Current-zero measurements of vacuum circuit breakers interrupting short-line faults

Current-Zero Measurements of Vacuum Circuit Breakers Interrupting Short-Line Faults

René Peter Paul Smeets, *Senior Member, IEEE* and Wim A. van der Linden

***Abstract*—Current zero measurements are performed during short-line fault interruption tests of vacuum circuit breakers. This switching cycle is characterized by a very steep transient recovery voltage. High-resolution measurements of near current-zero arc current and voltage were carried out. Various reignition modes (occurring between 0 and 75 ms after current zero) were observed due to insufficient arcing time or current in excess of the rated short-circuit breaking current. The relationship between post-arc current/charge, reignition mode, and transient recovery voltage is discussed in this paper. In addition to the "classical" post-arc current, already described in the literature, another "late" post-arc current was observed reaching values up to several tens of ampères after severe thermal arcing stress.**

All interrupters interrupted at the first or second current zero under the "rated" conditions of short-line fault current and transient recovery voltage.

***Index Terms*—Arc discharges, circuit breaker testing, current measurement, fault currents, plasma properties, short-circuit currents, switching transients, testing, vacuum arcs, vacuum interrupters.**

I. Introduction

CIRCUIT breakers are devices that interrupt fault currents in power supply networks, mainly through short circuits. Current interruption is by extinction of the high-current arc that is formed upon contact separation. Once such an arc is initially interrupted at fault current zero passage, the recovering contact gap is heavily stressed dielectrically by the transient recovery voltage (TRV) from the network.

In modern power distribution networks, TRVs with a very high rate of rise (up to a few kilovolts per microsecond) tend to occur more frequently than in the past [1] because of the following:

1) implementation of local generation because of the vicinity of transformers (coupling the generator to the grid) with an inherent small capacitance leading to high-frequency TRVs;
2) situations of voltage phase difference of generators and grid associated with (local) generator asynchronism because of high surge impedance of the relevant network parts [2];
3) increased use of current limiting coils for the reduction of fault current levels because of the inductive nature of the coils [3];
4) faults on the lower voltage side of transformers linking increasingly higher transmission voltage levels with distribution voltage [1].

An inventory of the situation was made by Conférence Internationale des Grands Réseaux Eléctriques Working Group (CIGRE WG) CC-03 [4].

Another case of a very steep TRV is a short-line fault (SLF), which is a fault on an overhead line a short distance (few hundred meters) from the breaker. Such a fault initiates traveling waves across the faulted line section, causing a very steeply rising triangular voltage transient.

Verification to cope with this very steep TRV is now included in IEEE Std. C37.04-1999. This standard requires SLF tests to be performed on circuit breakers intended for outdoor use that are connected to overhead lines with a rated voltage of 15.5 kV and above. Test conditions are described in IEEE Std. C37.09-1999.

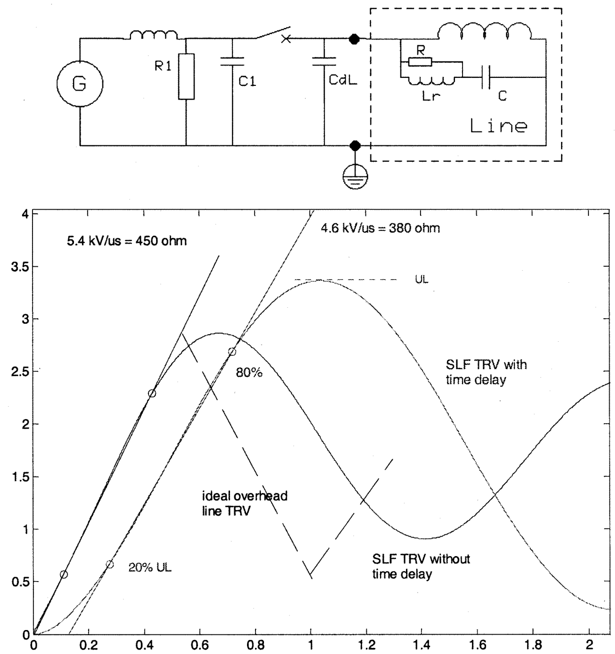

Fig. 1. Circuit simulating SLF TRV: from ideal line (dashed line), without and with time delay (standardized L90 duty for 24 kV/25 kA corresponding to 70 m equivalent overhead line length).

