



# Interpretation of NSDD and Restrike in Capacitive Current Switching Test on Medium Voltage Vacuum Circuit Breaker

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## Abstract

Capacitor banks are installed in an increasing number to control power quality issues and improving the power factor to counteract the reactive power in the transmission and distribution networks. Due to load fluctuations switching of capacitor banks is a typical phenomenon. Capacitor bank is normally having concentrated capacitance in contrast with distributed capacitance. It generally draws more current than unloaded cable or line in practical cases up to several hundred amperes. Hence, switching of capacitor bank causes a very high rate of rise of transient recovery voltage across circuit breaker contacts. This scenario can be simulated in testing laboratories by a voltage source connected to a circuit breaker which again is connected to a large capacitance in terms of IEC called capacitive current switching test. Non-sustained disruptive discharge (NSDD) is a voltage breakdown after the vacuum circuit-breaker open the fault current which will not cause the recovery of power frequency current. Restrike is different from NSDD, the recovery of power frequency current between the contacts will make the breaker failed. It's not easy to show the distinction between NSDD and restrike during some type tests. The paper presents the study of performance evaluation of the circuit breaker during the capacitor current switching duties. A statistical analysis of failure of circuit breaker during capacitor current switching tests are included in the paper to help the manufacturers & utilities, so that the care can be taken for trouble free services. The paper also discusses the changes made in the IEC 62271 – 100, Amendment 1:2012 for conducting the capacitive current switching tests.

**Keywords:** Capacitor Switching Duty Cycle, Non-sustained Disruptive Discharge (NSDD), Voltage Breakdown, Capacitive Current Switching Test, Current Switching Test, Inadequate Synchronization

## 1. Introduction

Any substation / power grid irrespective of its scale has to use circuit breaker as it is truly essential piece of hardware. In most cases, the circuit breaker will be the only suited switch gear to stop the power flow in a grid which has become flawed. Its job is to interrupt large currents through a system and as such, it will be designed to interrupt the largest current possible and to withstand the newly imposed voltage. The following are the requirements of a good circuit breaker<sup>1</sup>.

- It will be good conductor in closed position.
- In open position it will be a good isolator.
- It has to change in a very short period of time from close to open.
- It should not cause over voltages during switching.

- It should be reliable in operation.

Over the last decades, many types of circuit breakers have been designed, each called after the medium which extinguishes internal current arc, that will ignite when the contacts are opened. The most common types are air blast breakers, high pressure oil breakers, SF<sub>6</sub> breakers and vacuum breakers. Each with its own philosophies of design and its own peculiarities.

The interpretation of capacitive current is a typical switching case, unlike the making and braking of faults current. The usual cases in which capacitive current is switched are the following:

- Switching of unloaded overhead transmission lines or local station components.
- Switching of cables.
- Switching of capacitor banks.

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Capacitor bank circuits are widely used to implement larger capacity power system and achieve higher circuit power factor for the system. The capacitor banks are normally switched by circuit breakers of different arc extinguishing media. In capacitor current switching the interruption of high frequency current and high recovery voltage makes it to restrike due to sudden release of stored energy in the load, which some time leads to damage of breaker contacts. In case of switching of unloaded lines and cables is a rare event whereas the switching of capacitor banks is a very frequent operation. During energization of capacitor banks, one has to concentrate the phenomenon of transient current drawn by the capacitor bank so called inrush current. Capacitor bank inrush current management is of considerable concern to users and developers of switchgear.

In laboratory tests capacitors are used to simulate lines and cables. A non-inductive resistor of a maximum value of 5% of the capacitive impedance may be inserted in series with the capacitors during line and cable charging current switching test. Tests in the Laboratory show clearly when a capacitor bank is energized the resulting inrush current is a function of the applied voltage, capacitance, circuit impedance, capacitor charge at the instant of closing and the damping of switching transient. The inrush currents result in stresses for both circuit breakers and capacitors.

Capacitive current switching tests are applicable to all circuit-breakers to which one or more of the following ratings have been assigned.

- rated line-charging breaking current
- rated cable-charging breaking current
- rated single-capacitor bank breaking current
- rated back-to-back capacitor bank breaking and inrush making current

Preferred value of rated capacitive switching currents are given in Table 1 of IEC: 62271-100.

