21, rue d'Artois, F-75008 Paris
http://www.cigre.org

A3-303

Session 2004

ASSESSMENT OF NON-SUSTAINED DISRUPTIVE DISCHARGES (NSDD) IN SWITCHGEAR. TEST EXPERIENCE AND STANDARDISATION STATUS

R.P.P. SMEETS, A.G.A. LATHOUWERS*
KEMA HIGH-POWER LABORATORY
(The Netherlands)

L.T.FALKINGHAM
AREVA T&D MVB
(The United Kingdom)

1. INTRODUCTION

Occasionally, interrupters break down relatively long (up to 1 s) after the interruption of current and restore insulation immediately thereafter. This event is relatively rare, but tests show that there remains a finite probability of this occurring. Usually, such a "late" breakdown is associated with vacuum switching devices, although (undocumented) observations of self restoring breakdowns in SF_6 switchgear have also been reported, indicating that this phenomena may not be restricted to vacuum switching technology only. However this investigation only deals with vacuum based phenomena.
In the IEC (International Electrotechnical Commission) standard literature, such self restoring, 'late' breakdowns are termed 'Non-Sustained Disruptive Discharges' (NSDD) reflecting the inherent characteristic of vacuum interrupters to restore the insulating state almost immediately after the start of the NSDD. This is due to the outstanding capability of vacuum interrupters to interrupt currents of very high frequency. Such breakdowns are thought to be initiated by a combination of several mechanisms, the primary being; mechanical vibrations, leading to the release of macro-particles [1] or to a sudden increase of field emission level leading to breakdown [2].

The interpretation and assessment of NSDD have led to considerable discussion, particularly concerning what consequences, if any, NSDD would have in real life circuits. It must be remembered that vacuum interruption is not a new technology, with over 35 years in service and millions of interrupter-years service experience in medium voltage. Despite this huge amount of service experience, to date there are no direct indications that NSDD have any detrimental effect in service.
In this contribution the authors would like to give a conclusive summary of the electrical phenomena related to NSDD, to assess the consequences and significance of NSDD, and put forward a new proposal to greatly simplify the assessment procedure of NSDD in certification tests.

2. STANDARDISATION AND TESTING ISSUES

2.1 Difficulty of interpretation.

The detection of NSDD during testing is not easy, and in real life NSDD can actually have no effect due to circuit conditions. IEC and ANSI/IEEE (the US standardising body) both prescribe medium voltage current interruption tests in a three-phase test circuit that is usually ungrounded. In such a circuit, two interrupted phases automatically ensure the interruption of the third phase current, simply because of lack of a (ground) return path.

* KEMA High Power Laboratory, Utrechtseweg 310, 6812 AR Arnhem, Netherlands (rene.smeets@kema.com)

This implies that if an NSDD occurred in one phase (the others already open), the ungrounded circuit topology will prevent a measurable current from flowing, thus making it impossible to distinguish between a selfrestoring (NSDD) or a non selfrestoring (restrike) event. However the circuit topology is such that this really does not matter, as the event has no significant effect on the external circuit. Although the current following an NSDD is too small and too short-lasting to be measured in normal testing set-ups, the voltage-to-ground at one terminal (either load- or source side, depending on whether neutral or source is grounded) of all three poles can make a steep and clear excursion, that is currently used to identify the occurrence of an NSDD.

