represented a great risk and therefore should be replaced as soon as possible.

4.4 Explosion of capacitor from manufacturer C

The protection system signalled a high voltage phase-to-ground failure in a 300 kV GIS circuit breaker during start-up of a connected generator. The generator was energized but not yet synchronized with the grid when the failure occurred. Hence, the circuit breaker was in open position and with (non-synchronous) high voltage at both sides.

Dismantling of the single-phase circuit breaker unit revealed that one of the grading capacitors had exploded. This was assumed to have lead to the spark-over. Major repairs, including replacing the entire single-phase circuit breaker unit (the GIS enclosure not included) were necessary.

The failed capacitor was completely destroyed and no clues as to what caused it to explode could be found. Since new, the circuit breaker had operated as much as almost 2000 cycles. Thus, the utility feared that mechanical fatigue problems corresponding to those described above for capacitors from manufacturer B may have occurred here as well. Consequently, the remaining 11 grading capacitors of make C from the two circuit breakers of this GIS were removed, opened and carefully examined.

No indications of mechanical fatigue were found. The foil conductors in these capacitors are approximately 0.25 mm thick and thus considerably stronger than those in capacitors from manufacturer B.

Still however, after having scrutinized these 11 capacitors the investigators were left with the impression that the foil conductor between the last capacitor element and the end terminals of the
capacitor sometimes had been assembled in a somewhat hasty and careless way. In several cases the foil conductor was very sharply bent, see Fig. 6. This increases the risk of fatigue damage.

But again, no signs of fatigue were discovered. So even though the manufacturing process of these capacitors was not found to be entirely convincing, the investigations were inconclusive with regard to the cause and origin of the capacitor explosion.

4.5 Explosions of gas insulated capacitors from manufacturer B

The most severe problems, and unfortunately also the least understood, have been experienced with gas insulated grading capacitors from manufacturer B.

Over a four-year period, four grading capacitors on four different single-phase circuit breaker units on three different circuit breakers in two GIS exploded. Two of the breakers operate a reactor, whereas the third is connected to a transformer. The GIS have also many overhead line circuit breakers, but none of these have failed. Moreover, all failures occurred during opening operations. The capacitor housings fractured, resulting in a phase-to-ground short-circuits, and severe arcing, contaminations and other damages inside the GIS enclosure, see Fig. 7.

In one case extensive arcing increased the pressure inside the GIS enclosure to a level where the pressure relief shields were blown out, and large amounts of hazardous dust and arcing products were released from the GIS. The subsequent clean up of the large room where the GIS was installed took weeks.

The fact that all failures occurred during or immediately after breaking small inductive currents may indicate that the capacitor failures have a dielectric rather than mechanical origin. On the other hand, the reactor circuit breakers operate much more frequently than the line breakers, and the accumulated mechanical stresses they are subjected to become greater.

12 capacitors that were installed in series with those exploding or in neighbouring phases, were removed for examinations. Dielectric testing up to 100% of the ac test voltage (230 / 240 kV) showed increased tan $\delta$ values as well as discharges in two capacitors. A third was more or less completely short-circuited.

Opening the latter one revealed severe damages on the capacitor stack. The majority of the capacitor elements were punctured, and many were damaged along their edge. Furthermore, the entire stack and the inside of the epoxy housing had substantial soot deposits. Apparently, current has in some sections passed directly through the stack, and in others along the edge.

The two capacitors showing discharges had very clear signs of the same types of internal dielectric damages, although less comprehensive (fewer elements punctured, less soot). Examples of edge damages are shown in Fig. 8. No signs of mechanical fatigue or foil conductor rupturing were observed. Hence, the findings described above support the assumption that the origin of the failures is related to excessive dielectric stress during breaking of inductive currents.
Current chopping and subsequent overvoltages and reignitions are well known phenomena associated with interruption of small inductive currents. Marks on the nozzles of the circuit breakers indicated that reignition occurred, at least now and then. The dielectric breakdown in SF\textsubscript{6} during a reignition imposes a very steep voltage transient on the parallel grading capacitors. Hence it was speculated that such a fast transient may cause uneven voltage distributions between the individual capacitor elements in the stack (analogous to the stress fast transients cause on the end windings of transformers), and thereby puncturing elements.

In order to test this hypothesis two investigations were carried out. In the first, a grading capacitor of this type was put in parallel with a mercury relay in open position. The capacitor was charged to 100 V dc. Then the relay was closed, simulating a reignition or voltage breakdown in parallel with the capacitor. The voltage dropped in less than 5 ns. The capacitor housing was removed making it possible to measure the voltage drop across parts of the stack during this very fast transient. The voltage across the first 4, 10 and 20 elements from the end was measured to 2.7%, 8% and 12%, respectively, of the total voltage across the entire 180 element stack. A perfectly linear voltage distribution would yield fractions of 2.2%, 5.6% and 11.1%. Hence it was concluded that reignition does not lead to an uneven or non-linear voltage distribution internally in a grading capacitor.