II. Test Circuit for SLF

When a breaker interrupts a short line fault, the source side circuit reacts with a relatively slow transient voltage, whereas

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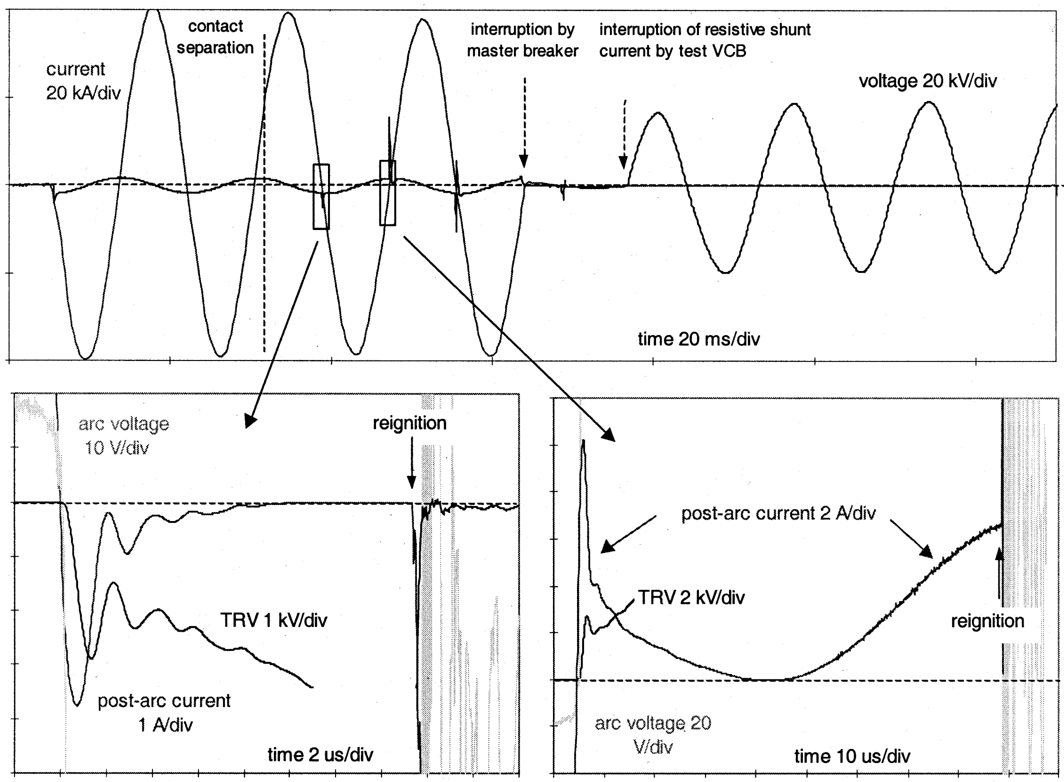

Fig. 2. Principle of multicurrent zero measurement of SLF interruption. After the first interruption attempt (enlarged, below left), the breaker reignites after approximately 15 μs. After the second interruption attempt (enlarged, below right), reignition occurs after approximately 95 μs, near TRV maximum. This reignition is preceded by a current, rising to 7 A, starting approx. 45 μs before reignition. The third reignition attempt (not shown) also fails, probably because of a too long arcing time. The current is interrupted by the laboratory breaker, which is shunted by a resistor, the small current of which is interrupted by the test breaker 15 ms later.

at the overhead line (OHL) side, a very fast triangular transient voltage wave arises due to traveling waves between breaker and fault.

Both transients contribute to the TRV. With an ideal OHL, the rate of rise of TRV (RRRV) is equal to $Z_L di/dt$, with $Z_L = 450\ \Omega$ the standardized characteristic impedance of the OHL and di/dt the rate of change of fault current at zero.

