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Determination of dielectric recovery characteristic of a pyro switch in commutation circuit

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Abstract

Pyrotechnic switches are used for overcurrent protection, e.g. in low-voltage DC circuits (battery disconnector). At fault current interruption, arc voltage built up by the switch must be sufficiently high to drive the current to zero (DC switching principle). Compared to AC interruption, the switch does not experience a transient recovery voltage (TRV). With increasing breaking capacity, comparatively large construction volumes are necessary. Possible reduction in design effort of the switch is found by using the commutation principle where the pyrotechnic switch is integrated as commutation switch in the low-impedance main current path.

This publication presents an experimental method for recording the dynamic dielectric recovery characteristics of a pyrotechnical switch for commutation circuits. An electrically equivalent network without a switch-off element in the commutation path was installed in the synthetic test circuit and stressed with currents up to 10 kA. From the moment of successful commutation by the pyrotechnical switch, the switch was loaded with voltages up to 4 kV using an RC circuit for recording the dynamic dielectric recovery characteristic. With the resulting dielectric recovery course and the verification of the switching capacity required for successful commutation, an optimally adapted switch-off element can be selected for realizing the overcurrent protection device based on the commutation principle.

1 Introduction

Traditional devices to protect in case of overcurrent in low voltage networks are fuses, circuit breakers and miniature circuit breakers. In circuit breakers, the detection of a fault current is usually done with electromechanical tripping units, and the current is also interrupted electromechanically.

Fuses, current limiting circuit breaker and miniature circuit breakers are able to interrupt high fault currents within a few milliseconds. Big circuit breakers with rated currents up to several thousand amperes usually need at least several 10 ms, if not intentionally time-delayed to provide selectivity.

In some cases these traditional protection measures are not sufficient, especially if

- the equipment to be protected does not have sufficient current carrying capacity for the let through current remaining until interruption, or
- protection against the effects of electric arcs is required, which can cause considerable damage to equipment and hazards to persons already in a very short time [1].

Therefore, protection devices are required which can interrupt the fault current in much shorter time. Semiconductor switches can interrupt currents in a very short time, but do not have the isolation distance in the off-state, which is often required for safety reasons.

In such cases pyrotechnical switches are increasingly used (e.g. to protect the battery systems in electric vehicles), which are one-time switches in normally closed condition [1] [2] [3].

In the case of the interruption of a fault current in a DC circuit, the switching arc voltage built up by the switch must be sufficiently high to bring the current to zero.

With increasing demands on the breaking capacity of the switch, relatively large construction volumes are required. One possibility to reduce the design effort for the switch can be the use of the generally known commutation principle as described in [1] and [2].

With this solution the pyrotechnical switch is integrated as a commutation switch in the low-impedance main current path, which is designed for carrying the operating current. When the fault occurs, which means a much higher current than the operating current, the pyrotechnical switch is activated with the help of a suitable fault detection. Due to the functionally very short switching time and the directly following significant voltage build-up, the fault current is completely commutated into the higher-impedant commutation path. Due to the higher impedance of this path, the fault current is limited and is subsequently switched off by a conventional switching device with a low current carrying capacity and short interruption time.

The switching capacity to be applied by the pyrotechnical switch during the commutation process is low compared to a complete switch-off. For the final interruption of the fault current in the commutation path, the integrated conventional switching device (e.g. fuse) builds up a high counter-voltage (switching voltage). The total voltage from the product of the current and the impedance of the commutation path and the switching voltage of the conventional switching device stresses the open switching path of the pyrotechnical switch (comparable to the transient voltage in AC circuits). For the safe and fast interruption of fault current, the dynamic voltage build-up by the switching device in the commutation path needs to be adapted to the time dependent dielectric recovery of the pyrotechnical switch immediately after completion of the commutation process.

Therefore, the task is to determine precise element combinations for each application in order to successfully interrupt both small (several 100 A) and large residual currents of up to several 10 kA which may occur in low voltage networks.

Due to the comparatively high commutation and switch-off speed, such overcurrent protection is possible for both DC and AC networks.

