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Experience of Testing and Evaluation of HV Capacitors for Endurance Testing with Reference to IEC Standards

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Abstract

It is essential to maintain the power factor near unity for effective utilization of the available apparent power as renewables are gaining importance in the power system. Capacitors form an important component in achieving the power factor near unity. Capacitors are being used in the ac network for reactive power compensation either in shunt or series mode. These capacitors must be evaluated for their performance to meet the requirement of various international/national standards International/ National standards for evaluation of capacitors are continuously evolving based on the application. Endurance testing is an important test to assess the performance of the capacitors for long duration application and to find the suitability for their availability in the network. The paper discusses the experience of two decades in performing Endurance testing for evaluation of capacitors used in the ac network with reference the IEC standards. Important observations in the evolution in the IEC standards for Endurance testing. Number of overvoltage cycles applied during over voltage test and duration of ageing test were also discussed in the paper.

Keywords: Ageing, Capacitor, Capacitor Stack, Endurance, Over Voltage Cycling (OVC), Shunt Compensation

1. Introduction

AC power system networks have voltage levels ranging from 11kV to 400kV, where capacitors are used for reactive power compensation. Capacitor banks for shunt compensation with high voltage capacitors are adopted in 11 kV to 132 kV. Most of the capacitor banks are of an outdoor type and required to be in operation in varying ambient conditions. The higher temperatures ranging from ambient to +55°C and lower ambient temperatures ranging from (0)°C to (-40)°C are required to be operational under these varied temperatures. Special tests - like an Endurance test- Over Voltage Cycling (OVC) test and Ageing test are covered in IEC 60871-2-1987[1] and IEC 60871-2-1999[2], and Over Voltage Test (OVT) is covered in IEC 60871-1-2014[3], Endurance testing – Ageing test is covered in IEC 60871-2-2014[4]. During the last three decades, Endurance Testing of capacitors has undergone many changes as explained here:

a) During 1977-1987, Endurance testing consisted of an OVC test shall be performed on the capacitors to withstand 170 overvoltage periods per day for 10 days totaling 1700 overvoltage periods at the specified lowest temperature. Ageing test shall be performed at 60°C for 500 hrs on a minimum rating of 30 kvar.

b) During 1988-2013, Endurance testing consisted of an OVC test shall be performed on the capacitors to withstand 170 overvoltage periods per day for 5 days totaling 850 overvoltage periods at the specified lowest temperature. Ageing test shall be performed at +60°C for 1000 hrs for a minimum rating of 100 kvar.

c) During 2014 onwards, Endurance testing consisting of OVT shall be performed on the capacitors to withstand 60 overvoltage periods per day for 5 days totaling 300 overvoltage periods at the lowest specified temperature. Ageing test shall be performed at +55°C for 1000 hrs for a minimum rating of 100kvar.

With the evolution of the IEC standards for Endurance testing, facilities of the testing laboratories were upgraded to meet the requirement of the IEC standards. Power Capacitor laboratory, CPRI, Bangalore, has the state of art facilities

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for evaluation of different kvar ratings and of different terminal voltages for endurance testing of capacitors. Endurance test has been performed on various ratings of capacitors and a large population of capacitors. Important results and observations of Endurance testing in meeting the requirement of IEC standards are presented.

2. Endurance Testing - Overvoltage Cycling Test (OVC)/ Over Voltage Test (OVT)

HV capacitors are generally tested at lower ambient temperatures using the test protocol of OVC test or OVT as per IEC 60871-2-1987[1] (1977-1988), IEC 60871-2-1999[4] (1989 to 2013), IEC 60871-2-2014 (2014 onwards) respectively, The differences in the test parameters in the IEC standard for OVC/OVT are shown in Table 1.

Table 1. Difference in test parameters of IS/IEC Standard for OVC/OVT

Standard	Numberof Over Voltage Cycles/Per Dayand Total Number	Voltage Application After OVC/ OVT	Initial and Final Capacitance Measurement
IEC 60871-2-1987	170 cycles per day for 10 days; Total: 1700 cycles	No voltage application after OVC test	After condition ing at 60°C to 75°C for 12 hrs (minimum)
IEC 60871-2-1999	170 cycles per day for 5 days; Total: 850 cycles	No voltage application after OVC test	After condition ing at 60°C to 75°C for 12 hrs (minimum)
IEC 60871-1-2014	60 cycles per dayfor 5 days; Total: 300 cycles	Within one hour of completion of OVT, application of voltage of $1.4U_N$ for 96hrs	At ambient temp within temp range of +15°C to +35 °C

HV Capacitors are subjected to OVC/OVT after completing routine testing at the manufacturer's facility.

