THE PERFORMANCE OF IN-SERVICE SHUNT CAPACITOR SWITCHING DEVICES AS INVESTIGATED BY CIGRE WG A3.38

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ABSTRACT

CIGRE WG A3.38 started their work in 2016. A major component of the WG's tasks is to update a survey on shunt capacitor bank switching from 1999 which was focused on transmission networks and to expand it into capacitor bank use in distribution networks. The survey shall give answers with respect to switching performance in the field, the types of switching devices used, and prevailing maintenance procedures.

The long-term performance of capacitor bank switching devices is investigated by studying the relationship between peak energization inrush currents and restrikes during current interruption. Publications show that inrush current has a considerable impact on the interrupting performance of the switching device, in particular when capacitors are switched in a back-to-back configuration.

Whereas the standards try to verify the classification of the device within 48 to 104 operations, capacitor switching devices are sometimes switched on a daily basis resulting in thousands of operations over their functional lifetime. Therefore, the WG aims to investigate whether type tests according to the standards are adequate to ensure the switching performance over the whole life of the equipment.

INTRODUCTION

Switching of shunt capacitors is a common operation for circuit breakers or load switches in the distribution and transmission network. International standards such as IEC 62271-100, IEEE C37.09, and others prescribe test procedures to verify the performance of circuit breakers concerning capacitive switching. IEC 62271-103 does the same for load switches.

In 1999, CIGRE conducted a survey on shunt capacitor bank switching focused mainly on transmission networks [1,2]. The results at that time were introduced into the IEC circuit breaker standard IEC 62271-100. Since then, the installation of capacitor banks and capacitive switching devices has increased considerably, resulting in widespread usage of switches classified as "C2."

In February 2018, the CIGRE WG A3.38 disseminated a new survey to collect service experience of users with respect to capacitor bank switching devices in distribution and transmission networks. The results shall be summarized in a technical brochure, which will also provide a summary on the state-of-the-art of existing interrupting devices, particularly for vacuum and SF_6 breakers. The technical and physical parameters that impact the breaking performance of the switching device – namely, amplitude of the inrush current, and the capacitive breaking current – shall be analysed.

The target of the work is to lay down life-extension rules for the switching performance of these devices based on the performance in type tests and substantiated with the results of the survey. The frequently asked question of the life-time expectancy of a capacitor switching device being operated on a daily base is discussed.

APPLICATION OF CAPACITOR SWITCHES

The switching of capacitive loads is described in publications [3,4]. There are three modes: (1) Energization of the capacitor(s), which produces a large temporary charging current of the capacitor called inrush current; (2) The switching off of the capacitor(s), which produces a recovery voltage with the probability of voltage breakdown; (3) The flow of capacitive current while the switch is closed, which is normally well below the rated continuous current of the switching device.

Reactive power demand in a given network changes throughout a given day, and can require capacitive compensation to be switched several times a day. This is in contrast to the rare operation of typical circuit breakers or load switches.

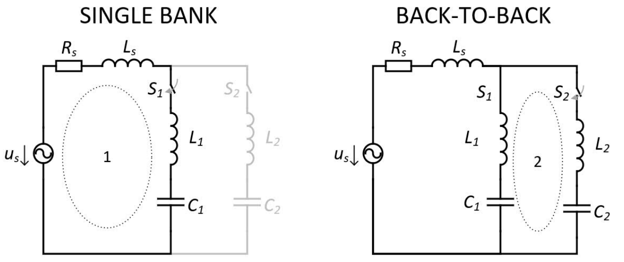

Figure 1: Single bank circuit involving a switch or circuit breaker S1 and BtB circuit involving S2

The required making and breaking capability of a switching device depends on the location of the switch. If the cap bank is the only bank in the vicinity, or when all nearby banks are disconnected (Figure 1), it is considered a single capacitor bank. If several banks are connected via several switches, the configuration is referred to as back-to-back (BtB) or a parallel capacitor bank.