1.1 Setup of an interruption installation on the basis of commutation principle

Figure 1 shows the equivalent circuit diagram of the commutation circuit described in this article. The total current i_0 represents the operational current which has to be carried continuously or the fault current to be interrupted in case of a failure. The total current is divided between both paths of the commutation circuit. Due to the dimensioning of these paths the larger part i_1 of the total current flows through the commutation switch with pyrotechnic switch, which can be triggered. The equivalent impedance Z_1 of the main path is nearly fully determined by the geometry of the path of the closed pyrotechnical switch. A smaller part i_2 of the current flows through the commutation path, which contains the interruption device, which is shown here as a fuse. Additionally other elements (e.g. resistors) can be installed to increase the equivalent impedance of the commutation path Z_2.

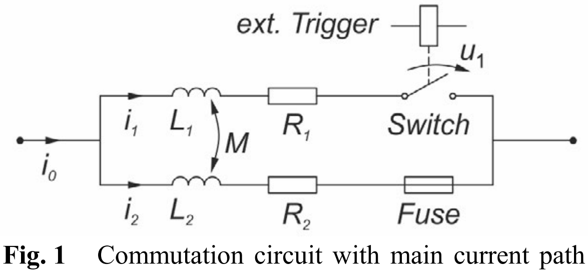

Fig. 1 Commutation circuit with main current path (1) containing triggerable pyrotechnic switch and commutation path (2) with its fuse.

By appropriate choice of the impedance ratio Z_1/Z_2 the load of the commutation path and therefore of the fuse can be reduced while the pyrotechnic switch is closed.

So a small cross section of the fuse-element can be chosen, which improves the response behaviour and the switching capacity of the fuse [4].

For the investigations presented here a commercial pyrotechnical switch was used as the test object, which is intended for DC networks in conjunction with electrochemical accumulators. The switch has a breaking capacity of 250 A at 400 V (2000 A at 32 V) and purely resistive load.

1.2 Description of the load of the commutation switch

The choice of the pyrotechnical switch in relation to the switching capacity and the dielectric recovery characteristic determines the possible elements of the complete commutation circuit.

The switching capacity of the switch determines whether the commutation process is successful. The following three parameters must be considered: The instantaneous value of the fault current I_0 at initiation of the commutation process determines together with the impedance of the commutation circuit the minimum voltage level to be built up by the switch U_{commu} [5]:

$$U_{commu} > I_0 * (Z_1 + Z_2)$$

Furthermore, the voltage must be present for the entire commutation time t_{commu}. The duration is essentially determined by the time constant of the commutation circuit τ_{commu}, which is calculated as follows:

$$\tau_{commu} = \frac{L_1 + L_2 - 2M}{R_1 + R_2}$$

In addition to the impedances of the individual paths, which can each be broken down into an ohmic (R) and an inductive (L) component, the magnetic coupling of the two paths via the common mutual inductance M plays an important role for in determining the time constant and the resulting commutation time.

Thus the maximum size of the impedance Z_2 and the possible impedance ratio are limited by the course of the commutation voltage and the self-impedance of the commutation switch, which essentially corresponds to Z_1.

The current i_0 is assumed to be impressed during the very short commutation period. After successful commutation and until the response of the interruption device (fuse), the now open switching path of the pyrotechnical switch has to withstand the voltage of the commutation path (u_1 in **Figure 1**), which is determined by the total fault current i_0, which now flows completely through the impedance Z_2. In most cases the voltage stress is lower than the commutation voltage built up previously. The load on the switching path is therefore estimated as non-critical.

Since there is no further energy input into the arc gap after the current zero crossing (CZ), the gas temperature drops over time. The conductivity in the switching path decreases. Also the contact distance still increases further. Both processes increase the process of the dielectric recovery.

When the switch-off element, corresponding to **Figure 1** a fuse, is tripped, a significant voltage build-up occurs in the commutation path, which still has to be withstood by the open switching path of the commutation switch. Any re-ignition of the switching path in the commutation switch must be prevented in any case. Therefore, at any time after CZ, the dielectric strength of the switching path must be higher than the applied voltage.