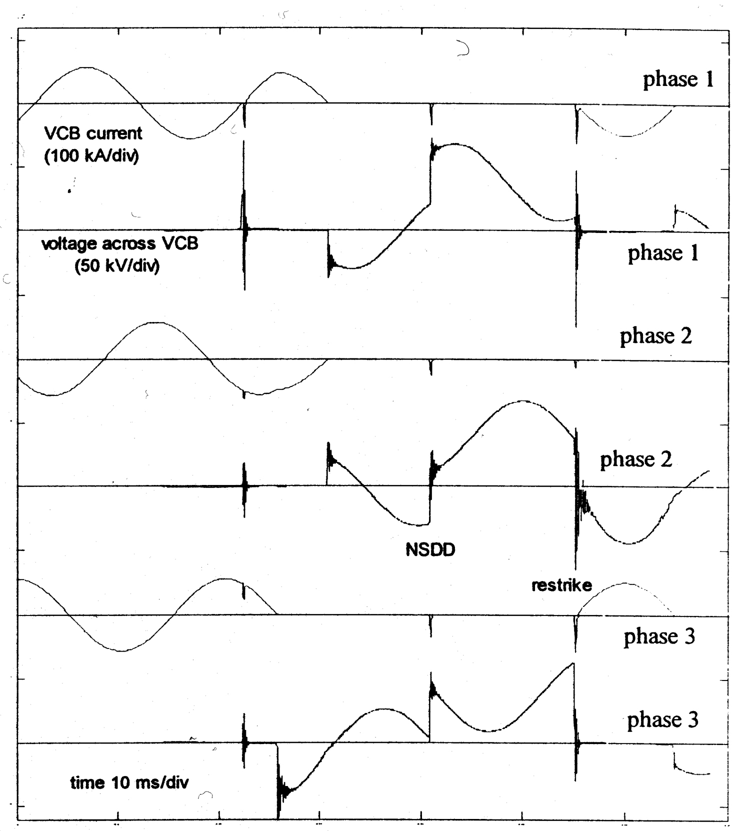

Fig.1: Electrical appearance of NSDD and restrike in a three-phase ungrounded circuit. Voltages across VCB, current through VCB

In fig. 1, examples of both a NSDD and a restrike are shown. Note that here the restrike is in effect caused by the NSDD: Initially an NSDD in phase 2 occurs, thereby raising the voltage in phase 3 to a value too high to be withstood by that breaker pole. A two-phase fault current arises, which is interrupted after a full power frequency loop. Resumption of power frequency current is clearly identifiable and is classified as a restrike, howsoever caused.

At this point a distinction must be made between short-circuit current breaking tests and capacitive current interruption tests:
In short-circuit tests, the circuit breaker must demonstrate (in a limited number of tests) its ability to interrupt fault current. As part of this, circuit breakers of all technologies are allowed to cause disturbances to the connected circuit for a limited period as part of the interruption process (air circuit breakers are particularly prone to this), and such disturbances are termed reignitions. The primary difference between a reignition and a restrike is time to occurrence.
Capacitive tests (much larger in number but at a significantly lower current) are intended to demonstrate the absence of restrikes - leading to the release of a significant amount of capacitively stored energy which might damage the circuit breaker and/or generate overvoltages in the system.

2.2 Standardisation history.

The discussion on NSDD as a phenomenon that possibly might affect users of switchgear started in the mid-1980s, once digital data recorders reached speeds which allowed these very fast phenomena to be detected. CIGRE did not at the time study this phenomenon as vacuum technology was limited to distribution voltages of < 40kV, and also due to the idea that problems for the end-users would be limited to problems with protection systems, both of which were out of CIGRE's switchgear committee scope.
The test laboratories (both independent and those operated by manufacturers), however, faced the problem of how to deal with this new phenomenon they were detecting, and termed NSDD. In addition the relevant switchgear standards did not refer to this phenomenon and so there was uncertainty as to how to interpret the new information. Therefore STL (Short-circuit Testing Liaison, an organisation of independent and manufacturer-operated test laboratories) commenced and is

continuing discussing on the interpretation of NSDD.
In 1985 STL decided that "Certification will not be allowed if there are four or more occurrences of the NSDD-phenomenon during a complete test series as required by the standard, including any test duties which are repeated or re-started for whatever reason". This statement has been further evolved over the last 20 years and was incorporated in the IEC standard. However, as this limitation to four NSDD was arbitrary and not based on any science this has resulted in considerable debate and discussions amongst test stations, manufacturers and users of vacuum switchgear.

2.3 Actual status At present, in short-circuit certification tests in accordance with the widely used circuit breaker standard IEC 62271-100 [3], the recommendations of STL are followed, insisting that the absence of multiple (> 3) NSDD must be verified by subjecting the interrupters to the rated power frequency voltage for at least 300 ms after interruption. If there are more than three occurrences of NSDD during the entire series of test-duties, certification will not be possible. Restoration of power frequency current is never allowed.
In capacitive current switching tests, the number of NSDD, allowed for certification is one ninth of the number of breaking operations in a test series. In order to simplify the interpretation of a breakdown, in IEC [3] it was decided to designate every breakdown occurring later than half a power frequency cycle after current zero as an NSDD. The consequence of this simplification is that potentially harmful restrikes leading to discharge and possibly capacitive voltage escalation [4], are not discriminated from normally harmless NSDD. Since this can be considered technically unacceptable [5], discussion on how to deal with late breakdown is continuing, and generating new proposals, one of which is being put forward in the present contribution.

After the publication of IEC 62271-100 a number of parties have continued to work on the subject of NSDD, and in particular their potential consequences. The new knowledge generated has resulted in a completely different assessment of the NSDD phenomena. As a consequence, NSDD are no longer considered to be a sign of distress of the breaker, and their number of occurrence is not considered to be important, and certainly not a reason to refuse certification.
NSDD were not specifically addressed by ANSI/IEEE and as a result the relevant standards did not prohibit NSDD, tacitly implying that these phenomena did not pose a significant problem - the position that IEC is now coming around to. The commission currently entrusted with the revision of the US circuit breaker standard ANSI/IEEE Std C37.09-1999 has chosen to continue with this policy for the time being and not to specifically address the issue of NSDD.