Back-to-back switching has some peculiarities compared with single bank switching. As the inductance between the capacitors is generally small, the inrush current when switching the second capacitor is much higher than the single bank (or first capacitor) inrush current. Good technical practice will comprise current limiting reactors for BtB applications (see L1 in Fig 1), while long cables between the capacitors may have the same limiting effect. For single core cables, at 36 kV rated voltage and 25 kA short circuit current, the minimum length of cable is 1.64 km, for 3-core belted cables 5.74 km. The dependence is given by

$$l_{cable} = \frac{U_{rms}}{4\pi f_0 I_{sc} L_{spec}}$$

where L_{spec} is equal to 1.4 mH/km for a single core cable and 0.4 mH/km for a belted 3-core cable. From that comparison, it is obvious that BtB configurations will not be rare.

Compared to short-circuit interruptions, capacitive switching occurs frequently. Thus, the mechanical and electrical stresses on capacitive switching devices are high, and could exceed the duty during type tests. Inrush current magnitudes and frequencies may have different impacts on the switching devices depending on the switching technology (air, SF_6 gas, oil, or vacuum). The differentiation by different technologies therefore requires special attention.

According to standard IEC 62271-100, circuit breakers are specified in two classes: class C1 for those showing low probability of restrike, and class C2 having very low probability of restrike. The test duty applied for a class C2 breaker does not allow a single restrike during the whole test series. The test procedure also defines the amplitude and frequency of the inrush current, and recommends a nominal capacitive current of 400 A for circuit breakers. A goal of the WG is to compare how a circuit breaker tested to the standard behaves in the field under different conditions. In particular, the how does the breaker perform when the total number of switching operations significantly exceeds the number applied during the type test.

RESTRIKE PERFORMANCE OF VACUUM AND SF_6 DEVICES

The perceived quality of a capacitive switching device is strongly associated with the restrike probability. In principle, users desire a restrike-free and NSDD-free device (non-sustained disruptive discharge) to avoid the occurrence of switching over-voltages. The standards community has recognized that assuring restrike-free performance is nearly impossible. As a result, a classification of devices with low or very low probability of restrikes has been introduced. This level of performance is verified through type tests on a particular design. The type tests are performed with two sets of making and breaking currents. The two main standards IEC 62271-100 and IEEE C37.09 provide the required number of operations and test parameters. IEEE C37.66 defines separate procedures for load break switches and capacitor switches.

The true purpose of these tests is to ensure that the switching device will meet the needs of the application. Fielded switches are subjected to a wide array of making and breaking currents, and the number of operations can be very high over the life of the device. The following sections list how the probability of restrike is related to several basic parameters/conditions that are likely to differ from the type test. The statements are drawn from publications and displayed separately for vacuum interrupters (VI) and SF_6 technology. Oil interrupters are only mentioned for information since they are no longer in production.

Amplitude of Inrush Current

A higher amplitude of the making current causes a larger deterioration of the making contacts during the closing operation due to arcing before contact touch (pre-arc). Strictly speaking, the energy of the inrush current during the pre-arc is the main parameter. Since making and breaking contact areas are most often the same, the inrush current will have an adverse impact on the capacitive breaking performance of a device.

VI: Welds originating from the making operation are ruptured during opening, generating dielectric weak points (Figure 2) and micro particles, which may become the reason for restrikes during the subsequent breaking operation [5, 6, 7].

SF_6: No publications exist on the arc appearance (or current density) during the pre-arcing period under a back-to-back or single bank inrush current flow.

Figure 2: Modification of the surface of vacuum interrupter contacts due to making operations.

Frequency of Inrush Current

The frequency of the inrush current does not play a significant role in modern switching devices.

VI/SF_6: There is no influence reported in the whole range of single bank (< 500 Hz) and back-to-back inrush current frequencies (> 4000 Hz).

Oil: The inrush current frequency has an impact on the performance of minimum oil breakers due to possible shock waves in the liquid and subsequent damage of nozzles. Limiting higher frequencies are recommended for oil breakers (max. 6000 Hz in IEC 62271-100).

Inrush Current Integral

The integral of the inrush current over the pre-arc time is called the inrush current integral (ICI). Some tests stipulate that it may play a role either in lieu of the inrush current amplitude or in addition to it. The ICI multiplied by the arc voltage provides the relevant energy that heats and melts the contact surface in the area of the pre-arc.

VI: The ICI may be a measure of the amount of contact material melted during the pre-arc and may give an indication of potential deterioration of the contact surface.

