The duration of arcing following late breakdown in vacuum circuit breakers

Citation for published version (APA):

DOI:
10.1109/TPS.2005.856503

Document status and date:
Published: 01/01/2005

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
The Duration of Arcing Following Late Breakdown in Vacuum Circuit Breakers

René Peter Paul Smeets, Senior Member, IEEE, Davy W. Thielens, Member, IEEE, and Rob W. P. Kerkenaar

Abstract—Vacuum interrupters occasionally show unexpected (late) breakdown after current interruption. As a result, the interrupter conducts briefly, carrying a high-frequency current due to the discharge of various (stray) capacitances in the vicinity of the interrupter. Thanks to the capability of vacuum interrupters to interrupt such high-frequency current, the conduction period is normally very short (normally in the order of 10 μs). In the discussion around the assessment of such late breakdowns (often termed non-sustained disruptive discharges in the standardization literature) regarding the possibility of generation of overvoltage in capacitive circuits, the duration of the conductive period is an important parameter. Experiments were carried out, in which discharges of various single frequencies (72 kHz–1.1 MHz) were generated following breakdown (spontaneous breakdowns as well as prestrike) of two commercial vacuum breakers. It is demonstrated that the duration of the discharge depends strongly on the discharge current frequency. At higher frequencies, the duration of the discharge tends to be shorter than at lower frequencies. For practical circuits, allowing simultaneous discharge from various circuit parts, it was observed that the highest frequency component determines the arc duration. Duration of up to 15 μs was observed. This duration is too short to allow significant overvoltages to develop in standard capacitive power delivery circuits.

Index Terms—Circuit breaker testing, circuit transient analysis, high-voltage techniques, standardization, vacuum arc, vacuum breakdown, vacuum interrupter, vacuum switching.

I. INTRODUCTION

Occasionally, interrupters break down relatively long (up to 1 s) after the interruption of current and restore insulation immediately thereafter. This event is frequently observed in tests [1] and seems to be unrelated to the current being interrupted [2]. Usually, such a “late” breakdown is associated with vacuum switching devices, although (undocumented) observations of self-restoring breakdowns in SF6 switchgear have also been reported, indicating that this phenomenon may not be restricted to vacuum switching technology only. However, this investigation only deals with vacuum based phenomena.

In the International Electrotechnical Commission (IEC) 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 breakdown. This is due to the outstanding capability of vacuum interrupters to interrupt currents of very high frequency.

The duration of the disruptive discharge is subject of the present contribution. As of yet, the origin of the breakdowns is not fully clear. They are thought to be initiated by a combination of several mechanisms, the primary being mechanical vibrations, leading to the release of macro-particles [3] or to a sudden increase of field emission level leading to breakdown [4].

The interpretation and assessment of self-restoring late breakdowns have led to considerable discussion, particularly concerning what consequences, if any, they would have in real life circuits.

II. EXPERIMENTAL RESULTS

In an attempt to get more quantitative information on late breakdown phenomena, a large number of switching tests were performed at Eindhoven University of Technology [5]. To this aim, a test circuit was realized consisting of three oscillatory circuits (with oscillation frequencies of 1.1 MHz, 430 kHz, and 72 kHz), see Fig. 1, each of which will (start to) discharge upon breakdown of the test-breaker. The discharge frequencies are chosen such as to simulate the various circuit parts that will contribute to a high-frequency (HF) discharge upon breakdown of a interrupter in a real circuit; various stray capacitances and inducances will contribute to a multifrequency oscillation through the arc.

In the experimental approach described here, the three inductance-capacitance (LC) circuits are meant to represent circuit parts that are in the immediate vicinity of the gap (L1C1: 1.1 MHz), at some distance (meters) away from the gap (L2C2: 430 kHz), and relatively remote (tens of meters) from the gap (L3C3: 72 kHz).

Two commercially available vacuum circuit breakers (12 kV rating, CuCr based contacts) were stressed with alternating current (ac) recovery voltage up to 40 kV after interruption of a very small current (<1 A) from a high-voltage transformer. This very high recovery voltage was applied in order to give a higher probability of late breakdown. The (randomly occurring) late breakdowns were monitored with high-frequency digitizers.