3. EXPERIENCE WITH NSDD IN CERTIFICATION TESTS

A systematic investigation was made of the occurrence of NSDDs during one full year (1999) of (mainly short-circuit) testing of vacuum circuit breakers (VCBs) at KEMA High-Power Laboratories. In that year, 133 test reports were produced on different VCBs that underwent current interruption tests. In 90 reports no NSDD occurred. In the remaining 43 reports (32 %) in total 134 occurrences of NSDD were mentioned[1]. The test-objects covering these 43 reports, originate from 10 different manufacturers (Europe, Asia and North-America). In 9 reports, more than 3 NSDD occurrences were reported during the entire test series, 4 cases of which showed a variety of problems with current interruption and 5 were refused certification purely on NSDD grounds (> 3 occurrences) and further testing was aborted. This experience is graphically outlined in fig. 2.
The rated voltage of the population that exhibited NSDD was between 12 – 50 kV, the rated short circuit current range was 12 – 40 kA.

It was observed that NSDD is not only a high-current phenomenon. This confirms the findings reported earlier [6], a study that shows that NSDD can actually occur even after interruption of negligible current, and clearly indicating that NSDD are not in themselves an indication of being close to the current interruption limit of a circuit breaker.
Keeping this in mind, it is not surprising, that also during capacitive current interruption test duties,

[1] A significant portion of these was described in a few reports of tests on interrupters which had been made specifically to investigate the NSDD phenomenon.

(current not exceeding 400 A), frequent occurrences of late restrikes are observed.
From the results, it cannot be concluded that NSDD is associated with VCBs in the higher rated voltage range only. During all the tests, the moment of occurrence of the NSDDs was recorded, showing a steep decline of probability of occurrence with time within the 300 ms of observation window [5]. It was observed in [5] that in the overwhelming number of cases, less than 4 NSDDs occur.

The numerical data show that approx. 25% of the certified circuit breakers have exhibited NSDD at tests, which implies that also in service conditions, NSDD must be a common phenomenon.

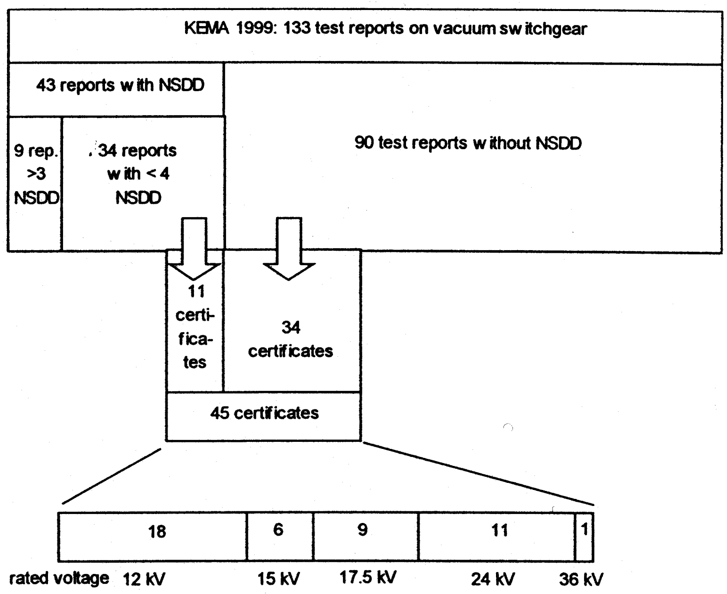

Fig. 2: KEMA's experience with vacuum circuit breakers in 1999

No correlation between NSDD and circuit breaker performance can be established based on the statistics reported here, and it is assumed that based on this investigation and others [6] that there actually is no relationship, clearly indicating that the occurrence of NSDD are not a sign of distress of a circuit breaker.

4. NSDD AND OVERVOLTAGES IN CAPACITIVE CIRCUITS

4.1. Circuit analysis approach

In order to assess the potential consequences of NSDD and their effects it was decided to model the behaviour of NSDD in a typical circuit. Failure of the interrupter to withstand the recovery voltage, leads to the discharge of various capacitances, and re-arrangement of energy within the circuit. In capacitive circuits, it is not excluded that this could generate undesired voltage transients (in parts of) the system.

