In Search for Performance Indicators of Short-Circuit Current Interruption in Vacuum

R.P.P. Smeets, E.P.A. van Lanen, M. Popov, and L. van der Sluis

Abstract - Current interruption in vacuum is characterized by a very rapid transition from an almost perfectly conducting arc plasma state to a very good insulating state. During the transition, the recovery process determines the success of the interruption.

The aim of this contribution is to derive characteristics from measurements of the initial ("current zero") stage of this recovery process, having the potential to indicate the quality of the interruption.

In the case of vacuum, a large number of measurements has been performed giving detailed information on the recovery process during the decay period of the post-arc plasma. The best-known indicator is the post-arc current, drawn from the decaying residual plasma by the transient recovery voltage. It turned out from measurement statistics, that post-arc current quantities (duration, peak value, charge) alone are not suitable as performance indicators. In addition, the role of conductivity (evolution) is examined, also showing not a very strong relationship with performance.

It must be concluded that current-zero performance indicators for vacuum interruption are more difficult to define than for SF6 interruption. This suggests that vacuum interruption success is strongly related to dielectrical stesses, that are still relatively mild in the current zero period of a few microseconds duration.

I. INTRODUCTION

Current interruption in vacuum, as practically applied in vacuum circuit breakers, is strongly related - at least in the initial several microseconds - to the capability of the interrupter to change its conductivity from very large (in the arcing phase) to almost zero (in the isolating position) in a very short time. During this "recovery" period, a residual plasma (the post-arc plasma), remnant from the arc, should decay against the rapidly developing (circuit generated) transient recovery voltage (TRV) across the plasma, drawing the so-called post-arc current from the plasma.

Earlier research, combining current-zero measurements and modelling [1, 2, 3] has contributed to the understanding of the post-zero processes of current interruption in vacuum [4].

From R&D point of view, it would be desirable to derive characteristics (from measurements) of the initial stage of this recovery process having the potential to indicate the "quality" of the interruption. With such indicator(s), the performance of the interrupter under the specific test conditions in terms of (arc) current and (recovery) voltage should be quantified. Such performance indicators shall allow evaluation of tests not just in terms of "pass" or "not pass", but may quantify a margin (in a positive or a negative sense) from a certain critical value of the indicator.

Such an approach has been successful in short-circuit current interruption in SF6 interrupters, generally applied at high voltage. In SF6, the measured arc conductivity 200 ns before current zero has been shown to be a very good predictor of interruption or failure [5, 6]. This result has triggered the authors to search for equally straightforward performance indicators in the case of vacuum interruption.

II CANDIDATE PERFORMANCE INDICATORS

For industrially produced vacuum interrupters, measurable quantities during the interruption process are usually limited to current and voltage. During short-circuit tests, measurement systems having extreme resolution in magnitude and in time are necessary [7], given the very low arc voltage (few tens of volt) before current zero and the small post-arc current (few amperes) of very short (few microseconds) duration after interruption.

Moreover, just before current zero, there is a constant and low arc voltage and vacuum arc conductivity is high, up to the very moment of current interruption. This leads to the conclusion that there is no noticeable interaction with the external circuit before current zero. After current zero, post-arc current is normally a few to several amperes, and due to this, the period in which the circuit interacts with the (former) arc is limited to this time domain.

In the case of arcs in SF6, the situation is completely opposite, as the table below summarizes.

<table>
<thead>
<tr>
<th>medium</th>
<th>arc voltage before current zero</th>
<th>post-arc current after current zero</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF6</td>
<td>few kVpk; changing</td>
<td>10 - 50 mA</td>
</tr>
<tr>
<td>vacuum</td>
<td>few tens Vdc; constant</td>
<td>several A</td>
</tr>
</tbody>
</table>

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From this, it becomes clear that performance indicators for vacuum, if any, have to be be sought in the time domain after current zero, whereas in SF6 this is the case before current zero.