## 2. NSDD and Over Voltages in Capacitive Circuits

The worst – case scenario for a typical capacitor switching operation is energizing an uncharged capacitor bank at voltage peak. Since typical switches close all three phases of a capacitor bank at the same time, the likelihood of one of the phases being at or close to voltage peak at the instant of circuit closing is high. When energizing an uncharged capacitor bank at voltage peak, the voltage transient might

reach a theoretical maximum value, the over-voltage on the terminal of the capacitor bank to earth varies from 1.5 to 4.2 p.u. and some time maximum 5.2 p.u. across the CB terminals. Typically, losses in the circuit will reduce the peak transient magnitude to lesser value.

Besides the peak voltage transient value, the behavior of the transient inrush current is also important. A typical capacitor bank with a normal average current of a few hundred amps might develop a transient inrush current of thousands or tens of thousands of amps for a brief period. The resulting high inrush currents can produce high mechanical stresses in the electrical components and induce transients in neighboring circuits that may affect connected electronic equipment.

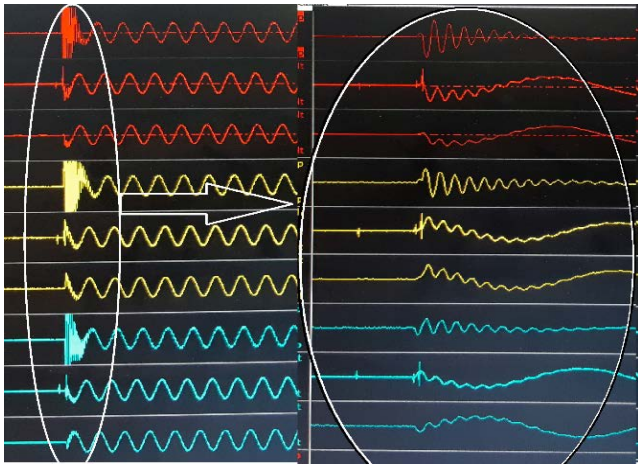
When a vacuum breaker is opened to interrupt the current flow, an arc between the opening contacts will emerge. When the steepness of the current and the resulting transient recovery voltage are below certain limits, this arc can be extinguished. After this process, the vacuum gap is most likely to collapse a few more times until the contacts are moved apart far enough for the vacuum to hold the imposed voltage. But even after a long period of time, at least on a microsecond scale, the vacuum can still collapse and an arc will emerge. This breakdown is called a Non-Sustained Disruptive Discharge. During this breakdown, all nearby inductances and capacitances will be discharged, until the arc is extinguished again by the vacuum. According to CPRI experience 20% of the vacuum breakers offered for testing at CPRI Bhopal have shown NSDDs, mostly within 300 ms after interruption.

During capacitor switching operation, the combination of short contact gap at current zero and high recovery voltage makes it possible for the breaker to re-strike (a breakdown of the opening gap later than a quarter power frequency cycle after current interruption). At re-strike, the sudden release of the energy stored in the load, can lead to damage of the breaker's contact system. Also, re-strike can lead to voltage escalation that maybe harmful for other station equipment.

Breakdown earlier than a quarter power frequency cycle after interruption is called re-ignition, considered as a harmless phenomenon inherent to the interruption process.

Capacitor bank switching is the most severe capacitive switching operation. Because of inrush the circuit breaker maybe conditioned negatively and because of the many switching operations the probability of re-strike during the breaker's lifetime is very high<sup>2</sup>.

Oscillogram (Figure 1) showing the Inrush current during test duty BC1 conducted on 12kV Vacuum Circuit Breaker.



**Figure 1.** Inrush current during Test Duty – BC1.

## 2.1 Reduction of Capacitor Switching Transients

There are several technologies available that help to mitigate capacitor inrush current.

### 2.1.1 Pre-insertion Resistors

The use of Pre-insertion resistors is an old but effective remedy. In a switch with pre – insertion resistors, the switch first contacts the resistors before making contact with the capacitors. The addition of pre-insertion resistors helps to reduce the severity of transient by momentarily introducing heavier losses in the circuit.