2.1 Over Voltage Cycling Test as per IEC 60871-2-1999 (During 2000 to 2014)

OVC test was carried out on different lower ambient temperatures on capacitors during 2000-2014 with the number of capacitors tested are given in Table 2. The OVC test is carried out on two or three capacitors based on the standard and specific customer's requirement.

Table 2. Result of capacitors subjected to OVC test as per IEC 60871-2-1999 various temperatures

Temp	No. of Capacitors Tested	No. of Capacitors Passed	No. of Capacitors Failed	% of Capacitors Passed
0 °C.	45	41	4	91%
-5 °C.	35	30	5	85%
-10 °C.	28	22	6	79%
-25 °C.	5	5	0	100%

As can be seen from the Table 2, 113 capacitors were tested for OVC, and a large number of capacitors were subjected to OVC in the lower temperature range of 0°C to -10°C. It is observed that the percentage of capacitors that have passed OVC were less at -10°C, which are indigenously manufactured, however a few capacitors have been tested at -25 °C, which are manufactured by the overseas customers. The results of the OVC test indicates in effect of lower temperatures on the materials used in manufacturing the capacitors. Indigenous manufacturers have considerably improved the manufacturing processes and use of suitable materials for improving the performance at lower temperatures.

2.2 Over Voltage Cycling Test (OVT) as per IEC60871-1-2014 (During the 2014 Onwards)

In the latest IEC standard, the OVC test has been named OVT and it is moved from IEC 60871-2 to IEC 60871-1 from the year 2014.

The sequence of OVT as per IEC 60871-1-2014 is as follows

a. Conditioning of units at $1.0U_N$ for 12 hrs (minimum)
b. Initial capacitance measurement at +15°C to + 35°C
c. Conditioning the capacitor at the lowest temperature category ranging from 0°C to -40°C, depending on the requirement of site conditions.
d. Within 5 mins of taking out the capacitor from the lowest temperature, the capacitor is subjected to overvoltage periods consisting of application of a voltage of $1.1\ U_N$ for 90 s followed by (ii) over voltage of $2.25\ U_N$ for 15 cycles ± 2 cycles (1 cycle = 20 ms) i.e., 300 ms ±40 ms without voltage interruption and immediately followed by (iii) $1.1\ U_N$ for 90 s (i) and (ii) consists of one overvoltage period.
e. Application of 60 overvoltage periods per day.
f. The sequence (c), (d), and (e) are repeated for 4 more days to complete a total of 300 overvoltage periods.
g. Within one hour of completion of OVT, a voltage of $1.4\ U_N$ is applied for 96 hrs at ambient temperature.
h. Within two days of completion of the voltage application of $1.4\ U_N$, final capacitance measurement as mentioned in (c) above is carried out to find a change in capacitance due to the application of overvoltage.

The above test sequence is followed for all the capacitors that are subjected to OVT to evaluate the performance of capacitors at lower ambient temperatures and for switching transients.

Acceptance criteria as per the standard IEC 60871-1-2014 are as follows:

One capacitor is subjected to OVT, if the capacitor fails to withstand the overvoltage periods, then two more capacitors are to be tested, and no breakdown/failure is allowed.

With the test sequence given, experience of the laboratory in evaluation of a total of 80 capacitors for OVT is presented in Table 3. The percentage of capacitors that have passed OVT remained the same even after the overvoltage were reduced from 850 cycles to 300 cycles. OVT at the lowest temperature of -40°C were performed for overseas application, and the pass percentage in OVT were observed to be lower at -40°C. It is observed that the characteristics of materials, selection of materials, and improved processing would play an important role for improving the performance of capacitors to withstand OVT at lower temperatures, in particular at -40°C.

