

TRANSIENT ARC CHARACTERISTIC OF A COMMUTATION SWITCH UTILIZING HIGH VELOCITY CONTACT SEPARATION

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Abstract. Commutation circuits are commonly used for low on state resistance and high current interruption capability if this can not be achieved by a single device or single current switching path. In case of fault detection, a very fast commutation of the current from the low-impedance main current path into the parallel high-current interrupting path is necessary. For single usage applications a low-cost approach is the utilization of a pyrotechnical switch in the low-impedance path. Compared to other electromechanical switches, those switches provide very high velocity of contact separation and thus a fast arc voltage rise with short commutation times. Here, measurements of the contact movement of a pyrotechnical switch were carried out using optical high speed imaging and an arc elongation up to 100 ms^{-1} was calculated. From this, transient arc characteristics were measured in a simplified commutation network during the period until current zero in the main current path.

Keywords: pyro switch, commutation network, dc arc switching principle.

1. Introduction

Lightning current arresters (SPD Type 1) are used to protect low-voltage electrical installations from damage caused by near or far lightning strikes. In addition to induced impulse currents, these arresters are capable of handling the high-energy impulse currents of direct lightning with a wave shape of $10/350 \mu\text{s}$ (intended with $I_{\text{imp}} = 25 \text{ kA}$). Typically, these arresters are used between phase and ground potential, which, in case of an over-voltage event, create a momentary short-circuit-like condition in the installation for the duration of the over-voltage event. In case of an overload of the arrester, the short-circuit-like state may not be cleared by the arrester itself. According to IEC 61643-11 [1], an arrester disconnector, mostly realized as a one-time switch (fuse), must be provided in series with the arrester, which then will be stressed at each over-voltage event. So, aging of the arrester disconnector may be an issue here. Also for high prospective short-circuit currents (50 kA , 50 Hz) provided by the network, the physical size of the disconnector is an issue too.

A possible solution is to design an arrester disconnector as a commutation circuit separating the feature of low on state resistance and high current interruption capability into two parallel paths. In normal operation mode of the arrester, impulse currents and possible mains follow current will flow through the main current path with low impedance. In case of a failure in the arrester, a very fast current commutation into the parallel commutation path with higher impedance and high rupture element must be realized. After suc-

cessful commutation, the rupture element will finally clear the fault current.

The switching power required in the main current path for a successful commutation is low compared to that needed for the interruption process for the total fault current. Here, a pyro switch seems to be appropriate and will be integrated as commutation switch into the main current path. To design the complete commutation circuit, knowledge of its switching characteristic is crucial and will be investigated subsequently.

2. Theoretical Background

The complete equivalent electrical network for the commutation network is shown in Figure 1.

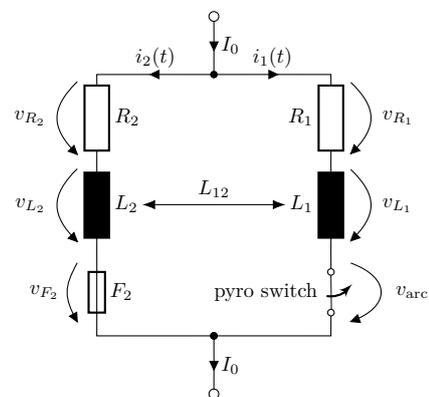


Figure 1. Commutation network with high rupture capacity commutation path (left) and low impedance main current path (right)

In the normal operating state the majority of the total current I_0 flows through the main path (right side in Figure 1) with a low impedance R_1 and L_1 and the integrated commutation switch, for which a pyro switch is used here. On occasion of a trigger signal, contact separation of the pyro switch is initiated. This leads to an electric arc with a very fast voltage rise of v_{arc} , resulting in a complete current commutation into the parallel commutation path (left side in Figure 1) consisting of higher impedance R_2 and L_2 including a switch-off element (fuse). After the commutation process, the total current I_0 flows through the commutation path. The switch-off element with high switching power (fuse) will then completely interrupt the current flow.

Taking magnetic coupling of the two parallel paths via the mutual inductance L_{12} into account, the commutation process can be described according to Fig. 1 with Kirchhoff's laws as (impedance of F_2 during commutation is included in R_2 and L_2)

$$0 = R_1 i_1 + L_1 \frac{di_1}{dt} - L_{12} \frac{di_2}{dt} + v_{arc} - R_2 i_2 - L_2 \frac{di_2}{dt} + L_{12} \frac{di_1}{dt} \quad (1)$$

and

$$i_2 = I_0 - i_1. \quad (2)$$

Even though the intended application is for AC (50 Hz), due to an expected very short commutation time, the total current is assumed to be impressed here and can therefore be described as constant value I_0 . Combining Eq. (1) and Eq. (2) then leads to