### 2.2.2 Inrush Current Limiting Reactors

This method employs reactors in series with the capacitor bank. The reactor increases the magnitude of the surge

impedance, effectively reducing the peak value of the inrush current. Also, since the current through the reactor cannot change instantly, the higher frequency components of the transient are limited and the severity of the current inrush is reduced.

### 2.3.3 Zero-crossing Switches

Also called synchronous switches or breakers, these switches represent a relatively new technology used to reduce capacitor switching transients. Zero-crossing switches time the closing of each phase to correspond with the zero crossing of the phase voltage.

## 3. Standardization of Capacitive Current Switching Test

The standardized requirements of capacitor bank switching are laid down in IEC<sup>3</sup> & IEEE<sup>4</sup>. Tests specified for capacitive current switching ratings are individual type tests, each comprising a tests series with two test-duties. The test circuit should fulfil the two requirements. One is the characteristics of the test circuit should be such that the power frequency voltage variation, when switching, should be less than 2 % for test-duty 1 (LC1, CC1 and BC1) and less than 5 % for test-duty 2 (LC2, CC2 and BC2). Second is the impedance of the supply circuit shall not be so low that its short-circuit current exceeds the rated short-circuit current of the circuit-breaker. The relevant test-requirements for 12kV Circuit Breaker are summarized in Table 1.

These test-duties may be combined in order to demonstrate the performance of a circuit – breaker for covering several applications or ratings (e.g. LC and/or CC and/or BC). If such combination method is used, the following rules apply:

**Table 1.** Requirements of IEC for circuit breakers for capacitor bank switching test duties

Class C1: Low probability of re-strike					
test duty	Current (A)	3-phase		1-phase	
BC1**	40 – 160	24 O	6 O*	24 O	6 O*
BC2***	400	24 CO	6 CO*	24 CO	6 CO*
CC1**	2.5 - 10	24 O	6 O*	24 O	6 O*
CC2***	25	24 CO	6 CO*	24 CO	6 CO*
LC1**	1 - 4	24 O	6 O*	24 O	6 O*
LC2***	10	24 CO	6 CO*	24 CO	6 CO*

Pre-conditioning does not required					
Maximum of Two re-strikes allowed inclusive of repetition of total series					
Class C2: very low probability of re-strike					
test duty	Current (A)	3-phase		1-phase	
BC1**	40 – 160	24 O	12 O*	48 O	12 O*
BC2***	400	80 CO	64 CO*	120 CO	84 CO*
CC1**	2.5 - 10	24 O	12 O*	48 O	12 O*
CC2***	25	24 CO	12 CO*	24 O+24 CO	6 O* + 6 CO*
LC1**	1 - 4	24 O	12 O*	48 O	12 O*
LC2***	10	24 CO	12 CO*	24 O+24 CO	6 O* + 6 CO*
additional pre-conditioning required with Test Duty T60					
Maximum of One re-strike allowed inclusive of repetition of total series					
*: Number of tests to be carried out at minimum arcing time					
**: The tests are performed at maximum operating voltage & minimum functional pressure					
***: The tests are performed at maximum operating voltage & rated pressure					

The test duties and test current should be as follows:

- A test duty 2, covering all test duties 2 of the combination, with a current not less than 100% of the highest capacitive current rating.
- A test duty 1, with a current between 10% and 40% of the highest capacitive current rating.
- A test duty 1, for each lower capacitive current rating if the range of 10% and 40% of that rating is not covered by a previous test duty 1.

### 3.1 Test Voltage

For three-phase tests, the test voltage measured between the phases at the circuit-breaker location immediately prior to opening shall be not less than the rated voltage  $U_r$  of the circuit breaker.

For single-phase laboratory tests, the test voltage measured at the circuit-breaker location immediately before the opening shall not be less than the product of  $U_r/\sqrt{3}$  and the following capacitive voltage factor  $k_c$ :

- 1.0 for tests corresponding to normal service in earthed neutral systems.
- 1.2 for tests on belted cables and for line-charging current switching test.
- 1.4 for breaking of capacitor banks with isolated neutral.

The power frequency test voltage and the d.c. Voltage resulting from the trapped charge on the capacitive circuit shall be maintained for a period of at least 300ms after breaking.

### 3.2 Waveform of the Current and Voltage

The waveform of the current to be broken should, as nearly as possible, be sinusoidal. The current to be interrupted shall not go through zero more than once per half-cycle of power frequency.