The triangular OHL voltage wave shape starts at current zero and reaches a peak value U_L after t_L (the transit time along the line to the fault and back). The peak voltage U_L is proportional to the reactance of the line multiplied by di/dt.

In the test laboratory, this part of the OHL is simulated by the basic circuit of Fig. 1 (dashed box, upper). Special care has to be taken to ensure realistic values of the rising edge parameters (time delay and rate-of-rise) because here, the dielectric stress to the gap is most critical. The exact reproduction of the triangular nature of the waveshape is of less importance, since the residual plasma already was able to cool down significantly at the moment of first TRV peak.

The initial RRRV is reduced by the presence of stray (or delay) capacitance Cd_L caused by stray capacitance between the breaker and the OHL. Such a time delay facilitates the interruption, since it allows the (forming) arcing gap recovery time before the onset of the TRV. The IEEE and IEC (International Electrotechnical Commission) allow for all medium voltage breakers a time delay $td_L = 0.2\ \mu$s. In test circuits, such a delay time is created by a capacitance, the size of which is derived from $Cd_L = \mathrm{td}_L/Z_L = 440$ pF.

For the very short length of faulted OHL, applicable in medium-voltage networks, delay time is a significant portion of the time-to-peak (typically 1 μs) and the effect is that the full (standardized) RRRV cannot develop fully after the time delay capacitor is inserted in the circuit once the circuit has been tuned to the standardized RRRV, as is common in testing practice. This is, however, no problem, since this is what occurs in practice due to the capacitance of, for example, measuring devices near the circuit breaker.

According to the standards, RRRV is defined by the straight line through the voltage ordinates of 20% and 80% of U_L (see Fig. 1, lower part), in this case leading to an equivalent characteristic impedance of 380 Ω.

Only faulted OHL lengths >250 m$(t_L > 8\ td_L)$ allow TRV to reach its full rated RRRV $= Z_L di/dt$.

III. Test Program

Single phase SLF tests were performed with three different vacuum interrupters (mounted in a single breaker) each rated 24 kV/25 kA. The tests were performed in KEMA's new medium-voltage test laboratory in a direct test circuit with an ac generator running at 60 Hz.

During the tests, current zero measurements were performed with a special measurement system [5]. Voltage and current are measured with a high-frequency ohmic voltage divider and a high-resolution Rogowski coil in combination with three custom made transient recorders (12-b resolution at 40 MHz

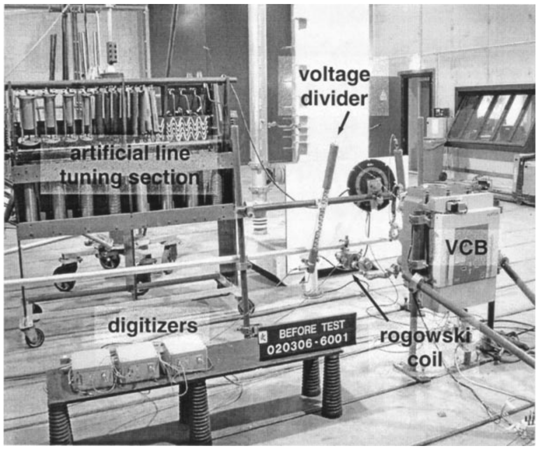

Fig. 3. Overview of setup in the laboratory.

sampling frequency) 2 m from the test object. Two of the transient recorders were used to acquire the voltage across the breaker: one capturing the arc voltage and the other the initial TRV, thus allowing unprecedented resolution in voltage (resolution 5 V, with maximum voltage of 7 kV). The third digitizer was connected to the Rogowski coil, allowing a resolution in current measurement of 50 mA with maximum current of 70 kA_{RMS}. As many as four arc zero crossings can be recorded per test.

Fig. 2 gives an impression of the current zero recordings related to the test current (here, 25% higher than rated). Fig. 3 shows an overview of the setup inside the laboratory.

The test program confronted each interrupter with an identical series of 14 SLF break tests, carried out within two test shifts of 8 h each.