$$R_2 I_0 = (R_1 + R_2) i_1 + (L_1 + L_2 + 2L_{12}) \frac{di_1}{dt} + v_{arc}, \quad (3)$$

where the left side only depends on the time independent total current I_0 and the resistance of the commutation path R_2 . This corresponds a DC Source of V_q . The combination of the individual elements (R_1 , L_1 , etc.) into corresponding substitute elements (R_{sub} , L_{sub}) yields

$$V_q = R_{sub} i_1 + L_{sub} \frac{di_1}{dt} + v_{arc}. \quad (4)$$

So, during the commutation process the electrical network can be described as a DC network with a time dependent arc voltage $v_{arc}(t)$ of the pyro switch according to Figure 2.

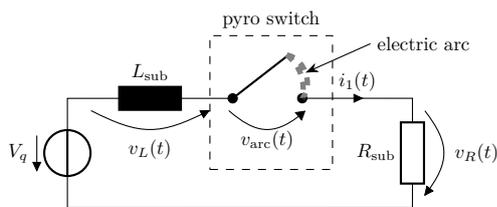


Figure 2. Simplified network for the analysis of commutation process in main current path

It is obvious, that for this DC network, two major factors determine the duration of commutation:

- the corresponding time constant $\tau = L_{sub}/R_{sub}$, depending on the elements of the electrical network,
- the characteristics of the arc voltage v_{arc} rise depending on time and current.

3. Experimental Setup

The presented experimental results were obtained using a commercially available pyro switch with rated breaking capacity for DC application of 250 A at 400 V for resistive loads only.

3.1. Determination of contact motion and arc length characteristic

The investigation of the contact motion was carried out under no-load condition for safety reasons of used high-speed camera (Photron FASTCAM SA-X2). To observe the mechanical motion inside the pyro switch, small openings were milled in the housing lateral to the area of the moving contact piece on both sides and cover plates of transparent PMMA were inserted in such a way, that the internal geometry of the switch is unaffected and the mechanical stability of the housing is maintained. Camera, with bandpass filter of 810 ± 10 nm, was pointed lateral to one opening. Due to the absence of an arc discharge, a pulsed laser (Cavitar Cavilux HF, $\lambda = 810$ nm), synchronized to the shutter of the camera, was installed on the other side of the pyro switch to illuminate the inside. The high-speed camera was set to an optical resolution of 320×240 px at a framerate of 150 kfps. In parallel to the pyro switch, a high-voltage RC -circuit [2] was used to determine the instant of contact separation.

With the high speed images, it was possible to observe the linear motion of the pyrotechnic drive with its sliding element and the resulting rotation of the moving contact piece. As the sliding element enters the arcing area between the contact pieces over time, the smallest free path length, the so-called thread measure, was determined, which would presumably correspond to the resulting arc length. On the basis of several measurements, it was found that the deviation in the motion-time characteristic is not significant and the averaged curves, shown in Figure 3, were derived for further evaluation.

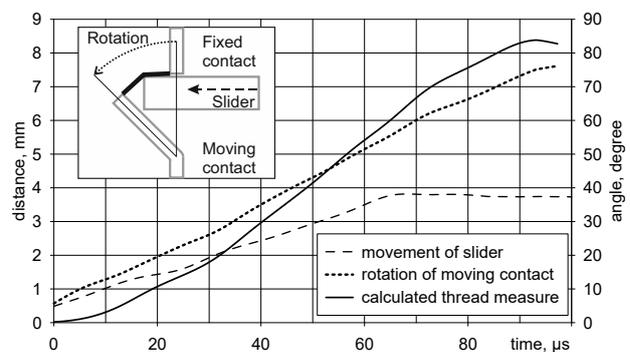


Figure 3. Averaged time courses of the mechanical movement of the investigated pyro switch

Time $t = 0 \mu\text{s}$ marks the instant of contact separation. With the determined thread measures over time, a maximum possible arc elongation velocity in the range of 100ms^{-1} was calculated over all measurements.

3.2. Determination of switching characteristic

A commutation network was built according to Fig. 1. The main current path is formed only by the pyro switch with its terminals and its inherent impedance of R_1 and L_1 . The commutation path was set up by an equivalent impedance R_2 and L_2 oriented to a later application, but without a switch-off element (fuse).

The total current I_0 was injected by a half-sinusoidal generator (50 Hz, $U_{\text{ch,max}} = 10 \text{kV}$, $\hat{I}_{0,\text{max}} = 15 \text{kA}$) via a controllable make switch. The trigger signal of the pyro switch was set for the instant of contact separation to be in the range of the peak of the sinusoidal current. The injected current I_0 , the current i_2 in the commutation path and the arc voltage v_{arc} of the opening pyro switch were measured. From this, the current i_1 in the main path could be calculated.