### 3.3 Passing Criteria

The circuit breakers shall have successfully passed the tests if the following conditions are fulfilled:

- The circuit breaker shall be capable of making and breaking capacitive currents in all prescribed test-duties.
- For Class C1 circuit breaker, either up to one restrikes occurred during test-duties 1 and 2 or if two restrike occurs during the complete test-duties 1 and 2, then both test duties shall be repeated on the same apparatus without any maintenance. During extended series of tests only one additional restrike allowed. External flashover and phase-to-ground flashover should not occur.
- For Class C2 circuit breaker, either no restrikes occurred during test-duties 1 and 2 or if one restrike occurs during the complete test-duties 1 and 2, then both test duties shall be repeated on the same apparatus without any maintenance. During extended series of tests no more restrike allowed. External flashover and phase-to-ground flashover should not occur.

- For circuit breaker with sealed for life interrupter units, the dielectric condition checking is to be performed.

## 4. Changes in the Old and New IEC

IEC: 62271-100 has released two amendments in the year 2012 and 2017. As per these amendments the following changes were incorporated in the standard. The changes shown in the Table 2.

**Table 2.** Changes in the Old and New IEC

S. No	Clause No. as per Amendment2:2017	IEC 62271 – 100, Amendment1:2012	IEC 62271 – 100, Amendment2:2017
1	6.111.5.3 Capacitor bank current switching tests	--	A non-inductive resistor of a maximum value of 5 % of the capacitive impedance may be inserted in series with the capacitors for testing single-capacitor bank current switching (making and breaking) and for back-to-back capacitor bank current switching (breaking).
2	6.111.9.2 Common test conditions for class C1 and C2 performance	<ul style="list-style-type: none"> <li>• Specified separate test conditions for class C1 &amp; C2.</li> <li>• Rated pressure for Test duties -1 of class C1.</li> <li>• Maintaining making angle is mandatory for both single &amp; back to back capacitive switching current test duties.</li> <li>• The preferred order for the class C1 tests is test-duty1&amp;test-duty2</li> </ul>	<ul style="list-style-type: none"> <li>• Specified common test conditions for class C1 &amp; C2.</li> <li>• Minimum functional pressure for Test duties -1 of class C1 &amp; C2.</li> <li>• Maintaining making angle is not mandatory for single capacitive switching current test duties.</li> <li>• There is no preferred order for the class C1 test duties.</li> </ul>
3	6.111.9.3.2 Three-phase capacitive current switching tests (Class-C1)	<ul style="list-style-type: none"> <li>• Step angle 30°</li> <li>• In Test Duty-1 6'0' at Maximum arcing time should be taken &amp; in Test Duty-2 6'CO' Should be taken at Maximum arcing time</li> </ul>	<ul style="list-style-type: none"> <li>• Step angle 10°</li> <li>• In Test Duty-1&amp; Test Duty-2 removed all tests to be taken at Maximum arcing time and it has to be taken at minimum arcing time in other polarity.</li> </ul>
4	6.111.9.3.3 Single-phase capacitive current switching tests (Class-C1)	<ul style="list-style-type: none"> <li>• In Test Duty-1 6'0' at Maximum arcing time should be taken.</li> <li>• In Test Duty-2 6'CO' Should be taken at Maximum arcing time</li> </ul>	<ul style="list-style-type: none"> <li>• Removed all tests to be taken at Maximum arcing time in Test Duty-1&amp; Test Duty-2.</li> <li>• Modified to take at distributed in other polarity.</li> </ul>
5	6.111.9.4.5 Single-phase capacitor bank (single or back-to-back) current switching tests (Class-C2)	<ul style="list-style-type: none"> <li>• In Test Duty-2 a total of 42'CO' to be taken at minimum arcing time on each polarity</li> </ul>	<ul style="list-style-type: none"> <li>• In Test Duty-2 a total of only 40'CO' to be taken at minimum arcing time on each polarity</li> </ul>
6	---	<ul style="list-style-type: none"> <li>• Specified test conditions corresponding to breaking in the presence of earth faults for single, back to back capacitor banks, lines and cables in clause no. 6.111.9.3</li> </ul>	<ul style="list-style-type: none"> <li>• Removed completely</li> </ul>

## 5. Interpretation of Restrike and NSDD during Capacitive Current Switching Test

During the different conditions the performance of Vacuum circuit Breaker were analysed:

### 5.1 Restrikes

A restrike is a resumption of power frequency current or inrush frequency current between the contacts of a mechanical switching device during a breaking operation

with an interval of zero current of a quarter cycle of power frequency or longer.