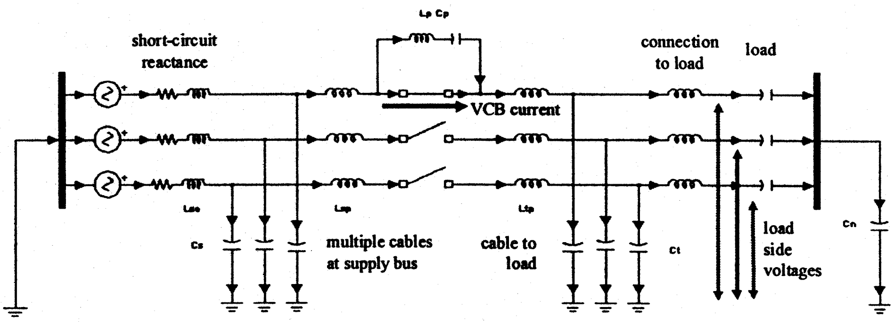

Fig. 3: Reference capacitor bank circuit for the simulation analysis

In order to gain an understanding of the characteristics of such transients and their origins, first a simulation study was performed, based on a "reference" capacitive (capacitor bank) circuit depicted in fig. 3. Later, measurements were performed (section 5).
The "reference" circuit represents a capacitor bank (200 µF), connected with a cable (approx. 100 m, having a a lumped element equivalent capacitance of 25 nF) to the circuit breaker. At the source side of the breaker a relatively large capacitance (100 nF), representing multiple cables is assumed. A 25 kA source with a 45 ms time constant is taken.
For a capacitive circuit, the most severe transients occur at breakdown of the breaker in the first phase-to-clear at recovery voltage peak (the voltage across this breaker is then at a level of 2.5 pu, see fig. 4 in which all initial capacitor voltages - just prior to breakdown - are entered in the "reference" circuit).

Given the full three-phase circuit of fig. 3, the transient voltages that develop can now be calculated (here MatLab SimPowerSystems is used). The "oscillogram" of interrupter current and load-side voltage transient to ground (as indicated in fig. 3), is given in fig. 5. As can be seen, a maximum excursion of approx. -5 pu (relative to ground) is reached after a time of some 35 μs in the healthy phase that had the initial voltage of - ½√3 pu (lower phase in fig. 3, 4). Here, it is assumed that the duration of the discharge is long enough to actually reach this value. Note that the maximum voltage occurs in the phase that does not break down, reflecting the typical three-phase interaction that has been taken into account here.

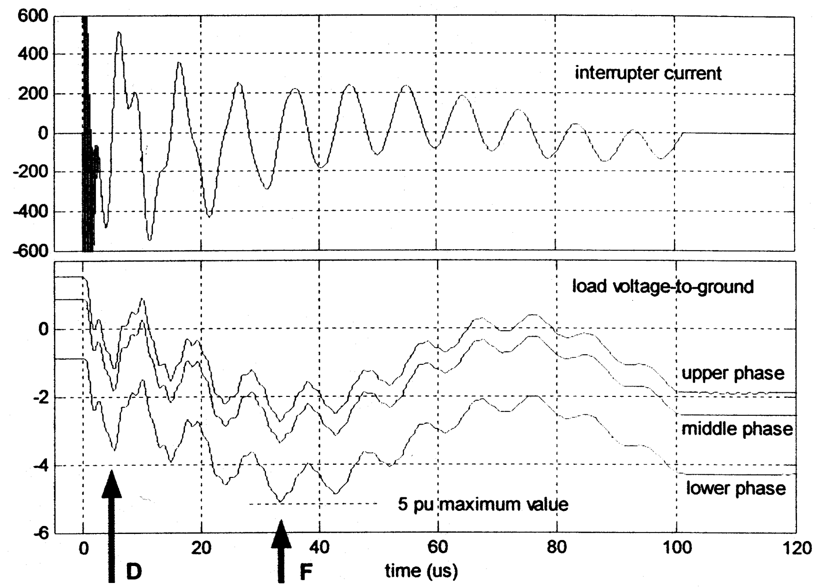

Fig. 5: Calculated current and load voltage-to-ground in ref. circuit

Various frequency components can be recognised in current and voltage, each of which is associated with different parts of the reference circuit. In fig A (appendix) six (A - F) main subcircuits have been identified causing these oscillations. Each circuit is characterised by the frequency of its discharge current (f_A - f_F) and its surge impedance (Z_A - Z_F) indicating the magnitude of the high-frequency current.

Linking each of these subcircuits to the voltage and current they commonly produce, it is clear that the major -5 pu voltage transient (indicated by the arrow "F" in fig. 5) is originating from the subcircuit F in fig. A.F. Physically, the load side capacitance Ct in the lower phase is charged up to -4 pu (in addition to its initial value of -½√3 pu) due to the oscillation excited in the whole three-phase circuit[2].

