# INVESTIGATIONS OF CURRENT INSTABILITIES BEFORE CURRENT ZERO FOR TYPICAL LOAD SWITCHING APPLICATIONS

Patrick Halbach[1]*, Benjamin Baum[1], Volker Hinrichsen[1], Kristian Ermeler[2], Jörg Teichmann[2]

[1] Technische Universität Darmstadt, Germany, [2]Siemens AG, Germany

*Email: halbach@hst.tu-darmstadt.de

**Abstract**: The first part of this contribution is concerned with the phenomena that occur during measurement of chopping currents. Here, the influences of the contact materials as well as the test circuit parameters with resistive and inductive loads are discussed.
For further comparison with former research as published in the literature the definition of the copping current used in this paper is presented and discussed. It is shown that chopping current is influenced by the test circuit parameters, which in many cases have not been published, thus making meaningful literature evaluations difficult or even impossible. It is therefore recommended for future investigations to better specify test parameters and to publish them together with measured data. To compare the measured data with the current physical understanding, a theoretical model based on the differential equation system concerning the extinction of a vacuum arc near current zero crossing is introduced. Special attention is given to the oscillating instabilities of the current at inductive load, which result in current chopping before the natural current zero.
The last part of this contribution compares measured data with simulation results and presents the correlations and limitations of the used model.

## 1 INTRODUCTION

In recent years, vacuum- technology has been established as a standard technology for switchgear at the medium-voltage distribution level. Nowadays the main research and development effort is the extended use of vacuum breaker towards other applications. One specific application is to establish the vacuum-technology at high-voltage transmission levels, and a second one is to optimize the present designs for use as medium-voltage load breakers. This makes sense for economical and ecological reasons.

Although vacuum-breakers have many advantages such as higher switching capacity, higher number of switching operations and smaller dimensions, the underlying principle of switching in vacuum has several drawbacks. In contrast to $SF_6$-breakers, the current in a vacuum-breaker is chopped before its natural zero-crossing. A consequence are overvoltages when switching high inductive loads. These overvoltages may damage the load-side equipment and even exceed the dielectric strength of the vacuum-breaker itself.

Previous publications have shown that in general smaller current levels cause higher overvoltages due to current chopping [1][2]. Normally a load breaker has to switch smaller currents in contrast to a circuit breaker [3]. In addition, a load-breaker also has to handle a large number of operations. Especially in combination with inductive loads like transformers or coils the generated overvoltages may lead to failures of the equipment. Furthermore it is known that the equipment itself affects the phenomena of current chopping. However, up to now no standardized test circuit for measurements of chopping currents has been introduced. Without such standardization no comparison of any measured data is possible. In addition to a standardized test circuit a uniform definition of the chopping-current has to be introduced as well.

To determine the influences of parameters that influence the chopping-current, investigations with different contact-materials and test circuit parameters have been performed.

In order to achieve a deeper understanding of the transient currents near the current zero, simulations have been performed. For this purpose a model is applied which is based on a specific theory concerning the phenomenon of current chopping. It is thus possible to investigate the influence of any test circuit parameters. The results of this investigation have been experimentally verified in a test circuit. Limitations and conformities of the applied model as well as the consequences for the future test circuit or possible applications are presented.

## 2 TEST-CIRCUIT

According to the literature, different test circuits were used to determine chopping currents. A series connection of an inductor, a capacitor and a resistor was shunted parallel to the investigated switch for most of the investigations. Some studies already exist, which show the influence of the test circuit [4]. For this work a circuit has been developed that is based on the load breaker standard IEC 60265-1 [5]. The essential difference to previous studies is that it is clearly distinguished between source and load impedance. The load impedance is built by a parallel connection of an inductor and a capacitor. **Figure 1** shows this test circuit for one-phase tests.