IV. Reignition Modes

As reported earlier [6], the interruption process in vacuum can be characterized by a smooth continuation of current beyond current zero until the interelectrode gap is free of electrons, whereupon the ion sheath "sweeps" the gap building up the post arc current. This phenomenon can be observed in every test.

In a number of cases, reignitions can be observed in four types (A–D) by the time interval between current zero and reignition /restrike.

A) Immediate reignition (see Fig. 4, upper) on the rising edge of post arc current during the period electrons are still present in the gap: In gas circuit breakers, this would be called "thermal reignition." In vacuum, its origin is not clear.

B) Fast reignition (see Fig. 4, middle) during the post-arc current decay period, less than 1 μs after current zero. Here, the combined effect of the residual plasma and the influence of the electrical field is probably the cause of reignition.

C) Delayed reignition (see Fig. 4, lower) after decay of the post-arc current and after the peak of short-line TRV. Here, reignitions up to 130 μs after current zero (near the absolute peak of TRV) were detected. This type of reignition is probably induced by high value of TRV and has a mainly dielectric reason.

D) Late restrike (see Fig. 5) is very long (here, 75 ms) after interruption. Were these tests performed in a three-phase ungrounded circuit, this restrike would have been identified as a "nonsustained disruptive discharge" (NSDD). After restrike, in these (single phase) tests, the breaker was not able to clear on high-frequency current zeros or on power frequency current zero (Fig. 5, middle).

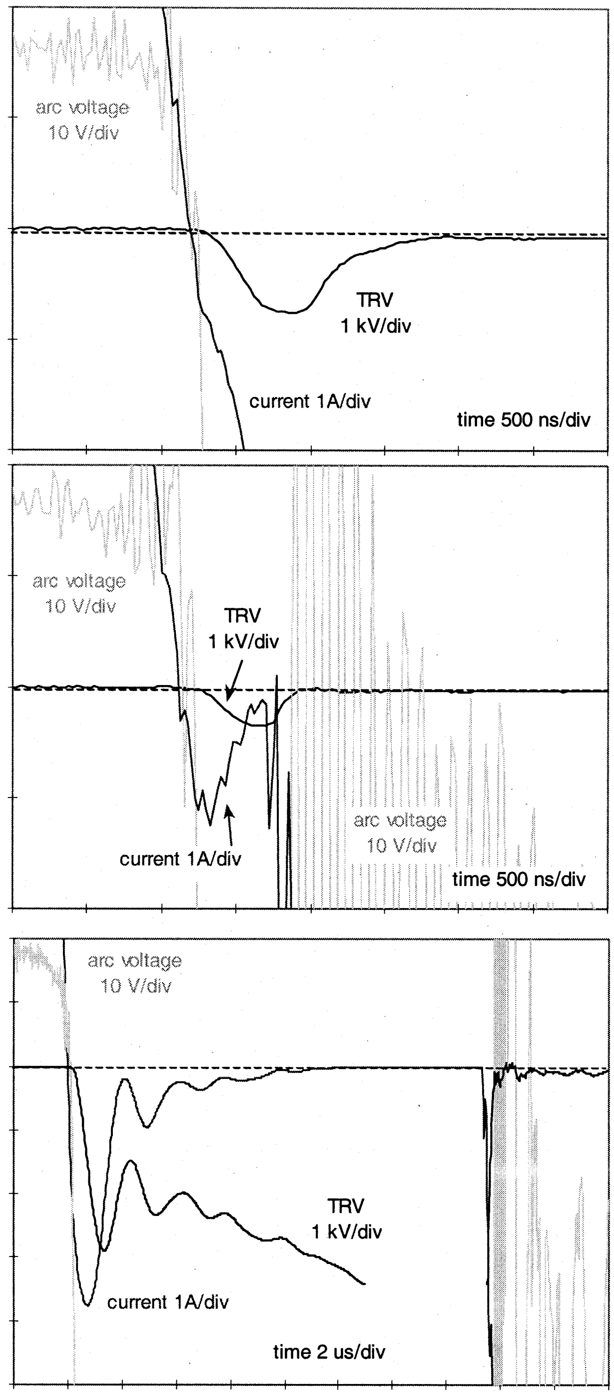

Fig. 4. Three reignition modes. Upper—immediate (A). Middle—fast (B, during post-arc current). Lower—delayed (C).