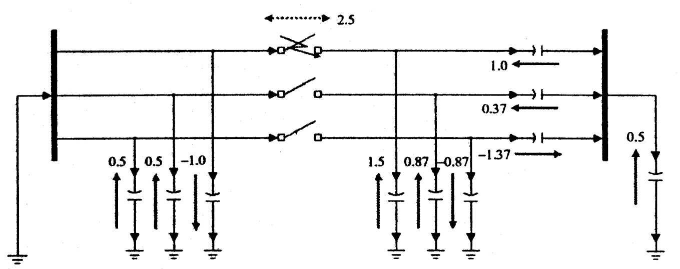

Fig. 4: Initial capacitor voltage voltages immediately prior to breakdown in first (upper) phase to clear at maximum recovery

The earlier occurring local maximum of -3.5 pu (see arrow "D") is due to the more localised oscillation "D" (from fig. A.D, appendix) between the connecting cables through the load. Although the main capacitor is not involved in any (ex)change of charge/voltage in this time range, its unfavourable contribution in the overvoltage generation lies in its initial voltage (- ½ - ½√3 pu across the capacitance) in the lower phase, leading to a shift of the lower phase voltage trace from +½ pu initially in the situation without capacitive load to - ½√3 pu initially with capacitive load.

As a conclusion of the present analysis, in the circuit examined it is the duration of the NSDD that will determine whether or not significant overvoltages can be developed. Short duration NSDD (< 10 μs), in VCBs with excellent capability to interrupt high-freqency current, such as vacuum interrupters, do not allow discharge of more distant and larger sources of capacitive energy and the NSDD phenomena remain confined to the vicinity of the breaker.

2 If damping was not accounted for, the additional voltage rise would be 5 pu, leading to a theoretical maximum excursion of 5 + ½√3 pu.

If the NSDD duration becomes longer (typically when the interrupter cannot interrupt high frequencies), the entire circuit becomes involved and more distant capacitances start to discharge and significant overvoltages may arise.

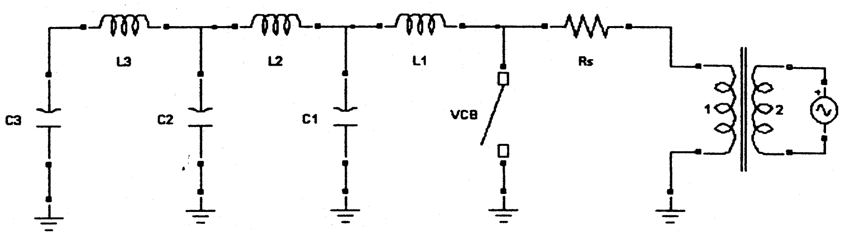

Fig. 6: Multiple frequency exp. circuit for NSDD duration evaluation

Only for capacitively loaded circuits, such overvoltages reach significant values. Thus, in the circuit modelled, NSDD are a clear example of interaction of interrupter and circuit, and the duration of NSDD (in other words the high-frequency interruption capability of the VCB) is the key parameter here.

5. EXPERIMENTAL RESULTS

In an attempt to get more quantitive information on NSDD phenomena, a large number of tests were performed at Eindhoven University of Technology [7]. To this aim, a test circuit was realised consisting of three oscillatory circuits (of 1.1 MHz, 430 kHz and 72 kHz), see fig. 6, each of which will discharge upon breakdown of the test-breaker. Two commercially available VCBs (12 kV rating) were stressed with ac recovery voltage up to 40 kV after interrruption of a very small current (< 1A) from a high-voltage transformer. This very high RV approximately double the rated value for these devices, was applied in order to give a higher probability of NSDD occurring. The (randomly occurring) late breakdowns were monitored with high-frequency digitizers.

5.1. Single frequency NSDD.

In the first series, NSDDs were monitored in oscillatory circuits of only one single frequency (L1C1 or L2C2 or L3C3). A striking difference in duration of the NSDDs is observed. In fig. 7 examples of the NSDD current (upper) and voltage across the interrupter (lower) are given, together with the cumulative fraction of duration of HF current flow for each of the two interrupter designs (solid, dotted curves respectively) and for each of the three discharge frequencies.

The difference is due to the reignition mecha-nism: for the highest frequency, the reignition process is purely thermal (di/dt is too high) whereas for the lower frequency the reignition is dielectrically dominated (sufficiently small di/dt but too high TRV peak to interrupt). The latter process can be sustained longer because of slower damping losses of capacitive energy at lower frequencies [8].