The influence of the fuse on the voltage stress on the switching path of the commutation switch is significant. The form of dynamic voltage stress depends on the choice of fuse, on its response time and switching characteristics.

If the time characteristic of the switching voltage of the fuse were known, the qualification of the commutation switch by means of a synthetic test circuit similar to the switching capacity test of high-voltage circuit breakers according to [6] could be applied, for example in the form of the Weil-Dobke circuit.

To find the optimum combination of impedance ratio, commutation switch and interruption device, knowledge of the switching capacity and, above all, the dynamic dielectric recovery characteristic of the commutation switch is of decisive importance.

The further described investigations do not serve to evaluate the switching capacity or the dynamic dielectric recovery of this specific switch, but are only intended to present the developed investigation method.

2 Test setup to determine the dielectric recovery characteristic

2.1 Method for determining dynamic dielectric recovery characteristic

Different methods are known to record the dielectric recovery characteristics. A selection is discussed in [7]. The methods differ in the number of recorded measuring points per switch-off operation and in the voltage load of the switching path after CZ.

For a multiple sampling of the dynamic dielectric recovery during a switch-off process, a method using a saw tooth oscillation generated by a capacitor connected in parallel to the switching path was presented in [8] (similar to **Figure 4**). The capacitor is short-circuited when the switch is closed or the arc resistance is low. Immediately following CZ, the capacitor is charged by a DC voltage source with a in series-connected high-impedance charging resistor. If the instantaneous value of the voltage applied across the open contact gap exceeds the present strength, the gap is ignited and the capacitor discharges abruptly. After the voltage drop, the process of charging starts again. A typical course of the voltage across the open contacts is shown in **Figure 2**. With a sufficiently high density of sampling points (ignitions of the switching path), an approximated dynamic dielectric recovery characteristic curve can be derived from the voltage maxima achieved for each switch-off process.

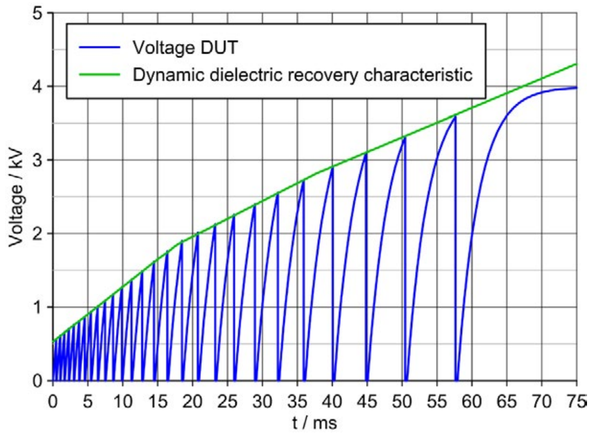

Fig. 2 Voltage course obtained by the method of [8] at no-load disconnection to derive the dynamic dielectric recovery characteristic.

Selecting the charging voltage, the charging resistor and the capacitance parallel to the switching path, the steepness of voltage rise and thus the possible density of the sampling points can be adjusted. It should be noted that with each discharge, energy is introduced into the switching path again. Any influence on the residual conductivity of the switching path must be excluded or minimized, otherwise the recorded characteristic curve will be distorted according to [7].

For the test arrangement, the maximum voltage stress of the switching path should be adjustable. It is assumed that the parallel fuse can be a commercial product for a nominal system voltage of 400 V or 690 V and an overvoltage category IV assigned to it. According to the insulation coordination [9] it is permissible that the fuse generates a maximum voltage of 8 kV itself. Accordingly, a power electronic DC voltage source with a maximum voltage of up to 10 kV was selected.