SF_6: Extended testing shows evidence for a correlation of ICI and the quantity of arcing contact erosion as well as a reduction in dielectric withstand. Wearing of contacts (Figure 3), wearing of the nozzle, and arc by-products can influence the restrike probability.

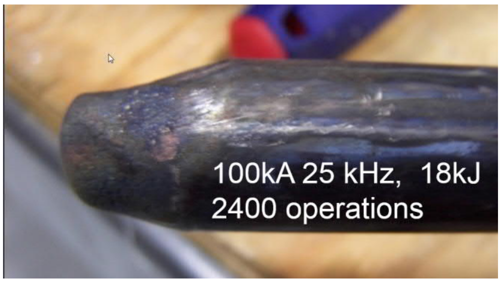

Figure 3: Modification of the arcing pin of an SF_6 interrupter due to making operations.

Capacitive Breaking Current

While most type tests are carried out with a capacitive current of 400 A as recommended by IEC 62271-100, the actual capacitive breaking currents in the field differ. Arcing durations are typically longer in the field than in type tests, as the standard requires a large number of operations with minimum arcing times.

VI: The cathode spots of the breaking arc erode and thereby condition the contact surface by smoothening dielectrically weak points. Field emission currents originating from such weak points are known to be considerably reduced [8]. Thus, for vacuum interrupters, the restrike probability is reduced for higher capacitive currents and longer arc durations.

SF_6: The erosion due to inrush currents is much higher than that of breaking currents. Since surface conditioning effects are not reported, the impact of higher capacitive currents cannot be assessed, but probably are not essential.

Number of Operations

The capacitor switching type tests only require 104 operations, with 80 closing operations producing the maximum inrush current (e.g. 20 kA) for BtB test duties and 76 breaking operations at minimum arcing times. This is a significant number of extreme-stress operations. Inrush current magnitudes in the field follow a Gaussian (normal) distribution based on the instant of pre-arcing in relation to grid voltage, sometimes referred to as “closing angle.” Also arcing times are distributed randomly and achieve much longer mean times than in the type test. The type tests are intended to represent the worst case and thus confirm the performance of the breaker over approximately 500 operations [2].

VI: After more than 200 operations, material build-up was observed on vacuum interrupter contact surfaces and an excavation on the opposite contact [9,10] (see Figure 2) which might have an impact on the dielectric withstand of the gap and the restrike probability.

SF_6: The erosion of arcing contacts distorts the geometry of the arcing contacts (see Figure 3) resulting in a modified electric field between the contacts in the open state. This can negatively influence restrike probability after approximately 1000 operations.

RESULTS OF SURVEY

At the time the paper was written, the survey was still open and 34 users of substation capacitor banks from 15 different countries responded to the questionnaire, on average representing 3 different voltage ranges (Figure 4).

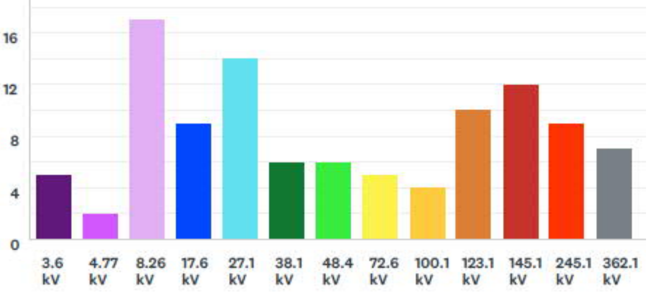

Figure 4: Number of respondents as function of voltage range

The main reason for the application of substation capacitor banks is voltage and VAR support (73%), and to a lesser extent, to reduce power losses or billing charges. Table 1 gives the size of the banks vs. the voltage range while the matrix elements represent the number of respondents indicating installed use. The power P of the capacitor banks increases with rated voltage U. Using the relationship $I = P / U / \sqrt{3}$, the mean capacitive current I for all rated voltages is between 165 A and 320 A. Although the survey allowed ranges of bank power and rated voltage and, hence, higher currents, it shows that capacitor currents are in the range of 400 A as recommended by the standards. Over all voltage ranges, 35% of the respondents say they only use single capacitor banks whereas 9% use solely BtB capacitor configurations. The weighted average over all ratings indicates 70% single banks and 30% BtB. Line banks (a common style in the US) are switched in single-phase mode and extend only to voltages up to 38 kV. They are smaller than substation banks and have switching currents well below 100 A.