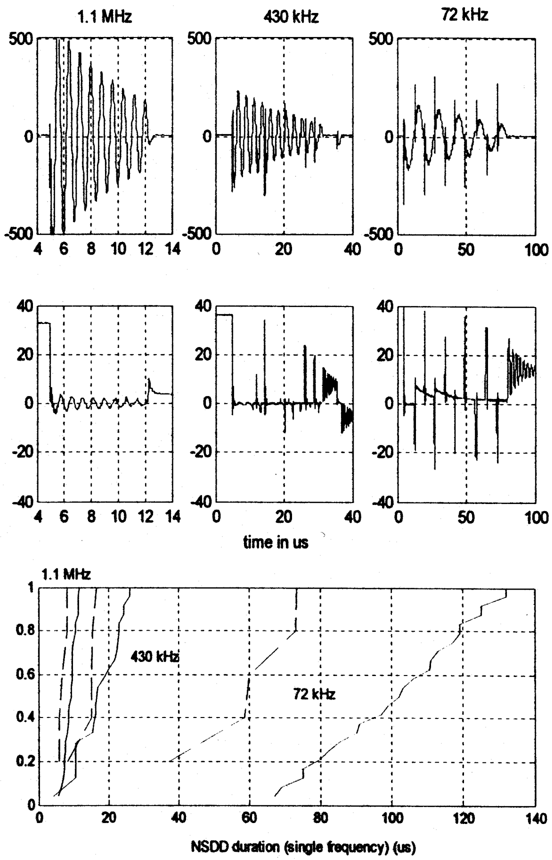

Fig. 7: Me   red NSDD i   single frequency circuits. Upper: current through VCB
Middle: voltage across VCB
Lower: Cumulative fraction of NSDD duration for NSDDs in the three circuits

5.2. Multiple frequency NSDD.

In the second series, all three circuits were con-nected to the VCB, so that current consisting of three frequency components arises upon breakdown of the interrupter. A typical current is shown in fig. 8, together with the statistical distribution of the 3-frequency NSDD duration. As can be seen, by comparison with fig. 7, the duration of these NSDDs is determined by the highest frequency component. The exact reason for this needs further investigation to clarify, but probably this is due to the different condition in the vacuum gap and/or cathode surface after different frequencies.

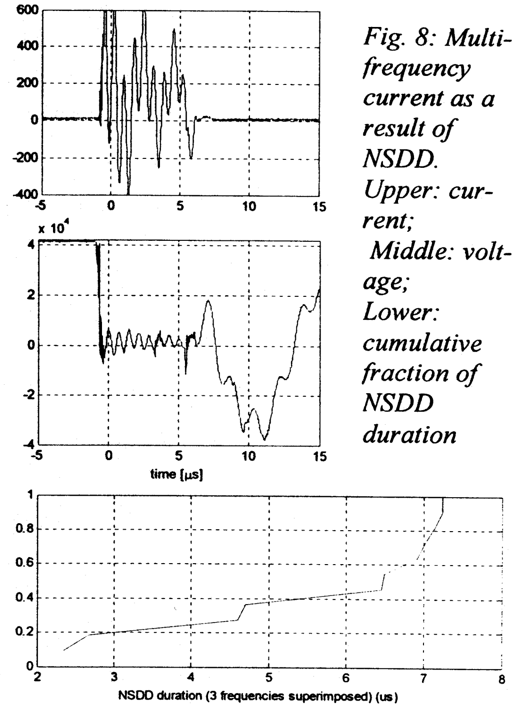

Fig. 8: Multi-frequency current as a result of NSDD. Upper: current; Middle: voltage; Lower: cumulative fraction of NSDD duration

6. DISCUSSION

The important information, gained from the experiments with commercial VCBs under a multifrequency NSDD discharge current, is that the duration of the discharge is below 10 µs for the breakers under study. Combining the short NSDD duration information with the overvoltage analysis of sect. 4, it may be concluded that a full type F discharge (see fig. A.F appendix) cannot develop in the "reference" circuit of fig. 3. Apparently, the NSDD remains localised in the circuit consisting of the VCBs and its connecting cables. As a consequence of this, the overvoltage generating capability of NSDD is very limited.

However, in very special cases, it is possible that even very short lasting NSDD, could cause significant overvoltages. Such a case is for example a short cable connection to the load, which will shift the 5 pu absolute overvoltage peak (fig. 5) to a time that may fall within the typical NSDD duration.