It turned out that the frequency of occurrence of late breakdown differed greatly from breaker to breaker, and in order to obtain a sufficiently high number of results for both breakers,
the approach was chosen to monitor the first prestrike that occurs upon closing of the contacts.

Comparison of the discharge characteristics (oscillogram, breakdown voltage, duration of discharge, HF current interruption mode) of the prestrike discharge with the actual late breakdown discharge showed no difference. Thus, it is assumed that the processes that determine the duration of the first prestrike arc are equivalent to those governing the late breakdown arc duration.

A. Single Frequency Discharges

In the first series, discharges were monitored in oscillatory circuits of only one single frequency (L1C1, L2C2, or L3C3). A striking and very clear difference in discharge duration is observed. In Fig. 2 examples of the discharge current [Fig. 2(a)] and voltage across the interrupter [Fig. 2(b)] are given, together with the cumulative fraction of duration of HF current flow for each of the two interrupters (solid and dotted curves, respectively) and for each of the three discharge frequencies.

For each of the three frequencies, a different reignition mechanism can be observed.

1) L1C1 (1.1 MHz, typical discharge duration 10 μs): At this frequency, the transient recovery voltage (TRV) following HF current zero is not important. Apparently, \( \frac{di}{dt} \) of the current is decisive whether or not HF current is interrupted. Once the HF current is interrupted, the feeding capacitor is discharged to a large degree because of the high damping in the L1C1 circuit at this frequency (damping time constant 6.8 μs). In this mode, thermal processes determine the duration of the HF arcing.

2) L3C3 (72 kHz, typical discharge duration 60–100 μs): At this frequency, TRV rises after every HF current zero. Apparently, the gap is able to interrupt at every HF current zero, but the TRV thereafter cannot be withstood. Hence, dielectrical processes determine fully whether arcing will continue or not. Because of the lower frequency, the driving capacitor C3 can maintain its voltage relatively long (damping time constant is 83 μs).

3) L2C2 (430 kHz, typical discharge duration 20 μs): In this intermediate discharge frequency range, a mixture of both of the previous processes (L1C1 and L3C3) is present. Initially, at high \( \frac{di}{dt} \), this quantity determines the HF current interruption result. In a later arcing stage, when \( \frac{di}{dt} \) is reduced due to the damping in the circuit, TRV becomes decisive (damping time constant 21 μs).

In Fig. 3, an overview is presented of a large number of test. Herein, every dot represents a measured HF current zero, with its \( \frac{di}{dt} \) value on the horizontal axis and the voltage immediately following HF current zero on the vertical axis. The circled dots represent successful interruptions, with the voltage being the TRV peak value. The uncircled points indicate reignitions with the corresponding reignition voltage. The three curves are the
maximum possible (prospective) TRV peak values for the three circuits, given as: $U_{tr} = AI\left(dI/dt\right)_{i=0}$, with $A$ the overshoot factor and $L_i$ the circuit inductance ($L_1, L_2$, or $L_3$). In Fig. 3, the data of VCB B have been used.

From Fig. 3, it becomes clear that at $dI/dt > 200$ A/$\mu$s, reignition can follow without any voltage, whereas at values below $dI/dt < 200$ A/$\mu$s, initially the gap will interrupt at every current zero. In this lower $dI/dt$ range, due to the influence of the residue of the arc (charged particles in the gap, remnants of hot electrode regions, field intensification), reignition can follow at any voltage between zero and the maximum available voltage $U_{tr}$.

B. Multiple Frequency Discharges

In the second series, all three circuits were connected to the VCB, so that current consisting of three frequency components starts to flow upon breakdown of the interrupter. This is the situation in a real network, since upon breakdown, various subcircuits start to oscillate, each with their characteristic frequency. A typical current is shown in Fig. 4, together with the cumulative distribution of the three-frequency discharge duration. As can be seen, by comparison with Fig. 2, the duration of these multifrequency discharges seems to be 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 different rate of rise of the TRV at different frequencies.