Due to the fast switching and commutation process by the pyrotechnical switch within a few 10 µs, a very fast sampling directly after CZ is preferred. This is achieved by adjusting the time constant of the RC element used. With selectable charging voltages of $U_{DC} \leq 10$ kV and the aim of a low energy input to the switching path during each ignition process, the capacity parallel to the switching path must be minimal. In contrast to other investigations [7] [8], a separate parallel capacitor is not used here. Instead, the capacitance of the RC high-voltage probe, which is arranged in parallel to the test object and used to measure the voltage curve across the switching path, is used. Its input capacitance corresponds to C_{V1} = 3 pF. A high-voltage resistant charging resistor R_{HV} = 100 kΩ is used to limit the charging current of the DC source and to set the time constant. This results in a theoretical time constant of τ_{HV} = 0.3 µs for the charging process.

In order to check the applicability of the selected parameters and to test the circuit, the circuit was built up and a single pyrotechnic switch was used as the device under test (DUT). An attempt was made to record a dielectric recovery characteristic. Since the pyrotechnic switch was not initially stressed by a current from a load circuit, the obtained curve in **Figure 3** shows the dielectric strength at no load. After contact separation, a rapidly repeating sequence of a saw tooth shaped voltage curve occurs, with an amplitude between 400 V and 500 V. As the contact distance increases, the voltage maxima are increasing. In the range of approx. 28 µs to 35 µs, the last breakdown of the switching path occurs and the voltage applied across the switching path then rises to approx. 4.6 kV. Due to the high steepness of the charging current and a low inductance of the circuit, overshooting occurs. The voltage oscillates following the externally applied charging voltage of 4 kV, which is permanently maintained by the DUT. The process of contact movement is not yet complete at this point. However, the voltage applied is no longer sufficient to cause a further ignition at the contact position.

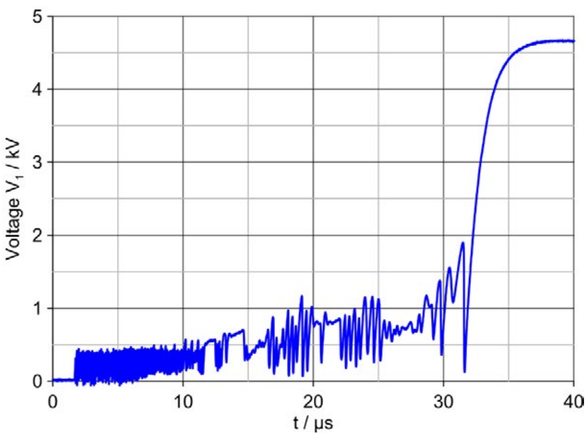

Fig. 3 Dielectric strength of the pyrotechnic switch (DUT) in no-load test (no-load characteristic).

For the last charging processes time constants τ_{HV} were determined in the range of 1.2 µs to 1.25 µs. The deviation from the previously calculated time constant can be explained by the equivalent circuit, hereinafter referred to as the voltage circuit, shown in **Figure 4**. In addition to the input capacitance C_{V1} of the high-voltage probe V_1, the intrinsic capacitance C_{DUT} of the open switching path of the DUT plays a decisive role. With open contacts 6.3 pF was measured for C_{DUT}. Other existing parasitic capacitances are not taken into account.

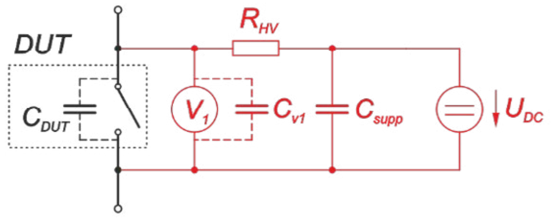

Fig. 4 Voltage circuit for recording the dynamic dielectric recovery characteristic of the DUT.

The DC source was set up locally separate from the test object for safety reason. To compensate the inductive influence of the long supply lines and to minimize the influence of the internal controller of the source, a supporting capacitor with C_{supp} = 5 nF was used at the input of the DUT and the RC element.

2.2 Experimental setup of the commutation circuit to obtain the dynamic dielectric recovery characteristic

The dynamic dielectric recovery characteristic is obtained from the combined loading of the commutation switch by a commutation process carried out by itself and the subsequent loading with the test voltage. Correspondingly, the voltage circuit from **Figure 4** shown above is integrated into the circuit in **Figure 5**.