7. PROPOSAL FOR NSDD ASSESSMENT

Based on the investigation described it is possible to make the following considerations:

- The duration of the observed NSDD is too short to let the relevant circuit parts reach significant overvoltages;
- NSDD must occur under service conditions very frequently but nevertheless reported overvoltage related problems are very rare;
- It is generally accepted that NSDD are inherent to interruption in vacuum which is the most common technology used in MV switchgear.
- NSDD is very difficult to assess in three-phase ungrounded test-circuits, and the relevance is questionable;
- there is a continuous search of circuit solutions in order to make easier distinction between restrike and NSDD;
- It is difficult to explain the (consequences of the) phenomenon to users of switchgear

The authors propose that NSDD can no longer be seen as a sign of distress of a circuit breaker and have no significance to the performance of a circuit breaker. Therefore it is no longer acceptable to refuse certification after the occurrence of any number of NSDD during a test series.

However, in capacitive circuits it is particularly important to differentiate between a harmless NSDD and a potentially harmful restrike, therefore a very simple distinction between restrike and NSDD is proposed:

- To define a restrike as a breakdown leading to at least one loop of discharge current of the main capacitive load: the "inrush" current[3]. Resumption of 50 Hz current is the result of a restrike too.
- To define NSDD as any breakdown, not having the characteristics (see above) of a restrike.

The authors feel that it is still necessary to retain the term NSDD in test reports / certificates as an explanation for the sudden jumps in the recovery voltage oscillograms which may be seen (see fig. 1).

[3] This is considered an improvement on the present IEC definition - IEC 50 (441-17-46) - that defines a restrike as "a resumption of current", not specifying the nature of the current (HF, inrush frequency or power frequency).

8. CONCLUSIONS

Selfrestoring late breakdown after current interruption in vacuum (termed Non-Sustained Disruptive Discharge - NSDD - in IEC terminology) is a common phenomenon. Due to displacement of charges within the circuitry around the vacuum interrupter, transient voltages may occur.

8.1. Short-circuit interruption.

In short-circuit interruption, there is no risk that such transients could reach a high value.

- In an ungrounded circuit: A problem can only occur if the voltage jump associated with the breakdown leads to high voltage across (one of the) other breaker poles, leading to breakdown there and a power frequency current flow in two phases (see fig. 1). In healthy breakers, the high-frequency interruption capability of VCB's normally prevents power frequency current flow.
- In a grounded circuit: A problem can only occur in the case where the high-frequency interruption capability is not able to interrupt the reignition current, resulting in power frequency current in one phase. In healthy breakers however, the high-frequency interruption capability of VCBs will again prevent power frequency current flow.

Therefore NSDD are not considered to be a sign of distress of the circuit breaker and are not detrimental to the performance.

8.2. Capacitive current interruption.

Here, because of the presence of a pre-charged load, that works out unfavourably for the transients in one of the healthy phases, a certain probability of significant voltage transients exists in theory. However, combining the experimental results with network analysis we conclude that the duration of the conductive period normally is too short to let severe transient voltages develop.
For special circuits, allowing a very fast building up of transients, it is theoretically possible to develop significant transient voltages, and so special care must be exercised in these cases, and the installation of surge arresters may be advisable.

8.3. Certification.

It is proposed to redefine the term "restrike" with respect to the IEC definition. Restrike should cover all breakdowns leading to a discharge of capacitive load and/or power frequency current. All other breakdown phenomena should be termed NSDD.
The user of switchgear, together with the manufacturer, should realise that NSDD is in principle a harmless phenomenon inherent to interruption in vacuum, but could in theory in some special capacitive circuits lead to significant overvoltages.
NSDD are no longer considered as a sign of distress of the circuit breaker. In those cases where a breakdown leads to power frequency current, the breakdown is no longer termed a NSDD and instead is defined as a restrike. Thus, based upon the above arguments, the authors believe that the identification of NSDD is no longer a reason to refuse certification of a circuit breaker.

9. REFERENCES

[1] R. Gebel, D. Falkenberg, “Mechanical Shocks as Cause of Late Discharges in Vacuum Circuit Breakers”, IEEE Trans. Electr. Insul., vol. 28, 1993, pp 468 – 72

[2] B. Jüttner, M. Lindmayer, G. Düning, “Instabilities of prebreakdown currents in vacuum I: late breakdowns”, J. Phys. D: Appl. Phys., vol. 32, 1999, pp. 2537 – 43

[3] IEC Standard 62271-100, "High-voltage switchgear and controlgear", First ed., 2001-05

[4] A. Greenwood, "Electrical Transients in Power Systems", John Wiley & Sons, New York 1991, chapter 5.3

[5] R.P.P. Smeets, A.G.A. Lathouwers, "Non-Sustained Disruptive Discharges: Test Experiences, Standardization Status and Network Consequences", IEEE Trans. on Diel. and Electr. Insul., Vol. 9, pp. 194-200, 2002.