Most devices (58%) are switched quite frequently, i.e. at least once or twice per day. This is valid for the whole range of rated voltages. On the other hand, more than 40%

of all respondents operate them less than once a week. Since almost all switching devices for capacitor banks are circuit breakers – rarely special capacitor switches are applied – these breakers are much more often stressed mechanically and electrically than other circuit breakers in the network.

Table 1: Qty of respondents using cap banks: size vs voltage

MVA /kV	8.26	17.5	27	38	48.3	72.5	100	123	145	245	362	550
1	6	10	4									
2.5	10	17	11	7	3							
5	15	21	16	15	7	2		2	2			
15	7	13	17	13	9	9	4	7	5			
30			5	5	7	9	7	14	13	4		
60					2	2	3	15	23	15	6	2
200								6	13	14	14	7
300										3	8	5

Over all voltages, Class C2 is the standard rating of switching devices, whereas C1 or C0 are not even mentioned. For high voltage equipment, 90% require class C2, whereas below 38 kV only 50% of the respondents require C2.

HV equipment has generally been installed/replaced within the last 10 to 20 years, whereas the reported MV equipment is up to 40 years old (Figure 5). There is hardly any MV equipment, which is younger than 10 years. It has to be mentioned that oil breakers are still in service and are obviously also used for switching capacitors. The fact that HV equipment is in the mean not older than 20 years, would indicate an increased installation of capacitor banks and breakers after the publication of the breaker standard IEC 62271-100 in 2000.

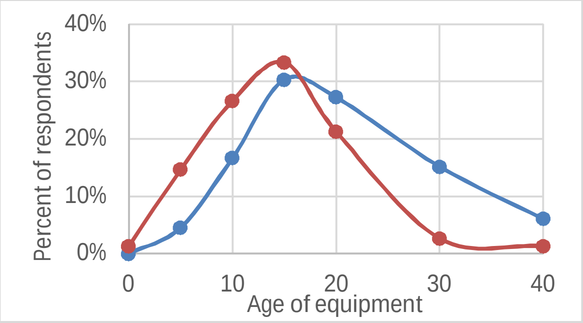

Figure 5: Most common age of medium voltage (blue) and high voltage (red) switching equipment

With respect to maintenance, switching devices of substation banks are maintained on a time-based schedule (89%) with an interval of between 1 and 5 years. There is a tendency for longer maintenance intervals with SF_6 devices. Few users (about 35%) consider the number of operations (between 200 and 2000 CO) as a useful or perhaps additional criterion for maintenance. This statement is valid for medium and high voltage switching devices and for vacuum or SF_6 breakers. Thus, time-based maintenance obviously is the standard practice, but may be enforced by regulations. Knowing that most of the capacitor banks are switched on a daily basis, and thus will reach a high number of operations in a short time, one can readily conclude that time-based maintenance practice is sufficient to ensure the reliability requirements of the network. Both the responses to the mean age of the equipment and the time-based maintenance indicate a relatively low failure rate.

Based on responses from the survey, the type tests appear to be a sufficient method of evaluating the performance of capacitor bank switching devices.

When users were asked about the causes of failures of their switching equipment, they stated 30% faults of their capacitor banks, 21% dielectric failures and 24% mechanical failures of the switching devices (Table 2). Surge arrester protection only failed by 9%, and faults in inductances were less than 4%. Assuming that capacitor failures can be caused by over voltage, it may be concluded that 50% of the observed failures are of dielectric nature. It is well known that restrikes in capacitive circuits cause over voltage and may be responsible for these failures. Under these conditions, it is surprising that surge arresters are not used more often. Surge arresters, which act as protection for the switching device but also for the capacitors are only applied by 14 to 25% of the respondents. However, the fraction increases to 40% for the high end of MV i.e. 27 to 38 kV and the high end of HV (362 to 550 kV). Conversely, 50% of the capacitors are protected by fuses which would limit the damage of the bank in case of a short circuit; however, fuses do not prevent damage due to over voltage.