Table 3. Result of capacitors subjected to OVT asper IEC 60871-1-2014 at various temperatures

Temp	No. of Capacitors Tested	No. of Capa Citors Passed	No. of Capacitors Failed	% of Capacitors Passed
0°C.	36	32	4	89%
-5°C.	26	22	6	85%
-20°C.	4	3	1	75%
-25°C.	2	2	0	100%
-30°C.	5	2	0	40%
-40°C.	7	2	5	29%

2.3 Case Study of OVC Test AT -40°C

OVC test was carried out on three capacitors of rating 108 kvar, 3.522 kV, 27.73 μF. Internal fuse HT capacitor with lowest temperature category of - 40°C. Due to the limitation of the high voltage source, OVC test was carried out in two batches, with two capacitors and one capacitor separately. The capacitors were conditioned at -40°C for 12 hrs (minimum). Figure 1 depicts the arrangement for conditioning the capacitors in the cold chamber maintained at -40°C.

Figure 1. Arrangement for conditioning of capacitors in cold chamber at -40 °C.

Figure 2 depicts the arrangement of OVC test on two capacitors connected in parallel & connected to the high voltage source.

Figure 2. A view of two capacitors connected in parallel-undergoing OVC test.

The capacitors are made up of 12 capacitor elements with 3 series groups and 4 parallel elements in each series group. The change in capacitance for one-element fuse operation is 2.77µF (as declared by the manufacturer).

Figure 3 shows a typical oscillogram of overvoltage period in compliance with the requirement of IEC 60871-1-2014, with respect to voltage and duration of application of over voltage to the capacitor.

One out of the three capacitors failed to withstand the application of over voltage. It failed during 3rd overvoltage period. Figure 4 shows the oscillogram captured during failure of the capacitor during of 3rd overvoltage period. The test on the other two capacitors was continued. One of the two capacitors has failed during 4th overvoltage period. Figure 5 shows the oscillogram captured the failure of the capacitor during the 4th overvoltage period.

Since two of the three capacitors failed, as per the acceptance criteria, the capacitors have not complied with the requirement of the IEC standard.

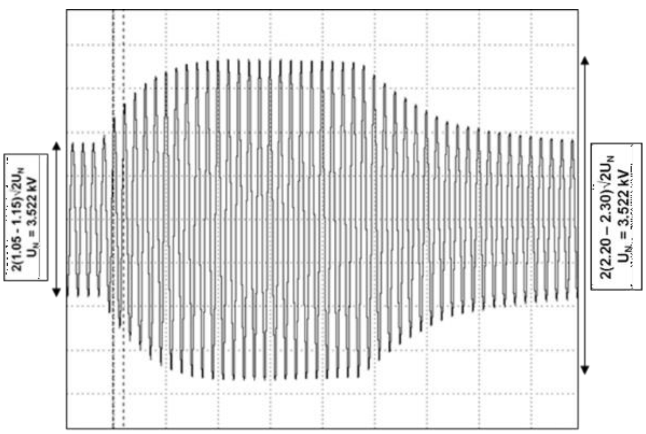

Figure 3. Typical oscillogram of a OVC period.

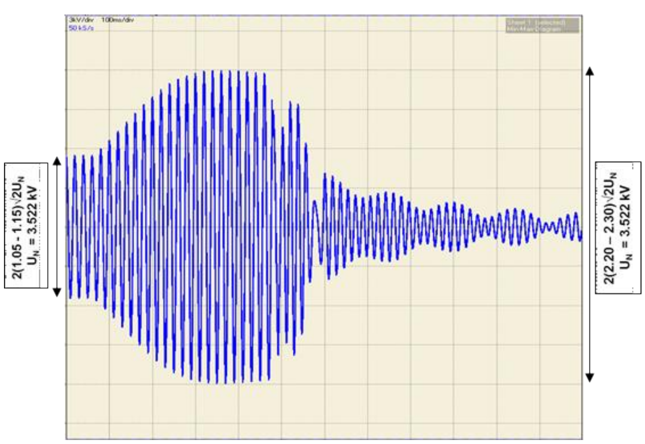

Figure 4. Typical oscillogram of OVC during failure at 3rd overvoltage period.

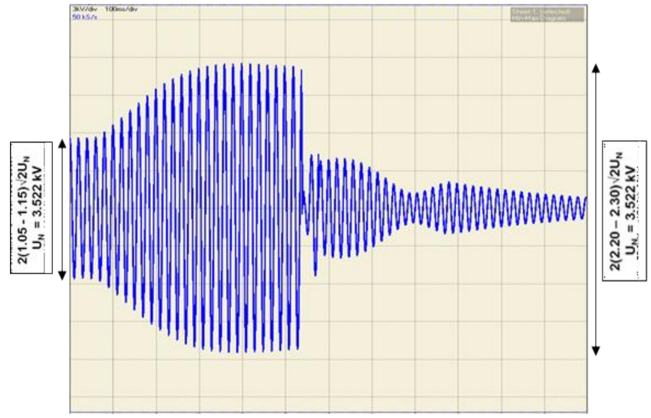

Figure 5. ypical oscillogram of OVC – during failure at 4th overvoltage period.