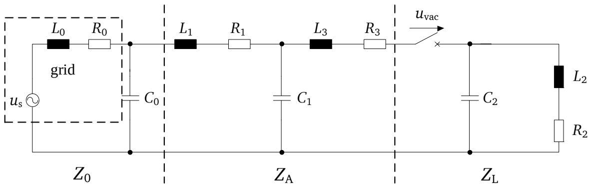


**Figure 1:** Applied test circuit

The actual test circuit is built according to Figure 1, based on the guidelines given in the standard. A series connection of inductor and resistor is used in order to have no damping effect by a parallel resistor, thereby resulting in more critical overvoltages. A one-phase supply voltage of 230 V (r.m.s.) is used as power source (source impedance $Z_0$). The supply side impedance $Z_A$ (with $Z_s = Z_0 + Z_A$) is realized by $L_1$, $R_1$, $L_3$, $R_3$ and $C_1$, the load side $Z_L$ by $R_2$, $L_2$ and $C_2$. Thereby, $C_2$ represents the capacitance between the switchgear and the inductive load. Unlike in the test circuit of a previous study [6] the parameters $C_0$, $L_3$ and $R_3$ are added. The current measurement is performed by a configuration of two anti-parallel high current diodes, which are parallel connected to a low-resistance ohmic shunt. Thus an accurate measurement of currents smaller than 30 A becomes possible through a Pearson current transformer (Type 110, bandwidth: 20 MHz). By choosing appropriate circuit elements in the load circuit a setting for the required total current and power factor cos $\varphi$ was possible. Measurement of the total electric current was performed by a LEM transformer (Type HTA 1000-S). For measuring the overvoltages on the load side terminal a damped-capacitive voltage divider with a low self-capacitance (47 pF) was employed. The individual test circuit parameters were dimensioned as follows:

| | | |
|---|---|---|
| $C_0$ | = | (0.03…50) nF |
| $C_1$ | = | (0.03…50) nF |
| $C_2$ | = | (0.03…100) nF |
| $L_1$ | = | (0…0.26) mH |
| $L_2$ | = | (0…12) mH |
| $L_3$ | = | (0…0.26) mH |
| $R_2$ | = | (0…12) Ohm |

## 3 GENERAL EFFECTS

As already known from the literature [7], for certain test circuit setups the vacuum arc current may oscillate at a high frequency (up to several 100 kHz), when the current decreases and approaches current-zero. Finally, these oscillations, especially those of high amplitudes, may lead to higher chopping currents. In general, it can be stated, that the oscillations are superimposed to the power-frequency (here: 50 Hz) current. They are caused by a series resonant circuit which is excited based on instabilities in the metal-vapor-arc. These instabilities may occur, if individual cathode spots are no longer fed with the necessary energy to keep the spots alive. Due to the frequency dependent load impedance, the high frequency component of the current flows through $C_2$, while only the 50 Hz component passes $L_2$. Therefore, an overvoltage according to formula bellow is generated.

$$u_{max} = i_{ch,\,50\,Hz} \cdot (L_2/C_2)^{0.5} \qquad (1)$$

Here, $i_{ch,\,50\,Hz}$ is the current value through $L_2$ when the current is chopped. In addition, formula 1 states, that the chopping current can be calculated by the related overvoltage, if $L_2$ and $C_2$ are known. **Figure 2** shows the overall arc current, its 50 Hz component and the related overvoltage.

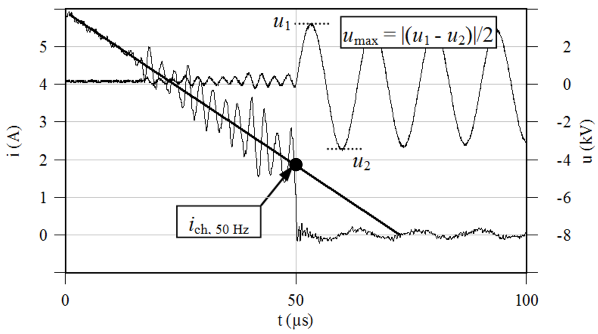


**Figure 2:** Current chopping with high frequency oscillation, 50 Hz component and transient recovery voltage

## 4 EFFECT OF CONTACT MATERIALS

Different contact materials in the form of plate electrodes were investigated. The gap distance of the industrially manufactured vacuum bottles was adjusted to 6 mm. The test series was performed with different values of $C_2$ (30 pF…50 nF) for any contact materials. The contact separation was specially tuned to achieve arc extinction in the first current half-wave. The arcing time was in the range of 5 to 6 ms. Depending on the test circuit setup with a power factor of 0.3, the effective current level was 150 A and 630 A respectively. For each configuration $n$ = 20 switchings were performed.