In the second investigation one of the nine apparently healthy grading capacitors among the 12 that were taken out of service was subjected to extensive and tough dielectric tests. 25 lightning impulses (1.2/50 µs) chopped after approximately 2-3 µs were applied for both polarities for nominal voltages up to 600 kV. (The lightning impulse test voltage for the capacitor is 610 kV.) Sufficiently steep chopping was achieved through a dielectric breakdown in SF\textsubscript{6} in a rod-rod gap placed in parallel to the capacitor. Subsequent partial discharge measurements at full ac test voltage, as well as careful examinations and dielectric testing of the individual capacitor elements, gave no indications of damages of any kind.

Consequently, these two fairly thorough investigations rather clearly rule out the possibility that the failures originate in unequal voltage distribution internally in the capacitor stack during reignition.

Furthermore, the fact that the capacitor passed its nameplate test requirements, even after 15 years in service is convincing. It clearly indicates that the dielectric quality of this capacitor is as specified and has not deteriorated notably. As far as the cause of the failures is concerned, this may suggest that it is related to dielectric stresses of an unforeseen nature or magnitude.

A second hypothesis, considering stresses not covered by the type tests and also relating to unequal voltage distribution during reignition, has been put forward. If the reignitions in the two or three interrupting chambers in series do not occur exactly simultaneously, the capacitor in parallel with the gap that breaks down last, may be subjected to a high transient voltage. The voltage that is supposed to be split between the two or three capacitors in series, may for a very short while be imposed on only one. (Thus, here the voltage is assumed to distribute unevenly between the capacitors, not internally in one capacitor, as in the case discussed earlier.) This may possibly cause a dielectric stress exceeding what the capacitor is built for, and lead to the observed punctures and other insulation damages.

However, no tests that confirm or disprove this hypothesis have been carried yet. Hence, the reasons for the four severe failures observed on SF\textsubscript{6}-insulated grading capacitors from manufacturer B so far remain unexplained.
5. CONSEQUENTIAL MEASURES

As mentioned in the foregoing sections, several of the flaws and failures found in the grading capacitors were considered so severe that the utilities decided to replace all the capacitors of some GIS as soon as possible.

Diagnostic testing of the capacitors was not considered a suitable alternative. The reason is partly that fast and reliable methods covering all the revealed failures modes do not exist, and partly that the dismantling work necessary to access the capacitors is very time consuming and expensive in itself. In this perspective the additional cost of a replacing the capacitor with a new one becomes bearable.

Hence, most Norwegian utilities have now included replacement of the voltage grading capacitors as a part of the “mid-life” revision of their GIS circuit breakers. Since most of these GIS were installed in the 1970s and 1980s, the majority of the more than 1700 capacitors are now replaced.

When assessing tenders for new capacitors the utilities have put large emphasis on the test voltages. The space available for a replacement capacitor is fixed, so the manufacturers are asked for the maximum test voltage they can offer for their capacitors, taking this constraint in physical dimensions into account. As long as the cause for some of the failures not has been found, the utilities want large dielectric safety margins, and a higher test voltage is assumed to indicate a greater dielectric strength.

Furthermore, the newer capacitor vintages appear to be better protected against leaks and also in general more mechanical sturdy, so at least some types of failures are hopefully avoided in the future.

6. STANDARDS AND TESTING

To the authors’ knowledge there are no standardized and internationally accepted tests for verifying the oil and gas tightness or the mechanical robustness of grading capacitors. This lack of standards is remarkable.

Some of the manufacturers perform some mechanical vibration testing and mechanical shock testing, but only according to in-house practices with rather low stresses, presumably not more than around 10 - 15 g. Measurements using accelerometers attached to the grading capacitors on two different GIS circuit-breakers revealed significantly stronger accelerations during opening operations; up to 20 g and 80 g, respectively.

If good testing and quality assurance procedures had been available and applied thirty years ago, many of the problems reported on here could have been avoided. Moreover, in relation to the replacement programs carried out in recent years, proper standards would make it easier to reassure that the grading capacitors do not for a second time compromise the otherwise high reliability of these GIS circuit breakers.

7. CONCLUSIONS

The main conclusions that can be drawn from the incidents described here are:

- The lifetime of the majority of the voltage grading capacitors in GIS circuit breakers put in service in the Norwegian grid in the 1970s and 1980s appears to be significantly shorter than for the other components in the GIS.

- Test procedures and standards that take into account the mechanical, dielectric and other stresses grading capacitors are exposed to in service, particularly during circuit breaker operations, should be established.

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