A typical time course is shown in Figure 4. The sharing of the currents within the parallel paths prior to the commutation process is related to the resistance ratio with $R_1 = 0.1 \text{m}\Omega$ and $R_2 = 18.5 \text{m}\Omega$. With contact separation at $t = 0$ the anode and cathode voltage drop of about $V_{\text{anode,cathode}} = 20 \text{V}$ is established. For the following very rapid arc elongation, the arc voltage is mainly determined by the arc column. The commutation process is accomplished after $t_{\text{commu}} = 48 \mu\text{s}$. The total current I_0 is not influenced by commutation process.

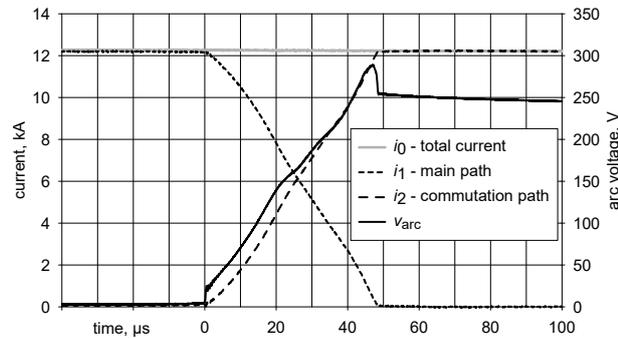


Figure 4. Time course of currents and voltage for commutation process ($\hat{I}_0 = 12.2 \text{kA}$, $t_{\text{commu}} = 48 \mu\text{s}$)

The experiments shown here, are carried out for current values of $\hat{I}_0 = 1.6 \text{kA}$, 4.0kA , 6.2kA , 7.9kA , 10.0kA and 12.2kA only, due to the thermo-mechanical strength of the commutation path. An adjustment would effect the impedance ratio of the investigated network and so alter the investigation conditions.

4. Results

In Figure 5 measured arcing voltages for the different current values are presented. With initiation of the

commutation process, the anode and cathode drop voltage occurs. It can be seen, that the subsequent arc voltage rise is linear over time for all measurements, comparable to the thread measure (see Figure 3), and seems to correlate with the current value to commute. In the last few μs of the commutation process, a significant decrease in the arc voltages is noticeable.

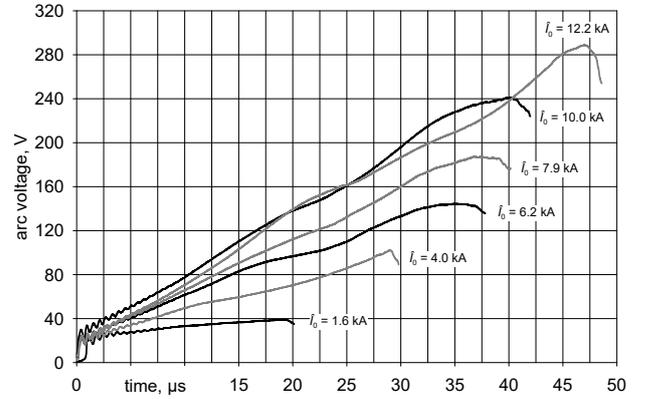


Figure 5. Measured time courses of arc voltage of pyro switch during commutation process with variation of used current amplitudes in experiments

4.1. Determination of arc field strength

In order to investigate the assumption, that the voltage built up over time may be directly linked to the thread measure, corresponding electric arc field strength curves were calculated by using the measured arc voltages minus the drop voltage of anode and cathode and the averaged thread measure from Figure 3. Results are shown in Figure 6. It must be stated here, that the measured voltage signal was superimposed with a damped high-frequency oscillation, which was caused by the measurement setup and not by the switching behavior of the investigated pyro switch. This superposition becomes particularly apparent when calculating the field strength.

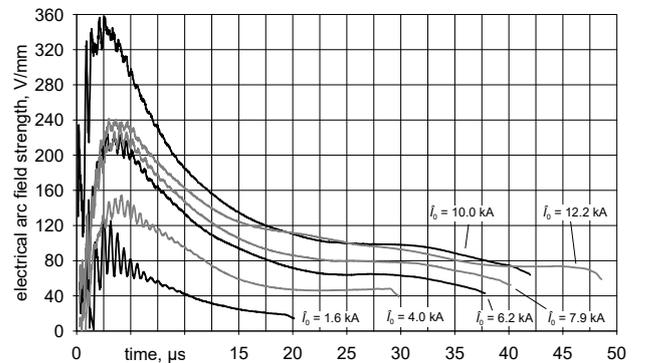


Figure 6. Calculated time courses of electrical arc field strengths with variation of used current amplitudes in experiments

At the moment of contact separation, the current flow i_1 is carried only by vaporized contact material. With increasing contact speed and distance, the arc

column is built up. The arc conductivity is increasingly determined by the surrounding air, which must be ionized. The electric power required is correspondingly high and is achieved via a significant voltage rise. So, after contact separation at very small contact distances, a remarkably high field strength is achieved because the ionization process is determined, among other factors, by the thermal inertia of the switching medium. For the switching medium used here (air), the thermal time constant is $\tau \approx 1 \mu\text{s}$ according to [3]. Hence, the maximum field strength is reached within the first $4 \mu\text{s}$ after contact separation and decreases subsequently.