Table 2: Switching Device Failure Modes

Kind of failure	total	Percent
Fault in capacitor bank	42	30.0%
Fault in related inductance	5	3.6%
Damage of protection elements	12	8.6%
Dielectric failure of switching device	29	20.7%
Mechanical failure of switching device	34	24.3%
Don't know	18	12.9%
Total	140	

In general, respondents had no significant nor sweeping claims about the quality of switching devices.

Generally, respondents are satisfied with the performance of their switching devices, but it's hard to state this definitively for any devices other than SF_6 or vacuum breakers.

Controlled switching (i.e. point on wave closing, use of pre-insertion resistors or reactors, and other methods) is applied to 65% of HV breakers. Most HV breakers utilize SF_6, where only 7% of the respondents indicated use of SF_6 for MV breakers. Point on wave opening is applied in high voltage quite rarely (10%).

22 of all 34 respondents indicated that they were knowledgeable of inrush currents. For MV applications, the majority of inrush currents range up to 10 kA, whereas for HV, values even beyond 25 kA are quoted (Figure 6). The use of current limiting reactors is not very common.

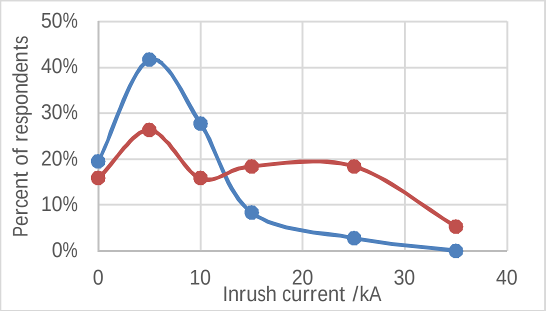

Figure 6: Occurrence of peak inrush currents in medium voltage networks (blue) and high voltage networks (red)

SUMMARY

This section summarizes the results of the WG’s research into switching performance, as well as the relevant results of the international survey on shunt capacitor banks.

Extension to Higher Currents

The performance of the device verified in a type test performed at 400 A - as preferred by the standards - is valid for all larger capacitive currents for vacuum interrupters. For SF_6 interrupters, there is no indication that this is not the case. The survey results indicate that higher capacitive currents are rarely needed in the network.

Extension to Lower Currents

Because the type test prescribes a duty with a current of 10 to 40% of the maximum rated capacitive current, the switching performance is verified and applicable to all lower currents, irrespective of the type of interrupter. In general, it is no problem achieving class C2 performance in cable and line switching with comparatively low currents, when class C1 or C2 is obtained for capacitor bank switching.

Extension to Smaller Inrush Currents

As long as the inrush current amplitude is smaller than the tested one, it can be assumed that the deterioration or erosion of the contacts (and therefore the restrike probability) is less than in the type test where the highest inrush currents are applied. This is valid for vacuum and SF_6 interrupters. In addition to amplitude, the ICI may be evaluated. Higher inrush currents than utilized in the type tests should not be allowed. Inrush-current limiting reactors are rarely used in fielded applications. Nevertheless, inrush currents are typically in the range of the values recommended by the standards i.e. 10 to 20 kA.

Extension to Other Inrush Frequencies

Except for oil interrupters, frequencies above 4250 Hz or the test frequency can be permitted since this reduces the ICI with the same inrush current amplitude. For lower frequencies than 77% of the tested frequency, it should be ensured that the ICI is equal to or less than the ICI of the mean pre-arc in the type test. Respondents of the survey indicated they do not readily have knowledge on the inrush frequencies, which is a likely indication that the frequency is of little to no critical importance.

Extension to More Than 500 Operations

As explained in the section above, the life expectancy of a switch verified as Class C2 can be extrapolated to at least 500 operations in the field. Switch degradation (build-up of macroscopic protrusion(s) on vacuum interrupter contacts, or considerable erosion of arcing contacts in SF_6 interrupters) must be considered when extrapolating performance to a larger number of capacitor switching operations. Survey responses indicate capacitor switches typically survive well beyond 500 operations. This is mainly achieved through regular time-based maintenance procedures, where each switch is visited typically once or more within a 5 year period. These switches cannot guarantee these life expectancies without (1) preventative maintenance or (2) increasing type tests beyond 500 operations.

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