Various compositions of copper-chromium, different in their manufacturing process, were used. Furthermore, cost-effective materials such as pure copper or stainless-steel were investigated.

The results of these investigations are presented in **Figure 3** and **Figure 4**. It can be seen, that the differences in the chopping current are negligible concerning different compositions of copper-chromium and stainless steel. Only the chopping currents of pure copper are considerably higher. However, it is obvious that the influence of the test circuit elements – in this case $C_2$ – have to be considered. Influences caused by other elements will be explained in more detail in chapter 5.

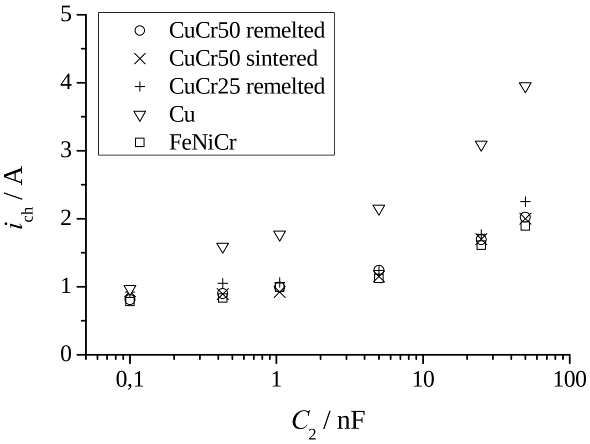


**Figure 3:** Dependence of parallel capacitance and chopping current for different materials with *I* = 630 A

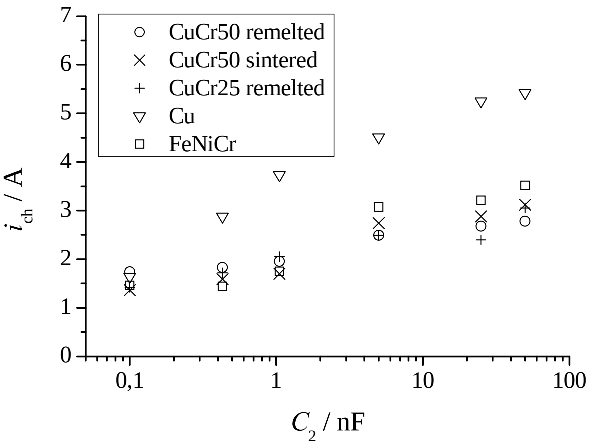


**Figure 4:** Dependence of parallel capacitance and chopping current for different materials with *I* = 150 A

## 5 EFFECT OF TEST-CIRCUIT PARAMETERS

Obviously, the value of the chopping current strongly depends on the value of $C_2$. Especially for small load capacitances, low chopping currents are measured, because most of the oscillations are suppressed. The larger the values of $C_2$, the higher oscillation amplitudes may arise, which in the end leads to an earlier and thus a higher chopping current. This phenomenon can be seen in Figures 3 and 4.

Furthermore, it can be shown, that the elements $L_1$, $L_2$, $C_0$ and $C_1$ are not negligible as well. The values of the main elements are in accordance to the standard IEC 60265-1. However, the parasitic capacitances and inductances on the supply side were replaced by discrete elements. Their relevance will be shown in chapters 6 - 8 when comparing the simulation results with the measured results.

The load side elements determine the current through the vacuum interrupter. As it can be seen from Figure 3 and 4, chopping currents are usually higher for a lower total current level.