The test current i_{HSG} is injected into the model of the commutation circuit by a half-sinusoidal generator (HSG, 50 Hz, U_{charge} = 10 kV, $\hat{I}$ = 15 kA) from an RLC circuit via a controllable make switch (MS). In the commutation current path with the current i_2, a fixed substitute impedance Z_2 is used. The switch-off element, which causes the actual voltage stress on the DUT, is not integrated here. The main current path with current i_1 consists of the voltage circuit (red) described above and the commutation switch (DUT) to be tested. A disconnecting switch (DIS) is installed in series to the DUT as a decoupling element to separate the DUT from the high current circuit after successful commutation.

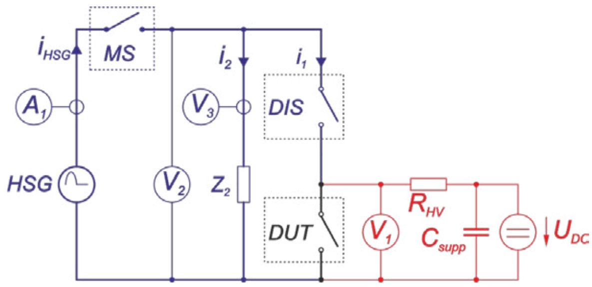

Fig. 5 Equivalent circuit diagram of test arrangement with high current circuit (blue) and voltage circuit (red).

As shown in **Figure 5**, essentially variables are recorded to determine the dynamic switching and dielectric recovery characteristics of the DUT. A high voltage probe V_2 is used to measure the total voltage across the commutation circuit. With the high voltage probe V_1

the voltage across the DUT during commutation and during the subsequent dielectric recovery is measured after CZ. For the measurement of the total current i_{HSG} a wide range current transformer A_1 is used. The partial current i_2 is measured indirectly by recording the output voltage V_3 on a self-built Rogowski coil, which is characterized by very small geometric dimensions and a very low self integration. Furthermore, the tripping signals for the switch under test (DUT) and the disconnecting switch are recorded. For the recording of the measured data a digital storage oscilloscope was used.

2.3 Selection of disconnecting switch

With the solutions described in [7] or [8] for determining the dielectric recovery characteristics at switching elements (e.g. switches, spark gaps), the test current from the high current circuit is interrupted. Following a disconnecting switch is opened to prevent a new current flow driven by the high current circuit during a possible subsequent re-ignition of the clearance between open contacts. This can be inserted theoretically at any point of the high current circuit.

In contrast a commutation is induced by the DUT here. The test current then continues to flow through the commutation path parallel to the DUT with the impedance Z_2. In order to avoid a back-commutation the disconnector (DIS) must be integrated into the main current path according to **Figure 5**. The required characteristics of the disconnector (DIS) are:

- Minimum current carrying capacity corresponding to the desired test current with a current magnitude of up to 15 kA over a period of 10 ms.
- Low contact resistance and ideally negligible self-inductance, as otherwise the impedance of the main circuit Z_1 is adversely affected. (This results in a small dimension of the DIS).
- Low variance in time to contact separation with $\Delta t_{open} < 10$ µs for a time-precise decoupling of the DUT with connected voltage circuit from the remaining current circuit directly after CZ.
- The DIS should theoretically only operate after successful commutation through the DUT, so the DIS does not need to have any switching capacity. However, the build-up of the dielectric strength after triggering should be faster than in the DUT, as otherwise a proper decoupling from the current circuit is not obtained.
- According to the installation locations of DUT and DIS in relation to the voltage circuit (**Figure 5**), the DIS must have a very low intrinsic capacitance C_{DIS} in open condition. This capacitance is via Z_2 connected in parallel to C_{DUT} and C_{V1} and thus influences the time constant τ_{HV} of the voltage circuit.