The capacitance measured for the capacitor which has failed during 3rd overvoltage period is 15.612 µF and the capacitance of the capacitor which has failed during 4th overvoltage period was 20.86 µF.

To verify the cause of failure, one of the capacitors was cut open and the capacitor stack was removed from the container for internal inspection. Figure 6 shows the view of the capacitor stack.

Figure 6. A view of the capacitor stack.

As can be seen from Figure 6, edge of the capacitor stack was found charred (burning of the outer paper insulation). It was observed that few elements have been burnt.

The change in capacitance for the capacitor which has failed during 3rd over voltage period was 11.22 μF showing the operation/opening of 4 capacitor element fuses. The capacitor which has failed during 4th over voltage period, the change in capacitance was 7.83 μF showing operation/ opening of 3 element fuses.

One of the capacitor elements was removed from the stack to identify the cause for charring. The capacitor element was unwound to find the cause of element fuse operation. It was observed that the capacitor element was punctured near the edge of the element as depicted in Figure 7. Significant wrinkles in PP film and aluminum foil were also observed.

Failure of more than one capacitor element indicates that internal fuse has not operated following the failure of the capacitor element. It appears that the internal fuse design and material are not adequately selected for capacitors. The capacitor elements have failed in the beginning cycles of the test, indicating the poor quality of capacitor dielectrics materials and the impregnant used for operating at -40^{0}C.

Figure 7. A view of puncture at edge of the element

A thorough analysis of the failure during the OVC test at -40^{o}C has been carried out by the manufacturer. Upon, improvising the materials and design of internal fuses along with the impregnant, the same manufacturer, has submitted capacitors of rating 104 kvar at two different voltage ratings for OVT at -40 °C as per IEC 60871-1-2014. It was observed that both the capacitors have with stood the OVT at -40 °C successfully.

3. Endurance Testing – Ageing Test

The long duration performance of the capacitors at higher temperatures are evaluated by performing ageing test. Based on the IEC standard, ageing test is performed at temperature of either 55^{o}C or 60^{o}C and at voltage of 40% more than the nominal voltage to give an output of 96% more than that of the rated output. The ageing test would check the thermal and electrical performance of the capacitors at the maximum operating temperatures. The arrangement of capacitors for ageing test is shown in Figure 8.

Figure 8. Arrangement for ageing test.

As per the requirement of IEC 60871-1-1999, the ageing test shall be carried out on two capacitors or three capacitors. As per the acceptance criteria, if two capacitors are tested – no breakdown is allowed, alternatively – if three capacitors are tested – the breakdown of one capacitor is allowed. After carrying out the routine voltage test, Initial capacitance and dielectric loss measurement at +60°C or +75°C. The capacitors have to be conditioned at +60°C until the capacitor case temperature attains +60°C for a period of 12 hrs (minimum) before the application of a voltage of 1.4 times the rated voltage and at +60°C for a duration of 1000 hrs.

Table 4 shows the result of the ageing test performed as per IEC 60871-2-1999. As can be observed from Table 4, the ageing test as per IEC 60871-2-1999 was carried out on 100 capacitors, and 82% of the capacitors have withstood the ageing test. Failure of capacitors was due to breakdown at the edges of the capacitor element.

Table 4. Result of capacitors subjected to Ageing test as per IEC 60871-2-1999 various temperatures

Temp	No. of Capacitors Tested	No. of Capacitors Passed	No. of Capacitors Failed	% of Capacitors Passed
+60 °C.	100	82	18	82%

In 2014, IEC 60871-2-1999 has taken revised to IEC 60871-2-2014, wherein, the OVC test has shifted to IEC 60871-1-2014 as a type test and Endurance testing consists of an ageing test in IEC 60871-2-2014.

As per the requirement of IEC 60871-2-2014, the ageing test shall be carried out on two capacitors or three capacitors. As per the acceptance criteria, if two capacitors are tested – no breakdown is allowed, alternatively – if three capacitors are tested – the breakdown of one capacitor is allowed. After carrying out the routine voltage test, Initial capacitance and dielectric loss measurement at ambient temperature between +15°C to +35°C. The capacitors have to be conditioned at +55°C until the capacitor case temperature attains +55°C for a period of 12 hrs (minimum) before the application of a voltage of 1.4 times the rated voltage and at +55°C for a duration of 1000 hrs.