In three-phase ungrounded systems this is only possible when two phases breakdown simultaneously and if high-frequency current interrupting capability of the breaker is poor. In a single-phase test circuit, the restrike current can be measured or, resulting in oscillation current in parts of the main circuit is not always easy to measure but can be detected by its resulting effects, such as:

- a change of polarity of the load side voltage in the case of an odd number of restrike current loops
- voltage escalation in case of multiple break downs

Oscillogram shown in Figure 2, two restrikes occurred within 300msec after current interruption during test duty 1 (CC2) (three phase) on 12kV, 21kA Vacuum Circuit Breaker. This failure attribute to the poor dielectric integrity of the interrupter.



Figure 2. Oscillogram during Test Duty – CC2.

### 5.2 NSDD (Non-Sustained Disruptive Discharges)

NSDD is high frequency current discharge of transient nature during recovery period. During this phenomenon,

the momentary collapse of voltages on one phase may result in a corresponding offset of the power frequency recovery voltage on all phases. Occurrence of NSDD could be interpreted as showing signs of distress or any late breakdown not evolving into a restrike. Oscillogram (Figure 3) showing the NSDD occurred during test duty CC1 conducted on 12kV, 21kA Vacuum Circuit Breaker.

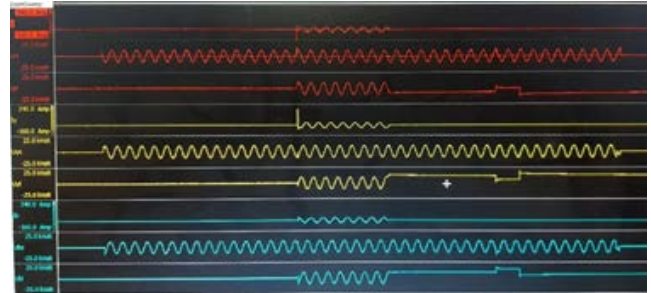


Figure 3. Oscillogram during Test Duty – CC1.

## 6. Testing Facilities and Statistical Data of CPRI, Bhopal

CPRI is continuously engaged in testing of various types of switchgear equipment from last six decades. CPRI has the facility to cater single-capacitor bank current, line and cable charging tests up to 12kV category class. A view of single capacitor bank current testing arrangement of 12kV,1250A, 26.3kA Indoor VCB with panel has shown in Figure 4. View of capacitor bank room to simulate line and cable charging currents also shown in Figure 4. CPRI has sufficient capacitor bank to conduct single-capacitor bank current switching test as per IEC<sup>3</sup> and IEEE<sup>4</sup> either



Figure 4. Testing sample arrangement during Capacitor Switching of 12kV, 26.3kA Indoor VCB with Panel.

in three phase method or single-phase method up to 12kV. In case of single-phase method testing current up to 1000A is possible which is beyond the specified current levels in standards.

Statistics shows (refer Table 3) that the Capacitive current switching test performed as per the IEC<sup>3</sup> and IEEE<sup>4</sup> in CPRI, Bhopal are total 179 equipment tested out of which 161 passed and 18 failed due to restrikes, mechanism failure, dielectric failure.

**Table 3.** Statistical Data

Period	Total			Fail in %
	Passed	Failed	Tested	
2000 to 2005	44	8	52	15.4
2006 to 2010	51	3	54	5.5
2011 to 2015	38	4	42	9.5
2016 to 2019	28	3	31	9.6
Total	<b>161</b>	<b>18</b>	<b>179</b>	<b>10.1</b>

## 7. Conclusion

Capacitor switching duty is very typical duty because rate of rise of recovery voltage in capacitor switching is very high, which needs the breaker should be capable of building the dielectric strength in smaller time. Mostly failures of circuit breakers during capacitor switching can be related to closing speed too low, bouncing of contacts, Inadequate synchronization of closing of three poles or Contact material.

## 8. Acknowledgement

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