During the commutation process, the steepness of the field strength decline decreases and is almost constant in some cases. Consequently, the voltage build up appears to be directly proportional to the arc lengthening. It should be noted that in addition to the increase of effective arc length, the current continues to decline. In the last few μs the field strength decreases significantly again. Here, too, due to the thermal inertia of the switching medium, the conductivity will not dissipate as quickly as the current is driven to zero.

Due to the high arc elongation speed, according to Rieder [4], it can be assumed that the electrical conductivity and so the electric field strength varies along the path of the arc. In areas that have been stressed by the arc for a longer period of time, the conductivity is significantly higher than in the area of the moving contact piece, where the arc extension takes place. Thus, the curve shown in Figure 6 corresponds to an average field strength.

4.2. V-I-Characteristic for commutation process

For the measured commutation processes, the dynamic $V_{\text{arc}}-I$ -characteristic is shown in Figure 7. With arc ignition a voltage jump occurs, which equals the sum of anode and cathode voltage. The arc voltage then follows approximately linear with current over a wide range, which is collateral to the source characteristic. The difference of both curves equals the inductive voltage drop over L_{sub} and so, it is a measure for the current steepness di_1/dt , see also Eq. (4), which is almost constant for each commutation process.

Finally a significant decrease in the voltage at low currents is noted, which, as already mentioned, takes place in last few μs before current zero. Replacing the arc voltage v_{arc} in Eq. (4) by the arc resistance R_{arc} and current i_1 flowing through it, leads to

$$(R_{\text{arc}} + R_{\text{sub}}) i_1 = V_{\text{q}} - L_{\text{sub}} \frac{di_1}{dt}. \quad (5)$$

Assuming at this instant of time $R_{\text{arc}} \gg R_{\text{sub}}$ and a time independent source voltage V_{q} , the voltage decrease only depends on $R_{\text{arc}} \cdot i_1$ with current decreasing faster to zero than the resistance in arc column can

rise due to thermal inertia. Hence, the inductive voltage is decreasing too, resulting in lower di_1/dt to the end of commutation process. The commutation process is completed when $V_{\text{arc}} = V_{\text{q}} = R_2 I_0$.

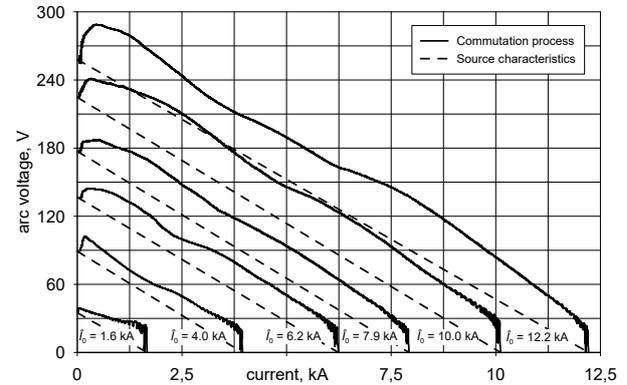


Figure 7. $V_{\text{arc}}-I$ -Characteristic during commutation process in comparison with the static source characteristic with variation of used current amplitudes

5. Conclusions

An essential aspect for the design of a commutation circuit is the knowledge of the switching behavior of the commutation switch, since this influences the commutation time quite significantly. Such a switching behavior was investigated for a commercial pyro switch in a commutation circuit. An almost linear voltage build up of this switch was found over the commutation time for different current loads up to 12.2 kA. A major effect assumed here is the very fast arc elongation ($\sim 100 \text{ m s}^{-1}$) especially in comparison to conventional mechanical switching devices ($\sim 10 \text{ m s}^{-1}$). It is assumed that the spacial distribution of the electrical conductivity of the arc column does have significant impact on the arc voltage build up. It is not only varying in the radial direction, but also in the axial direction due to the high speed and thermal inertia of the switching medium. A more in-depth investigation was not possible with the commercial pyro switch used. So, an experimental setup with adjustable speed is the next logical step including also pressure measurement and contingently optical observation of the switching arc.

References

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