Table 5, shows the result of ageing test performed as per IEC 60871-2-2014. As can be observed from Table 5, ageing test as per IEC 60871-2-2014 was carried out on 44 capacitors and 86% of the capacitors have withstood ageing test.

Table 5. Result of capacitors subjected to ageing test as per IEC 60871-2-2014 various temperatures

Temp	No. of capacitors tested	No. of capacitors passed	No. of capacitors failed	% of capacitors passed
+55°C.	44	38	6	86%

For brevity, ageing test was carried out as per IEC 60871-2-2014 on two capacitors at the request of the customer. After 458 hrs out of 1000 hrs of ageing test at +55°C, one of the two capacitors has failed with a change in capacitance greater than one element breakdown/failure. After failure of the capacitor, the capacitor container was opened to check the failure. Figure 9 shows the capacitor stack after removing the capacitor container.

Figure 9. A view of the capacitor stack after removing from the capacitor container.

As can be seen from Figure 10, one of the element has failed to break down at the edge of the capacitor element.

Figure 10. A view of the capacitor element indicating failure at the edge of the element.

Figure 11 shows the failure of one of the element away from the edge of the element.

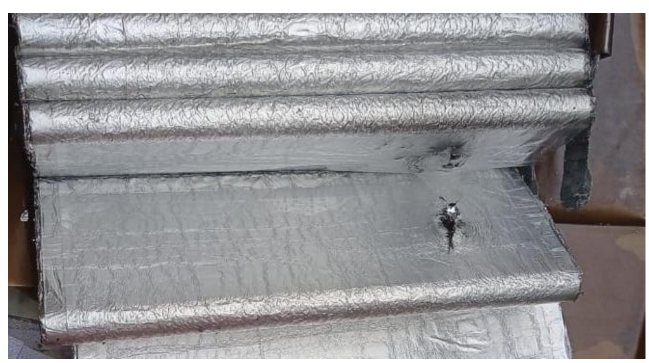

Figure 11. A view of the capacitor element indicating failure away from edge of the element.

Failure of capacitors during ageing test is attributed to inadequate design and manufacturing processes. Failure of element at the edges is probably attributed to insufficient margin and failure away from the edges is probably of high stress concentration due wrinkles occurred during the winding process.

4. Summary

HV Capacitors manufactured and being used in ac power networks requires meeting the relevant international standards to ensure the performance of the capacitors. To ensure the performance for long duration test like endurance testing comprising of Overvoltage Cycling/Over Voltage test and Ageing test as per international standard IEC 60871-2 is required to be carried out. This standard is being revised periodically since 1987 as discussed in the paper. Capacitors laboratory of CPRI, Bangalore, has performed evaluation of capacitors for Endurance test on as many as 213 capacitors as per IEC 60871-2-1999. Out of 113 capacitors 98 capacitors have withstood Overvoltage Cycling test. Out of 100 capacitors 82 capacitors have withstood ageing test for 1000 hrs.

Regarding the latest standard IEC 6087-1-2014. Overvoltage Test has performed on 80 capacitors, out of which 64 capacitors withstood overvoltage test. Endurance-Ageing test as per IEC 60871-2-2014 was carried out on 44 capacitors, out of which 38 Capacitors have withstood the ageing test for 1000 hrs at 55°C.

The failure during OVC/OVT is attributed to the characteristics of the materials used in the manufacture of capacitors and their behaviour at lower temperatures. Most of the capacitors failed during the ageing test mainly due the design inadequacies leading to edge failures at the margin area of the element. Some of the element failures are observed away from the edges, which could be attributed to the wrinkles during the capacitor element winding process.

The facilities of the capacitors laboratory are being availed by many capacitor manufacturers for evaluating the performance of the capacitors for Endurance testing. The facilities have helped them to improve the design parameters of the capacitors and complete the Endurance testing after design modifications. The test results indicate general adequacy of the quality of materials, design, and manufacturing techniques are found to be meeting the requirements of international standards and specific customer requirement.

5. References

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3. IEC 60871-1-2014. Shunt power capacitors for ac power systems having a rated voltage above 1000V – Part-1-General – Type Test-Over Voltage Test; 2014.
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