Thus, it is concluded that the late breakdown discharge (which is believed to have similar characteristics as the prestrike discharge), has a duration in the order of 10 $\mu$s in realistic multifrequency circuits.

C. Observations in Three-Phase Circuits

Late breakdowns are observed frequently in high-power testing of vacuum interrupters [1], both at short-circuit current interruption, but equally well at (small) capacitive current interruption. Such tests, aimed at certification, are normally carried out in three-phase circuits which can lead to complicated transients due to the interaction of the three phases. Because of this interaction, a single breakdown in one phase can evolve into a breakdown of a neighboring vacuum interrupter phase. When this occurs, another situation arises, because much higher currents can start to flow.

This is outlined in Fig. 5, where a typical oscillogram (after interruption of a capacitive current by a vacuum breaker in a 38 kV circuit) is shown of three late breakdown events.

1) At 229.12 ms (see upper left), the middle phase breaks down, which can be recognized by the collapse to zero of the corresponding voltage across the breaker. Because the tests are usually carried out in an ungrounded circuit, the voltage jump in the middle phase is transferred to the other two phases, causing a voltage peak of 120 kV across the lower phase interrupter.

2) By this, the lower phase interrupter also breaks down. Now, there is arcing in two phases, resulting in a discharge current with a low frequency (57 kHz here) combined with a high amplitude and thus, as with the L3C3 oscillation of Fig. 2, the duration of the discharge is relatively long, here approximately 90 $\mu$s.
3) Finally, at 229.45 ms, a third breakdown occurs (in the middle phase), that initiates a discharge maintained by parasitic circuit elements resulting in a very high frequency discharge current with a typical duration of 10 μs, as with L3C3 of Fig. 2. This time is estimated, since high-resolution current measurement near the VCB is normally not carried out during testing.

In case of late breakdown in three-phase circuits, normally the latter (short-lasting) type of discharge is observed.

As outlined in Fig. 5, the path in which the discharge current runs, is essential for the duration.

**Situation 1)** This is the standard single phase (late) breakdown, causing only current of very high frequency and low amplitude in a path having high impedance. The duration of arcing is very short, typically < 10 μs.

**Situation 2)** This is the case when due to the three phase interaction, a second breakdown creates a path for a two phase current. This current has a much lower frequency but a much higher amplitude. Arc duration can be up to 100 μs. In this case, because another current path is involved, the discharge current frequency is much lower than in situation 1, but the amplitude is significantly higher. Depending on the ratio of capacitance on both sides of the breaker, there may be a discrepancy between practice in test stations and in network service, unaccounted for in the standards.

**Situation 3)** In this situation, the two conducting gaps do not succeed to interrupt the high-frequency current for situation 2 and a much larger part of the circuit becomes involved: the load capacitance discharges, and when even this low frequency current cannot be interrupted, followed by reestablishment of a power frequency current. Duration can be in millisecond range.

From test experience, all these situations are observed, but the situation 1 is dominant.

For standardization purposes, it is proposed to call the phenomenon occurring in situation 1 and 2 as an NSDD, and to reserve the term restrike for situation 3 [7].

### III. CONSEQUENCES FOR OVERVOLTAGE GENERATION

Considerable discussions have developed in recent years on possible consequences (if any) of late breakdown followed by a (very) short arcing period for the application in practical networks, and on the correct assessment in the standards [6].

The emphasis so far is on the capacitive switching (especially capacitor banks) where a considerable amount of energy remains trapped in the capacitive load after power frequency current interruption. During the discharge following late breakdown this energy might (partially) be released, which might lead to overvoltages in the process of redistribution of capacitive energy over the various parasitic elements.