Different options for a disconnector were examined and evaluated. Electromechanical switchgear showed a too large variance in time to contact separation and a too low dielectric strength after no-load opening due to the comparatively low contact separation velocity. Mostly large dimensions causes a comparatively high self-inductance. Triggerable spark gaps with a high extinguishing capacity influenced the course of the test current in the main current path and showed disadvantages in the dielectric strength after CZ. Extinguishing diodes would be the means of choice, since they theoretically extinguish automatically in a circuit without external control. However, the available diodes had too large inherent capacitances so the time constant of the voltage circuit τ_{HV} was increased undesirably. Based on these considerations, a pyrotechnical switch of the same design as the test object itself was used as the DIS in the tests shown here.

A direct current of 5 A was used to trigger the pyrotechnic drive in the DUT and DIS. A programmable microcontroller was used to provide the trigger signal and to control the sequence with the HSG at an exact time. Prior to this, the inherent delay of the used devices were determined. The pyrotechnical switches showed an average time to contact separation of about 230 µs ± 15 µs in no-load operation.

Despite the low variance in time to contact separation, the following problems arise when controlling the DIS: For an ideal decoupling of the current circuit to the DUT, the DIS should open in the instant of CZ. Since the commutation time varies in an unknown manner with each operation, even under identical preconditions, it is difficult to determine the time offset of the command. Probably the greater influence is the variance in time to contact separation of the used pyrotechnical switches. In the worst case, the error in the contact separation is about 30 µs. This is considerable high with an expected commutation time of a few 10 µs.

If the contact separation of the DIS is too early, a resulting voltage built up will influence the commutation process. If the DIS is tripped too late, the dielectric strength in the DUT might be higher. Then a no-load characteristic of the DIS would be recorded by the voltage circuit. To differentiate between the cases that may occur, it is essential to evaluate the voltage across both switches. The voltage characteristic curve from the previously performed no-load tests helps for the evaluation of the measurement.

2.4 Commutation circuit for determining dielectric recovery characteristic

The main current path is formed by connecting two identical pyrotechnic switches in series **(Figure 5)**. Since these are commercial components, the influence of the switch internal conductor paths is limited. An attempt has been made to keep the effective length and the resulting impedance Z_1 of the main current path as small as possible. For this purpose, a copper connection module was attached to each of the two open ends, which is used to contact the main current path with the circuit and with the auxiliary current path.

As a replacement for the switch-off element, the commutation path contains only a resistance element which consists of 3 parallel round wires each with a diameter of $d = 2$ mm made of the non-magnetic material NiCr 80:20. The arrangement of these wires was chosen with regard to the following criteria: The resulting impedance Z_2 should be selected close to the impedance of the real switch-off element installed in the future (e.g. fuse). Furthermore, the mechanical and thermal loads occurring during the tests must be withstood.

According to the relationship between the time constant of the commutation circuit τ_{commu} and the effect of the self- and mutual inductances between the main and commutation current path, it is evident that a better magnetic coupling can partially compensate the effect of the self-inductances given in (see 1.2). The two paths have been moved together as far as possible to achieve maximum coupling. It is taken into account that a real switch-off element (e.g. fuse) can still be integrated in the bypass path without great design effort.

The resistance of the main current path was determined by measurement with $R_1 = 1{,}15$ mΩ and that of the commutation path with $R_2 = 22$ mΩ. The comparably small inductances could not be measured. Using the geometries, the self-inductance of the main current path was estimated to be $L_1 = 100$ nH, the self-inductance of the commutation current path to be $L_2 = 250$ nH and the mutual inductance to be $M = 35$ nH.

3 Determination of dielectric recovery characteristic

3.1 Description of typical experiments

Following five experiments are presented, each carried out with the same type of pyrotechnical switch and the same arrangement. The load current of the commutation circuit was varied in the range of 2 kA up to 10 kA with sinusoidal wave shape and frequency of 50 Hz.

The trigger signal to the DUT was set shortly after the peak of current. A typical course of the measured signals is shown in **Figure 6** and enlarged in time base for the commutation process in **Figure 7** for the experiment #2.