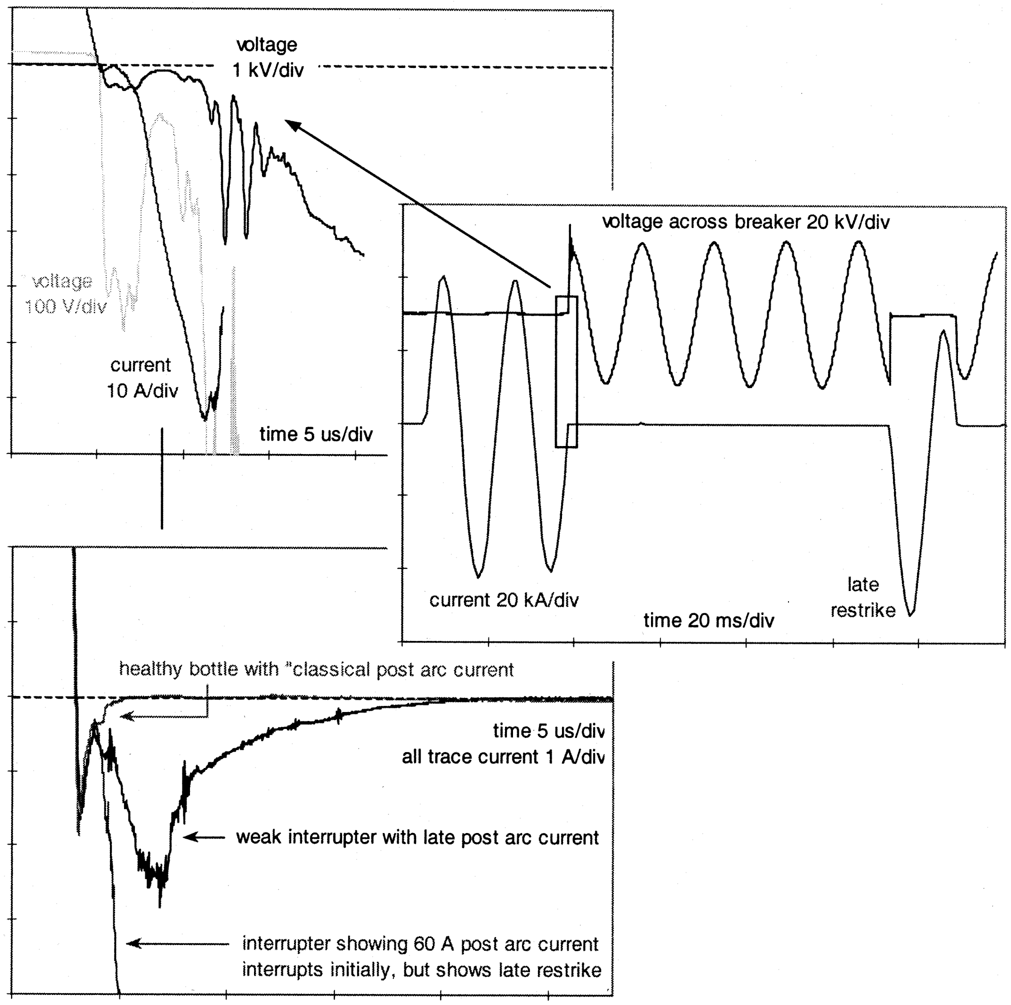

Fig. 5. Upper: Current zero detail of "late post-arc current" preceding late restrike observed at 125%. Middle: Late restrike. Lower: Comparison of "classical" post arc current, and two cases of "late" post-arc current in three interrupter designs at the same arcing time, both of which ultimately decay to zero, but one of which shows late restrike (as upper part of the figure).

In all tests "classical" post-arc currents develop, characterized by peak values of a few ampers and a duration of up to few microseconds (see Figs. 4 and 5, upper).