A. Post-arc current
The post-arc current has been subject of investigation for many years, since it is one of the most distinctive electrical phenomena of short-circuit current interruption with vacuum interrupters. Because the post-arc current shows a clear relation with the arcing conditions, it is reasonable to assume that it reflects the conditions inside the breaker immediately after current zero. This could provide researchers with a tool to investigate the interruption performance without having to open the interrupter to look inside. However, the post-arc current contains, unfortunately, a considerable scatter that masks a possible relationship between the arcing conditions and the post-arc current, see for example fig. 1, showing typical post-arc currents from two tests in succession with identical parameters.

This is probably due to the final position of the last cathode spots which, until now, can only be determined by inspection of the inside of the interrupter (see fig. 2).

Nevertheless, a relationship can be found between arcing stress and post-arc current. Plotting the peak value of post-arc current (i_{pa}) as a function of arc duration (from a test series with 50 Hz current 25 - 35 kA and rate-of-rise of recovery voltage (RRRV) 7.5 - 14 kV/μs), a significant increase of post-arc current can be identified for an arc duration > 7 ms, as expressed in fig. 3. It can be safely assumed that this indicates a significant increase of electrical stress, although no sign of failure to interrupt is observed yet.

In standard tests, the contribution at increased arc duration to the post-arc current is two-fold: longer arc duration (higher thermal stresses to the electrodes) and increased contact distance (larger post-arc plasma volume). Which of the two contributes most cannot be concluded easily from such tests.

It is even more challenging to find a relationship between post-arc current magnitude and interruption success/failure. Several cases are observed in which very large post-arc currents (up to many tens of ampères) are observed, without failure to interrupt. Fig. 4 shows some post-arc current traces, two of which ("late" and "extreme") are intuitively sign of approaching an interruption limit. This, however could not be confirmed by test-results: the current was interrupted even with exceptionally large post-arc current. The fact that - through interaction with the circuit - high post-zero conductivity results in mitigation of the transient recovery voltage (TRV) may be one of the decisive factors for this behaviour. Similar experiences were gained with vacuum generator breakers for very high current [8].

These post-arc current phenomena cannot be explained with the models published so far.

B. Post-zero conductivity
By quantifying the voltage across the post-arc plasma,
the (development of) conductivity can be evaluated. This seems to be a more straightforward approach, because conductivity, by definition, includes the arc-circuit interaction automatically.

Typical conductivity traces are shown in fig. 5 for three values of TRV rates-of-rise. Note the very rapid (the vertical scale is logarithmic) recovery. Here, the circuit does not influence the conductivity until approx. 1.5 μs after current zero, inspite of the widely varying current and voltages during this period.

A clear observation from fig. 5 is that the fastest recovery (in terms of conductivity) coincides with the steepest TRV and the highest post-arc current.

The next step is to consider the arc conductivity (G) at a certain instant after current zero, for example G0.5: the conductivity 0.5 μs after current zero. There is a clear dependence of G0.5 on the arc duration, as demonstrated by fig. 6, where two different circuits have been used. It can be recognised that the relationship between the conductivity-indicator G0.5 and stress (here arc duration) is more evident than between post-arc current peak Ipa and arc duration (cf. fig. 3), although a varying current (fig. 6b) introduces a considerable scatter again.

### C. Post-zero charge

The integrated post-arc current, Qpa = \( \int I_{pa} \, dt \), quantifies the charge present in the intercontact gap. It has been demonstrated that a clear relationship exists between post-arc charge and conductivity at a specific instant after current zero. If the interrupter's conductivity after current zero is small, little charge can transport through the gap, whereas the opposite is true for a high post-arc conductivity. As a result, the post-arc charge is proportional to the post-arc conductance. This is depicted in fig. 7. Although the results shown in this figure are from measurements with different arcing times, they show a distinctive trend.