The current distribution between main and commutation current path is almost solely determined by the resistance ratio R_1/R_2 until start of commutation. Commutation is initiated at an instantaneous value of 4 kA and is successfully completed after 36 µs. Contact separation of the DIS takes place 3 µs before CZ, so that the latter has a supporting effect for a short time but with little influence when the current in the main current path is interrupted. The shape of the voltage measured at V_1 across the DUT corresponds to the no-load characteristic (see **Figure 3**). The time constant of the charging pulses was determined to $\tau_{HV} = 1{,}57$ µs and is almost the same as for the no-load characteristic. It can be assumed that here the dielectric strength of the DIS corresponds to the character of the measured voltage. Thus, the dielectric strength of the switching path of the DUT should be comparable or higher despite the previously applied breaking capacity.

The stress of the switching contact gap by the voltage circuit is withstood successful within approx. 0.4 ms after CZ. Subsequently, partial drops in the voltage across the switching gap down to 2.2 kV are detected. Both the voltage drop and the subsequent charging characteristic show RC behavior with significantly increased time constant in the range of $\tau_{HV} \approx 230$ µs. This time constant is not determined by the test circuit. Rather, an increase in conductivity in the switching gap of the DUT can be assumed. What causes the change in conductivity can only be speculated. In any case, this effect occurred with all pyrotechnical switches under stress, which realized commutation at high current.

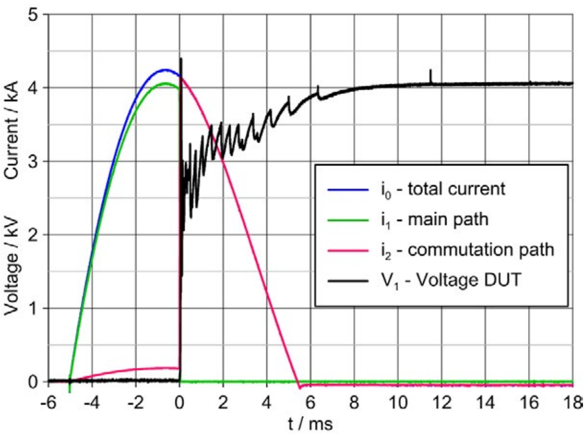

Fig. 6 Characteristic time courses for experiment #2.

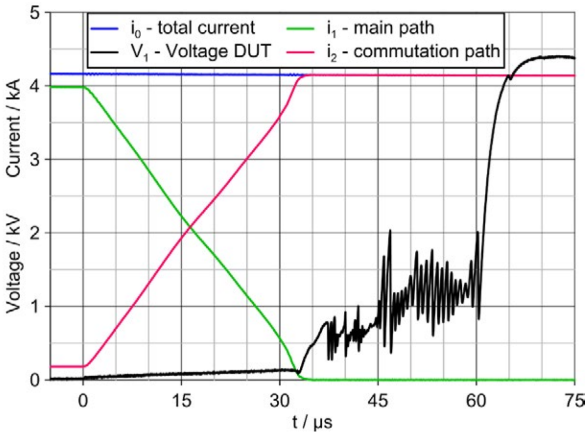

Fig. 7 Characteristic time courses for experiment #2 enlarged in time base for the commutation process and following voltage stress by voltage circuit.

3.2 Comparison of measurement results

The recorded time curses are qualitatively the same for all experiments. In **Table 1** the parameters that are decisive for commutation are listed. In addition to the instantaneous value of the total current I_0 and the commutation time t, the charge Q converted during the commutation process and the Joule integral I^2t were evaluated.

The product of the charge Q and the electrode drop voltage is responsible for the heating of the arc root, whereby the heating promotes thermos-field emission. Due to the short duration of the commutation of a maximum of 46 µs, an adiabatic heating at the root point can be assumed. The Joule integral I^2t is the extent of energy converted in the arc column, which is largely responsible for the ionization of air and for the conductivity of arc.

Tab. 1 Characteristic parameters for the commutation process in 5 experiments.