The oscillation on the tail of the post-arc current is due to a capacitive current, drawn by the TRV through the stray capacitance of the gap. It was found, that a constant value for this stray capacitance could not be used to compensate for this capacitive post-arc current component. Application of a time-dependent stray capacitance (because of decaying space charge in the gap) may give better results.

Sometimes, in addition to the "classical" post-arc current, extremely high "late" post-arc currents flow with peak values up to 60 A and durations up to tens of microseconds still ultimately decaying to zero and not leading to reignition (Fig. 5, upper and lower).

The single late restrike (current 25% higher than rated) was preceded by such a "late post-arc current."A relationship between late restrike (Fig. 5, middle) and an abnormal condition of the interrupter cannot be excluded.

Fig. 5 (lower) shows post-arc current of three tests under similar conditions (125% rated current) from three interrupters, two of which show "late" post-arc current. Its physical origin is not clear, but it is probably related to unacceptable thermal stress by the arc.

V. Influence of SLF-TRV Shape

Tests were carried out with four different equivalent lengths of "artificial" overhead lines (simulation circuits of overhead line, all with 0.2 μs of time delay) of: 10 m (no line at all, simulating a short-circuit directly at the breaker terminal); 70 m of OHL (570-kHz oscillation frequency), which is the standardized L90 test condition for the breaker under test; and 140 m (350 kHz) and 250 m (200 kHz). Supply circuit parameters were adjusted to keep current (and, thus, RRRV) constant. The only difference thus is the duration of continued voltage rise.

In Fig. 6, post-arc currents, drawn by the various TRVs are shown. Post arc current duration seem to be strongly influenced by the time to TRV peak.

It is observed, that for a given TRV, the post-arc charge is proportional to arcing time. This is easy to understand, since a longer arcing time (associated with a larger contact gap at current zero) corresponds to more charge carriers in the gap that take longer time to be collected. Therefore, a "normalized"

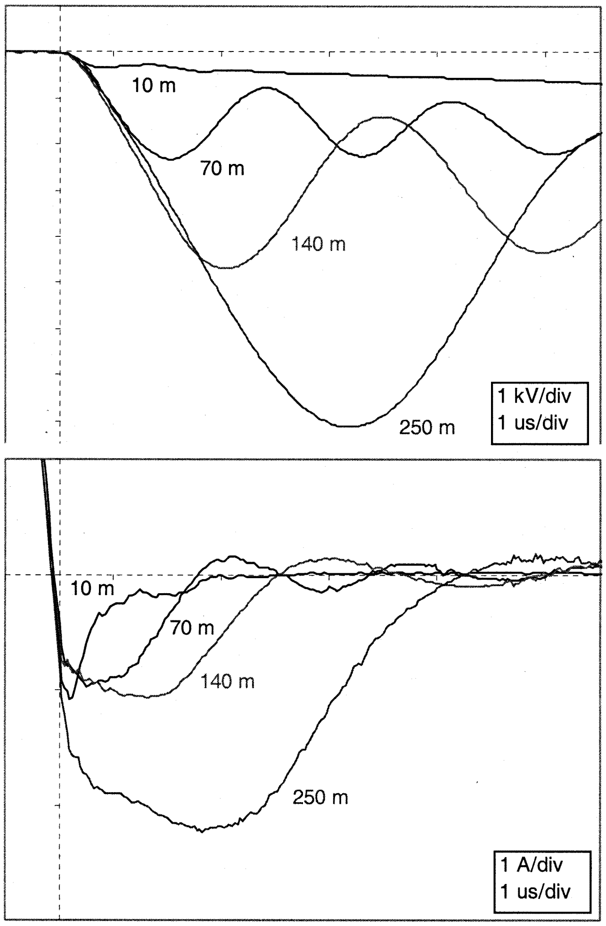

Fig. 6. Measured post-arc current (lower) caused by TRV (upper) of various line length (current, RRRV, and arcing time kept constant).

quantity is defined: $\mathcal{Q}_{\mathrm{ta}} = \int_{\mathrm{cz}}^{\infty} \mathrm{idt}/t_a$, the collected post-arc charge divided by the arcing time (t_a).