## 6 DESCRIPTION OF THE THEORETICAL MODEL

The applied model is based on the energy balance of a *single* stationary cathode spot as described by Lippmann [8]. Here, both the ohmic losses due to electron and ion current flow as well as the ion bombardment serve as energy sources. On the other hand, ionization of the metal vapor, emission of electrons and heat dissipation off the cathode consume the gathered energy. Following the same assumptions as made by [8], a very simple equation for the current-voltage-characteristic of a cathode spot can be found.

$$u_{\mathrm{vac}}(t) = \frac{K_1}{i(t)} + K_2 \qquad (2)$$

With the typical cathode spot radii, the values of $K_1$ are in the range of 25 W to 250 W. To ensure an adequate arc voltage for high currents, the value of $K_2$ is set to 15 V. The complete model shown in Figure 1 has been implemented in Simulink® version 6.6. To run the simulation an initial condition at time zero is necessary. Here, the simulation shall start with the peak value of the current. Therefore in a first approximation, the influence of the cathode spot can be neglected for this calculation at time zero. Furthermore, the time-step used in the simulation has been chosen in relation to the maximum possible resonance frequency of the equivalent circuit.

## 7 COMPARISON OF THEORETICAL MODEL AND EXPERIMENTAL RESULTS

As explained before, the applied model is only valid for one stationary cathode spot. Therefore, this model is not valid for high currents. Thus, either the peak value of the current in the experimental circuit has to be limited to the maximum current value, which can be carried by one cathode spot, or the model has to be corrected. Due to economic reasons, it is not possible to further reduce the current level in the experimental circuit, because this would require a lot of air coils which are too costly and time-consuming in their production. Therefore, it is necessary to introduce correction factors for the model. It can be shown, that a correction of the inductances will lead to the same behaviour of the current near the natural zero crossing. In this model, inductance $L_2$ has been increased by a factor of 10 to decrease the current level such that one cathode spot is able to carry the whole current. Nevertheless, the inductances $L_1$ und $L_3$ have to be decreased by a factor of 5 to 10 to achieve basically the same behaviour near the current zero, because their inverse is mathematically responsible for the magnitudes of the oscillations. Due to these correction factors, it is no longer possible to compare the absolute values. Yet the influence of the circuit parameters can be investigated by a simulation or a measurement by changing the values in reference to standard parameters, shown in **Table 1**. That means that for example the change of the chopping amplitude and frequency can be compared. On the contrary, the related absolute values can't.

**Table 1:** Standard parameters of simulation and measurement

| $L_1$ mH | $L_3$ mH | $C_0$ pF | $C_1$ pF | $C_2$ pF |
|---|---|---|---|---|
| 0.13 | 0.13 | 100 | 100 | 10000 |

For comparison, **Figure 5** shows the results of a measured and a simulated current chopping.

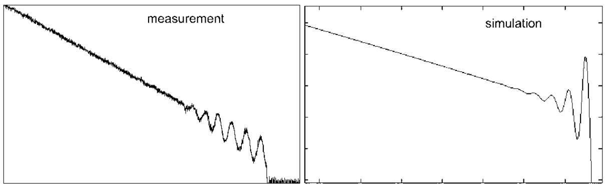


**Figure 5:** Measurement vs. simulation

## 8 RESULTS AND LIMITATIONS OF THE MODEL

Measurements and simulations generally show the same behaviour of current chopping. For the sake of simplicity, only the measurement results are presented in the following. Furthermore, the following investigations are focused on the oscillations, which may or may not occur near current zero. Here, a value of 4 mH was chosen for an inductive and 7 Ω for a resistive load.

### 8.1 Effect of capacity $C_1$

To determine the influence of this capacitance, four test series were performed. For any series, either the value of the capacitance or the load factor cos $\varphi$ was changed (each series consisted of ten measurements). The results are shown in **Table 2**.

**Table 2:** Influence of $C_1$ and power factor cos $\varphi$

| $C_1$ in pF | cos $\varphi$ | $I_{ch}$ in A | $f_{ch}$ in kHz |
|---|---|---|---|
| 100 | 0.99 | 1.19 ±0.28 | Noise |
| 25,000 | 0.99 | 1.84 ± 0.52 | 124 |
| 100 | 0.3 | 1.21 ± 0.71 | 98 |
| 25,000 | 0.3 | 2.41 ± 1.65 | 178 |

It can be seen that copping current and oscillation frequency are notably affected by the value of the capacitance $C_1$ for inductive as well as for resistive loads. This is due to the small impedance of the capacitance for higher values of $C_1$ in contrast to the impedance of the source and the cable ($L_1$ and $R_1$). Compared to former publications [8], this investigation has additionally shown that even with a resistive load an oscillation may occur if the value of $C_2$ is high and exceeds a certain threshold.