[6] M. Schlaug, L.T. Falkingham, "Non-Sustained Disruptive Discharges (NSDD) - A New Investigation Method Leading To Increased Understanding of this Phenomenon", XIXth Int. Symp. on Disch. and Elec. Insul. in Vac., Xi'an, China, 2000, pp. 490

[7] D.W. Thielens, "Circuit Influences on Non-Sustained Disruptive Discharges in Vacuum Switching Devices", Eindhoven University, M.Sc. report S433649, October 2003

[8] R.P.P. Smeets, D.W. Thielens, R.W.P Kerkenaar, "Characteristics of late breakdown in vacuum interrupters", XXI Int. Symp. on Disch. and Elec.Insul. in Vacuum, 2004 (submitted)

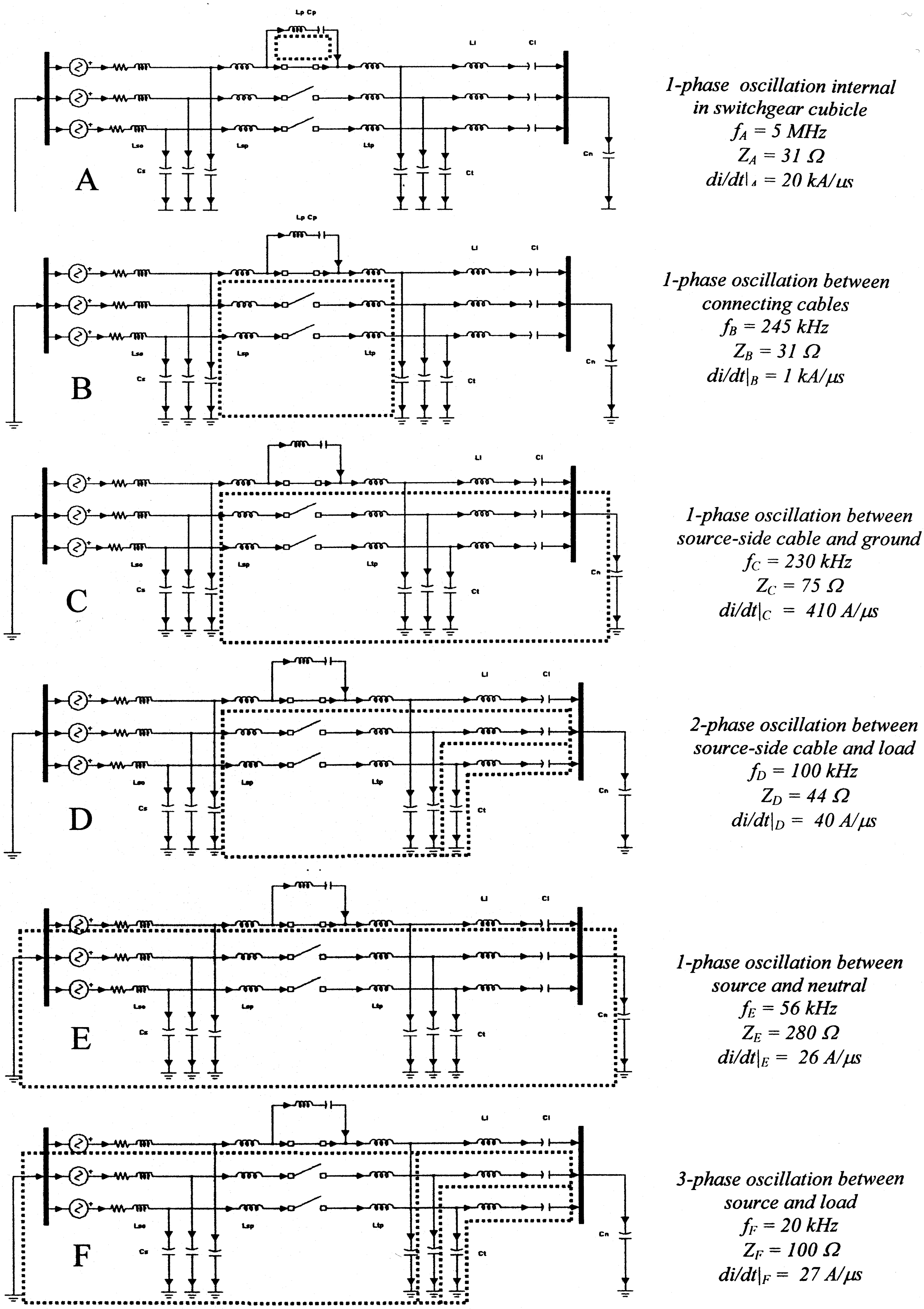

Fig. A: Identification of individual circuits that contribute to high-frequency current following breakdown of an interrupter pole in a capacitive circuit.