In Fig. 7, the cumulative distribution of this quantity is plotted for all the tests (at constant current) for the various OHL simulations. As can be seen, the longer OHLs draw significantly more post-zero charge than the shorter lines. This is probably attributable to the longer duration of the TRV to rise to its peak value.

Assuming a higher severity of interruption with higher post-arc current (at constant gaplength), greater difficulty is expected to interrupt under conditions of a continuing steep TRV.

From the tests, the impression is obtained that post-arc current is very sensitive to initial TRV, as is illustrated in Fig. 8. Without artificial line, when the initial TRV (ITRV) is determined by the busbar length of approx 10 m, the ITRV step in voltage immediately following interruption (step of 850 V within 300 ns) causes a post-arc current of 2 A. When this ITRV step is damped by a capacitor directly across the breaker, the post-arc current duration is significantly reduced.

VI. Overview of Complete Series

To relate the SLF interruption performance of different interrupters to post-arc current, the ratios of peak post-arc current /arcing time are collected in one "performance" chart. This chart is shown in Fig. 9.

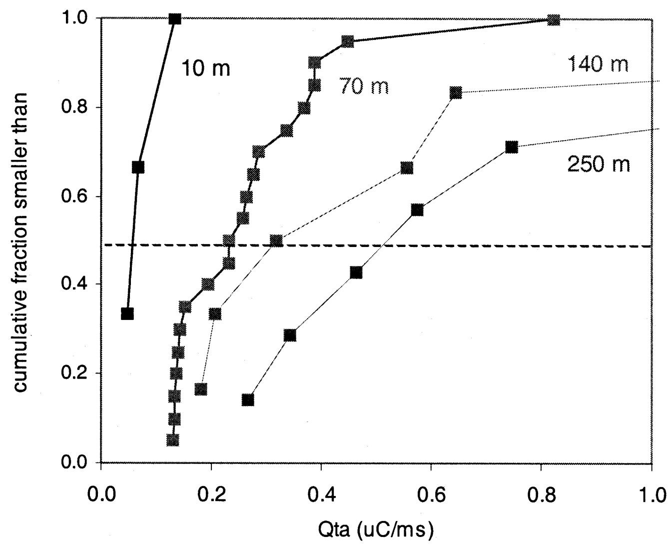

Fig. 7. Cumulative distribution of ratio of post-arc charge/arcing time for four different equivalent overhead line lengths (RRRV kept constant).

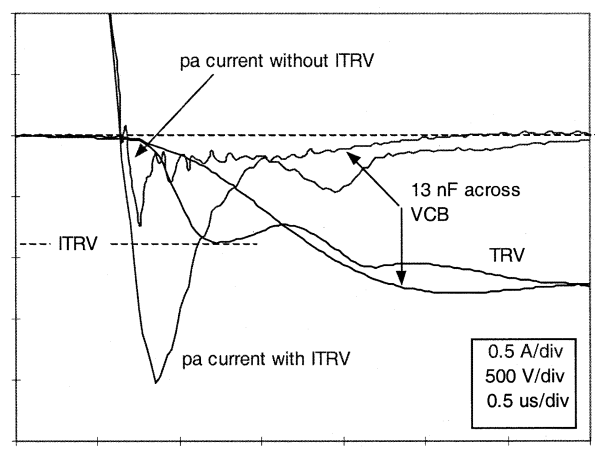

Fig. 8. Comparison of post-arc current (pa current) with initial TRV (ITRV) and without initial TRV across vacuum circuit breaker (VCB).

Three tests (one on each interrupter) were performed with the same current, arcing time, and line length (see horizontal axis), forming one of 14 groups. Cases of reignition/restrike are indicated with arrows. These are mostly due to insufficient arcing time, but lead in one case to failure—without initial interruption—(current interrupted by laboratory master breaker) and in one case to a late restrike. Both failures were preceded by unusually high post-arc current: the direct failure by a "classical" post arc current of high value (10.2 A) and the late restrike by a "late post-arc current" of 60 A (see Fig. 5).

From the tests, it is clear that reignition is very often, but not always, related to a high ratio post-arc current/arcing time. In all but one case, if the ratio post-arc current peak/arcing time is >0.5 A/ms, the breaker reignites, restrikes or does not interrupt.