### 8.2 Effect of $L_1$ and $L_3$

The impact of inductances $L_1$ and $L_3$ is not the same for different power factors. **Table 3** shows the results for resistive loads. It can be seen that the chopping current is nearly unaffected by the inductance values. Furthermore, no oscillations occurred.

**Table 3:** Results for resistive loads

| $L_1$ in mH | $L_3$ in mH | $I_{ch}$ in A | $f_{ch}$ in kHz |
|---|---|---|---|
| 0.13 | 0.13 | 1.19 ±0.28 | - |
| 0.13 | 0.013 | 1.31 ± 0.48 | - |
| 0.13 | 5 | 1.36 ± 0.29 | - |
| 0.013 | 0.13 | 1.23 ± 0.24 | - |
| 5 | 0.13 | 1.64 ± 0.21 | - |

But in case of an inductive load, the influence of the inductances is significant. As it can be seen in **Table 4**, the chopping current, for each variation of $L_1$ and $L_3$, is lower if the inductance is bigger. Furthermore, the chopping current is even smaller if the inductance is placed closer to the switch. This is confirmed by the fact that any high frequency oscillation has to pass $L_3$. On the contrary, for a large value of $L_1$, the high frequency current is bypassed by the capacitance $C_1$.

**Table 4:** Results for inductive loads

| $L_1$ in mH | $L_3$ in mH | $I_{ch}$ in A | $f_{ch}$ in kHz |
|---|---|---|---|
| 0.13 | 0.13 | 1.21 ± 0.71 | 98 |
| 0.13 | 0.013 | 1.64 ± 0.74 | 118 |
| 0.13 | 5 | 0.86 ± 0.42 | noise |
| 0.013 | 0.13 | 2.09 ±1.18 | 133 |
| 5 | 0.13 | 1.65 ±0.59 | noise |

### 8.3 Effect of the current level

The current level is determined by the value of inductance $L_2$. If only a series resonant circuit with the voltage-current-characteristic of a cathode spot is considered as shown in **Figure 6**, the differential equation 3 can be applied.

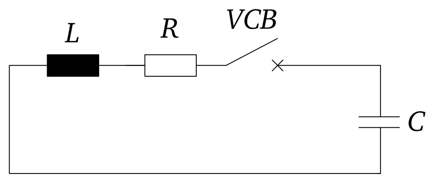


**Figure 6:** Resonant circuit

It can be seen that if the current reaches a certain value, the damping becomes negative.

$$0 = \frac{\mathrm{d}^2 i}{\mathrm{d}t^2} + \frac{\mathrm{d}i}{\mathrm{d}t}\left(\frac{R}{L} - \frac{K_1}{i^2}\right) + \frac{1}{LC} i \qquad (3)$$

It is obvious that damping becomes negative once the current reaches a certain value. Thus, an increasing oscillation may occur. If the current level is higher, this happens later. The moment of natural current zero is fixed by the source. Therefore, a higher current level causes shorter oscillation durations and lower oscillation amplitudes, which results in lower chopping currents.

## 9 CONCLUSION

Based on a practical test circuit, general current chopping phenomena were investigated. In particular, a definition of the power frequency chopping current was formulated and used for any comparative measurements. Thus, a relationship between the measured chopping current and the related overvoltage could be established. In addition, it was shown, that the influence of test circuit elements is more significant than the influence of contact materials with regard to current chopping. Nevertheless, different materials were tested for finding most economic solutions. As a cost-effective alternative to copper-chrome composites application of stainless steel has been investigated. Regarding chopping characteristics both materials are similar. In order to determine the influence of certain test circuit elements a wide range of parameter variations are necessary. Therefore, a simulation model was developed and verified using the test circuit. By means of this model, the dominant factors for instabilities near current zero could be found. Nevertheless, the model cannot be used for a complete simulation of all chopping phenomena because only one cathode spot with a limited ampacity has been realized. Consequently, direct comparisons of absolute values between the test circuit and the simulation are not yet possible, but relative changes and parameter variations can be systematically investigated.

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