In an attempt to model the single phase discharge (situation 1 of Section II-C) in a practical three-phase circuit [7], it is shown that the possibility of severe overvoltage generation is strongly related to the duration of the late breakdown discharge. This is because the oscillation that generates the highest overvoltages is associated with a circuit oscillation of relatively low frequency (several tens of kilohertz). In Fig. 6, the (sub)circuit that is responsible for such an oscillation is outlined by the dashed lines. In Fig. 7, the complete simulated discharge current, with all its frequency components, as well as the load side voltages, are shown. It can be seen that the theoretically maximum overvoltage of 5 pu (to be reached in the healthy phase, see the arrow) can only develop at sufficient duration of the discharge, i.e., at a duration longer than a quarter period of the relevant oscillation.

### IV. CONCLUSION

From single phase experiments, it has been observed that the duration of discharge after “cold” breakdown of a vacuum gap (either by prestrike either by late breakdown) is strongly depending on the frequency of the discharge current (10–120 μs in the 1 MHz–70 kHz range). In case the discharge current is composed of multiple frequencies, it is the highest frequency component that determines the overall discharge duration, which is observed to be in the order of 10 μs in a practical circuit.
Fig. 5. Oscillogram and equivalent circuit of single and two-phase late breakdown in a capacitive circuit.

Late breakdowns in a three-phase circuit (dotted lines are zero). First breakdown occurs in the middle phase, immediately followed by breakdown of the lower phase. Thus, situation 2 (see middle left) arises, path for a two-phase discharge. Ultimately, a third breakdown occurs in the middle phase, but this time without another phase breaking down. Thus, situation 1 (see upper left) arises, a single phase discharge path.

Fig. 6. Simulation circuit and discharge path causing most onerous overvoltages. Breakdown in upper phase at 2.5 per unit recovery voltage.
This is confirmed by results from certification tests in three-phase test-circuits: for the most frequently occurring single phase late breakdown, it is found that discharge duration lies in the 10 $\mu$s range. When the breakdown spans two phases, longer arcing is possible. Ultimately, the high-frequency current interruption capability will determine the arc duration.

From circuit analysis of overvoltages due to a single phase late breakdown in a three-phase capacitor bank circuit, it becomes clear that maximum overvoltages can be expected only after a time that normally exceeds the measured duration the discharge.

Thus, the short duration naturally limits the probability of overvoltage generation to a great extent.

However, care must be taken to generalize these findings.

1) The circuit can be such that the overvoltage generating oscillation can peak during the “normal” discharge duration.

2) In case the interrupter’s ability to clear high-frequency current is affected, the discharge duration will be longer than observed in the investigated test-objects. The results presented here have been obtained in vacuum interrupters with CuCr contacts. The conclusions may be different for other materials.

3) When two phases breakdown almost simultaneously, the situation becomes more complex and has to be judged case by case. Very long arcing (including re-establishment of power frequency current) is possible.

REFERENCES


Davy W. Thielens (S’99–M’03) received the M.Sc. degree in electrical engineering from Eindhoven University of Technology, Eindhoven, The Netherlands, where he also received the business and marketing management certificate, Faculty of Technology Management.

During his studies, he was an Intern for half a year at TSI, the Commercialized Research Department, Eskom, Republic of South Africa. He has participated in various projects since he joined KEMA, Arnhem, The Netherlands, in November 2003. Since November 2004, he has been employed as a Specialist at the High Voltage Installations Department (Transmission and Distribution), KEMA. He works on projects involving high-power engineering, magnetic fields, and influences on electrical systems.

Mr. Thielens is Member of the Royal Institute of Dutch Engineers (KIVI), the Technical Economic Society (TEG), and an Honorary Member of the Power Engineering Students’ Society, “Waldur,” Eindhoven University.


After fulfilling his military obligations at the Royal Military Academy (K.M.A.) Breda, the Netherlands, he joined the HOLEC firm HEEMAF, Hengelo, The Netherlands, as a designer of large asynchronous machines. From 1981 to 1985, he was educating power engineering and electronics at the two different polytechnic schools in The Netherlands. In 1985, he joined the group Electromechanics and Power Electronics, Eindhoven University of Technology, Eindhoven, The Netherlands. Since 1996, he has been working in the High-Current Laboratory, Eindhoven University of Technology, researching switchgear phenomena. His main interests are electrical machinery and switchgear. In December 2004, he retired.