VII. Conclusion

The test results prove an adequate interruption performance of the three tested interrupters with respect to short-line fault TRV. This may reflect the ability of metal vapor in vacuum as

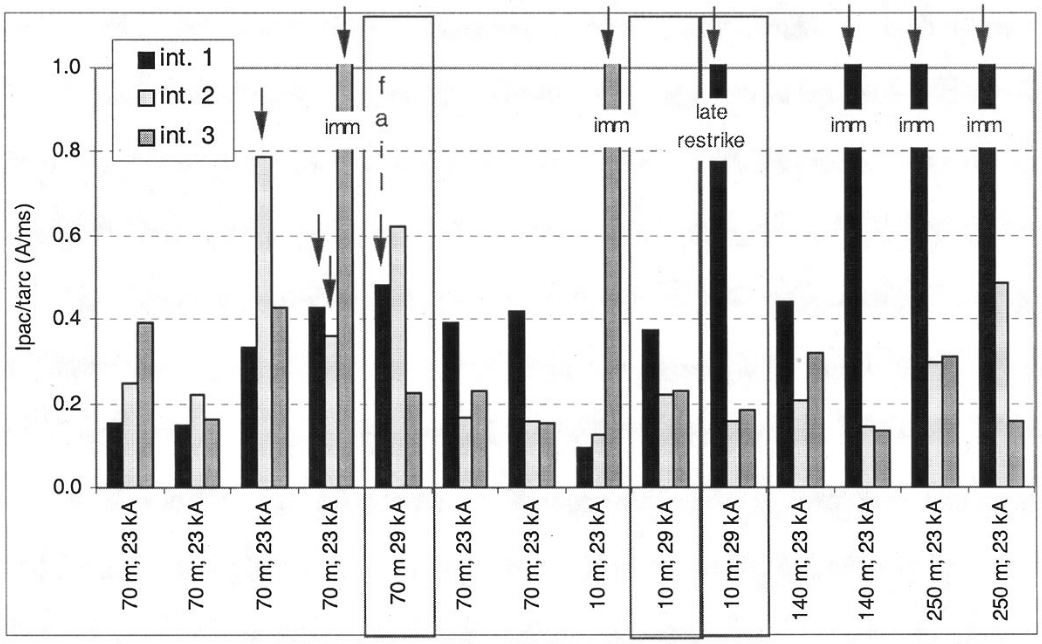

Fig. 9. Performance chart of three interrupters (1–3) each subjected to 14 similar tests. Vertical: peak of post-arc current/arcing time at first current zero after contact separation. Horizontal: current and OHL length. Arrows indicate reignition/late restrike/failure; boxed series indicate current 125% of rated value; imm: immediate reignition (post-arc current peak value not evaluated) fail: failure to interrupt.

an interrupting medium to generally have few problems (compared with SF6) with steep rising transient recovery voltages in combination with adequate handling of the high-current arc energy by well-designed arc control measures (axial and/or radial magnetic fields). Only when the current is increased to 25% above the rated value, do differences in performance between the interrupters tested here become clear. In this study, different reignition modes are observed. Their physical explanation remains unclear and will be clarified in follow-up studies.

Post-arc current at SLF-TRVs are higher and have longer duration than in terminal fault tests having higher current but reduced rate of rise of TRV (Fig. 6).

Post-arc currents associated with reignitions are usually, but not necessarily, larger than in the case of interruptions.

Failure to pass tests is found to be associated with even larger "late post arc current," that may be a sign of distress of the interrupter. The increasing post-arc current duration (and magnitude) with TRVs having longer time to peak, suggests that such TRVs may be more severe for vacuum interrupters than TRVs having higher frequency but lower amplitude.

Translated to the practical situation, test cycles with lower than 90% SLF current (L90) may be more severe. IEEE Std C37.09-1999 requires three opening operations at 90%–95% short-circuit current and three opening operations at 70%–80%. These values are directly taken from high-voltage SF6 test practice and, having a different recovery characteristic, may be reconsidered for vacuum.

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