Experiment	#1	#2	#3	#4	#5
$\hat{I}_0$ / kA	2	4	7	10	10
t / µs	29.6	36.0	42.9	42.0	45.6
Q / As	0.04	0.08	0.15	0.22	0.24
I^2t / kA^{2}s	0.06	0.22	0.73	1.64	1.77

Basically, it can be assumed that with an increasing flowed charge Q or a higher converted Joule integral I^2t, the conditions for rapid dielectric recovery after CZ deteriorate, since higher residual conductivity in the switching gap can be assumed. For this purpose, the determined dynamic dielectric recovery characteristics for the tests 1 to 5 are shown in **Figure 8**. Contrary to expectations, the characteristics are close together despite the significantly different energy conversion. It can therefore be assumed that the energy conversion in the examined current range has no significant influence. The dielectric recovery characteristics are only determined by the repeated partial re-ignition of the switching gap starting in the range of 0.3 ms to 0.6 ms after successful commutation.

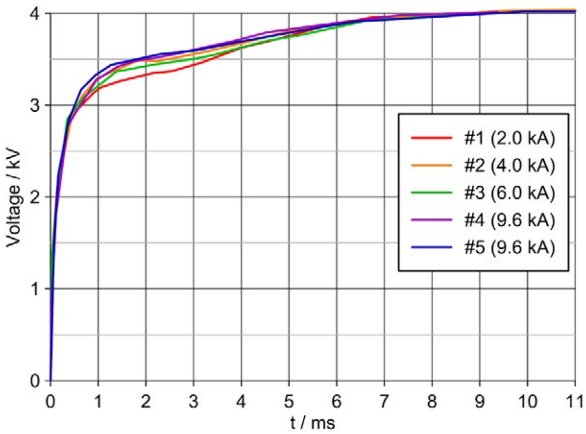

Fig. 8 Derived dynamic dielectric recovery characteristics for the examined pyrotechnic switch under various load currents.

For setting up a model for simulate the commutation behaviour the evaluation of the arc voltage, which is built up by the commutation switch as a function of time and the current to be commutated, would be interesting. For practical reasons of contacting the high-voltage probe above the device under test, however, voltages over the conductor path of the switch and additional magnetic couplings into the measuring loop [10] are partially measured. Therefore the actual arc voltage was calculated from the measured currents and impedances, derived from the geometry and material parameters. The calculation method will not be discussed further here.

With the help of the measuring arrangement presented here, it is basically possible to investigate and characterize the behavior of the commutation switch based on pyrotechnical drive. The relationships obtained with the aid of the measurements can be used as a basis and comparison for a possible physical modelling of a pyrotechnical switch for commutation processes.

4 Summary

This paper presents an experimental method which allows the recording of the dielectric recovery characteristic of a pyrotechnical fast acting switch for commutation circuits. For this purpose, an electrically equivalent network without a switch-off element was installed in a specifically adapted synthetic test circuit and stressed with currents of up to 10 kA. From the moment of successful commutation the dynamic dielectric recovery characteristic was recorded using a saw tooth shaped voltage curve with amplitudes up to 4 kV.

With the verification of the switching capacity required for commutation and the derived dynamic dielectric recovery characteristic, an optimally adapted switch-off element can be selected for the final implementation of an overcurrent protection device based on the commutation principle.

In case of searching for a suitable fuse as a switch-off element its characteristic behavior must be determined first. Comparatively high current amplitudes with high steepness are commutated into the fuse before current limitation. The delayed tripping behaviour of the fuse after commutation and the subsequent voltage build-up over time must be known. Corresponding investigations were carried out and will be presented in a later publication.

For the selection of the pyrotechnical switch, a suitable fuse and the determination of the optimum impedance ratio, an electrical network model is available which simulates the characteristic behaviour of the commutation switch with pyrotechnical drive and the fuse as a switch-off element.

The resulting solutions based on the commutation principle with a commutation switch with pyrotechnical drive can be used in both AC and DC networks. Depending on the speed of fault detection, the prospective short-circuit current can be significantly higher than the 10 kA examined here.

5 Literature

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