Vapour particles are either generated directly by a cathode spot, or indirectly by vaporisation from the anode. If (after current zero), the amount of vapour is related to the amount of charge, then the post-arc charge Qpa might be an indicator for the amount of vapour at current zero. However, it is impossible to calculate Qpa when a reignition takes place during the post-arc current, since the determination of Qpa requires the entire post-arc current. Qpa relates rather linearly to G0.5 (see fig. 7), and its coefficient changes only with the TRV values. In the first microsecond after current zero, the TRV is generally rather low, and probably for this reason, the gap only occasionally re-ignites during this time. Therefore, it is always possible to measure G0.5 within the first microsecond, and with a fixed coefficient, it is possible to determine Qpa even if the gap re-ignited during a post-arc current. This leads to the idea of investigating G0.5 (as an estimator proportional to vapour pressure) times contact distance (d) in order to find a critical value to discriminate between interruption and re-ignition. Such a reasoning would hold in the mechanism of vapour-induced Townsend-type breakdown as an early failure mechanism in vacuum.

Fig. 8 shows G0.5d of 30 measurements from one test series (current 25 - 35 kA, arc duration 1.5 - 9.6 ms and equal RRRV). It shows a smooth transition from values of G0.5d for which "early" re-ignition is rare to values for which "early" re-ignition occurs more frequently. Beyond G0.5d = 70 mm.F\(^{-1}\) (indicated in fig.7 with the dashed line) the test object always fails.
In vacuum, from current-zero analysis, the following types of re-ignition can be distinguished:

a. Immediate re-ignition (on the rising edge of post arc current) during the period that electrons are still present in the gap. The occurrence of this type is very rare, and has been observed exclusively when the rated current short-circuit current of the breaker is exceeded significantly [7]. This type of re-ignition is observed frequently in SF6 ("thermal" re-ignition), and is the reason to verify its absence with the so-called "short-line fault" tests.

b. Early re-ignition (during the post-arc current period); this type of re-ignition occurs only rarely. This is also called sometimes a thermal re-ignition, initiated by post-arc current and initial TRV input of energy into the ex-arc plasma.

c. Delayed re-ignition (after decay of the post-arc current). In this case, re-ignitions occur under the influence of a TRV close to its peak value. The vast majority of re-ignitions fall into this category.

d. Late re-ignite (> half power frequency cycle after interruption). In switchgear standards, this failure is called "restrike" in stead of re-ignition. These re-strikes are commonly called "non-sustained disruptive discharge" (NSDD), and are inherent to vacuum switchgear. They seem to be independent from current zero phenomena.

Attempts to relate the voltage at which re-ignition starts with $G_{0.5}d$, in order to reconstruct in this way a Paschen-type vapour related breakdown curve, were not succesful [3].

### III RE-IGNITION

Straightforward current-zero performance indicators for short-circuit current interruption can not be readily identified. It has been demonstrated that post-arc current on its own is not a suitable measure for interruption performance because a large post-arc current can mitigate initially the effect of transient recovery voltage.

The arc conductivity, as a measure for recovery seems to be a better candidate: multiplication of this conductivity (shortly after current zero) with current-zero contact distance has shown to have value in establishing a critical distinction between interruption and re-ignition.

A reason for not being able to identify near-zero indicators could be explained by the fact that re-ignition occurs (as observed) mostly after the post-arc period at relatively large values of the transient recovery voltage. This could imply that in vacuum - unlike the "thermal region" in SF6 - the current zero region is of less importance in the interruption process than the elevated TRV-related dielectrical stresses at a later time. The experience from testing, that well-designed vacuum interrupters normally show minor problems with steep values of TRV may support this assumption.

Hundreds of tests in direct as well as in synthetic test circuits, with transient recovery voltages rising far steeper than the standardised value for the short-line fault test-duty value in IEC 62271-100 suggest that typical "thermal re-ignitions", as known from SF6 circuit breakers are rare events in vacuum.

Further study should reveal whether this test-duty, newly introduced in the circuit breakers standards, is really relevant for vacuum switchgear.

### REFERENCES


