Dimensioning of switches made up of a series and parallel connection of numerous low-current contacts

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Summary

It is studied how to reach higher switching capacities by a series and parallel connection of fast and low-current contacts. Naturally given effects of these contacts, like the minimum voltage of a steady arc after contact separation and the withstand voltage after arc extinction, can be multiplied by a series connection of contacts in a path. Paths are added in parallel to a so-called matrix to obtain a higher current capacity. Basic experiments and a model for the calculation of such matrices with a great number of contacts show the difficulty of current commutation between the parallel paths due to the jitter at contact separation. This commutation is accelerated by switching in an area with a negative voltage-current characteristic of the burning arcs. Experiments show that in contacts having gaps in the range of some mm and a current capacity of some amperes, this negative characteristic can be avoided, and that the arc voltage is determined uniquely by the gap of the contacts. These findings are fundamental for the optimization of such switches as part of a hybrid system or for the realization of a matrix as self-contained switchgear.

Key words:
Hybrid switch – Small-contacts matrix.

1. Introduction

In conventional ac circuit breakers, used to break currents in transmission and distribution systems, separation of the contacts and the resulting switching arc occur several tens of milliseconds after the opening command. The arcing voltage ranges from some tens of volts (short arcs) up to some kilovolts (strongly cooled arcs). For these reasons, conventional electromechanical high-voltage switchgears are not suitable for limiting fault currents and can not be applied to switching dc currents at distribution and transmission voltage levels.

A potential current-limiting breaker technology may involve the use of a hybrid system. Research on such systems [1-3] led to a design of a high-voltage circuit breaker including switching elements realized with series or parallel connection of numerous low-current contacts to commutate and interrupt the current in the parallel paths. These contacts have low mass and a small gap distance. Due to the low mass the contacts are able to be separated very fast. The voltage of a steady arc, burning after contact separation, increases with increasing arc length starting from a certain minimum arc voltage (cathode fall) of the order of 10 V, depending on the contact material and insulating medium [4]. After arc extinction, the gap withstands voltage for contact gaps greater than a few µm instantaneously is in the range of 300–400 V [5]. Building up the switches of this hybrid system with a series connection of small contacts these naturally given effects can be utilized. To achieve a higher current carrying capacity several such paths of small contacts in series have to be added in parallel to a so-called matrix switch.

Basic experiments with such a matrix show the difficulty of current commutation between the parallel paths due to the jitter at contact separation and by switching in a region with a negative voltage-current characteristic [6]. To dimension these switches and to coordinate the commutation and interruption processes it is necessary to know the voltage-current characteristic of the opening contact gaps and to have a model to calculate the currents in the parallel paths of a hybrid switch as well as in the paths of the matrix.

Therefore in order to find out the voltage-current characteristic of opening switches realized by such small contacts an experimental setup with a switch, driven by a pneumatic actuator has been built up. The experiments show that in contacts having gaps in the range of some mm and a current capacity of some amperes, a negative characteristic can be avoided, and that the arc
voltage is determined uniquely by the gap of the contacts. So current commutation is only caused by the jitter at contact separation. Basic experiments and calculation of the current commutation in the parallel paths of a matrix show that the resulting current overload can be limited to uncritical values.

The findings of the experiments and the models describing the current commutation in a hybrid switch and between the parallel paths are presented in this paper.

2. Arc characteristic

2.1 Experimental setup

Switches, installed in hybrid systems and made of small low-current contacts, have circuit times in the range of some tens of μs. Current commutation and the resulting current overload in the parallel paths of a matrix happen directly after contact separation. This means that for opening velocities of some m/s arcs are burning in contact gaps up to some hundred of μm. For dimensioning the switches and calculate the current waveforms it is necessary to know the voltage-current characteristic for these distances. The aim of the experiments is to investigate the behavior of arcs in small contact gaps up to one mm and a load current up to some ampere. To gather this information a DC circuit as seen in fig.1 has been set up.

![Design of the DC test circuit](image)

The capacitor C has been charged to a voltage $U_Q$. The value of the current $I_{S0}$ at the beginning of the switching operation is defined by $R_V$. Defining the test parameters it has to be considered that the voltage across the opening switch reaches the system voltage to bring the current of the test circuit to zero for a successful switching operation. The time constant ($\tau = R_V \cdot C$) of the circuit is high enough that switching is not influenced by the discharge of the capacitor C. The switch S is realized with a one pin wrap connection and is driven by a pneumatic actuator. With help of a modulating valve the opening velocity can be varied up to 2 m/s. To investigate the influence of different contact materials the contact pin of the switch can be replaced. The voltage $U_S$ over the opening switch and the current $I_S$ in the test circuit are measured. Fig. 2 shows typical voltage and current waveforms during an interruption process.

![Voltage and current waveforms during interruption of $I_{S0} = 0.78$ A ($U_{\text{min}} = 14$ V, $I_{S\text{min}} = 0.63$ A).](image)

The opening command is given at $t = 0$ and the contact separation occurs about 1.2 ms later. At contact separation a steady arc is burning and the voltage $U_S$ increases with increasing arc length starting from a certain minimum arc voltage $U_{\text{min}}$ depending on both electrode material and surrounding gas (kind and pressure) [7]. Fig. 2 shows the result of a test setup with a gold-plated pin with $U_{\text{min}} = 14$ V and an opening velocity of 1 m/s. The current $I_S$ is suppressed by the linear growth of the voltage over the switch and the interruption occurs sharply when the current falls below $I_{S\text{min}}$. Several tests have been made by varying the parameters of $I_{S0}$ (up to 5 A), the opening velocity and the contact material.

2.2 Arc model

The voltage waveforms, measured over the opening switch, show a linear increase starting from the voltage $U_{\text{min}}$ at the time of contact separation. The value of $U_{\text{min}}$ depends on the electrode material and the gradient of the linear voltage increase is defined by the opening velocity of the switch. Switching of different currents $I_{S0}$ has no influence on the voltage waveform and all the experiments show that there is no nonlinear increase of the arc voltage close to the moment of current interruption. That means that the value of the arc voltage correlates only with the gap of the opening switch.

As mentioned, the current $I_S$ in the test circuit is suppressed by the upcoming voltage of the opening switch. The experiments show that the value of $I_{S\text{min}}$, where the current in the circuit is interrupted, correlates with the gap of the opening switch. Due to different opening velocities and different values of $I_{S0}$, current interruption happens at different times after contact separation. Fig. 3 shows the correlation between $I_{S\text{min}}$ and the contact gap d for gold-plated contacts.
The experiments show also two interesting facts:

- For small gaps up to some tens of μm the value of $I_{\text{Smin}}$ correlates with $I_{\text{min}}$ of an arc ($I_{\text{min}}$ being the minimum current for a stable burning arc. The value of $I_{\text{min}}$ depends on the contact materials and is 0.35 A for gold-plated contacts [8]). This means also that for $I_S < I_{\text{min}}$ no stable arc is burning at contact separation.

- Subsequently to the region where $I_{\text{Smin}}$ defines the interruption of the arc we have a strong increase of the value of $I_{\text{Smin}}$. In literature [7] the transition from a metal arc to a gas arc is described for this area of contact gaps.

The experiments show that for these small distances the voltage of the burning arc correlates only with the contact gap and that we have a linear increase of the voltage till current interruption. So the voltage over a switch with a stable burning arc can be described with eq. 1:

$$U_S = U_{\text{min}} + V_{\text{open}} \cdot t_{\text{open}} \cdot E_S$$  \hspace{1cm} (1)

This equation describes the voltage waveform starting from contact separation ($t_{\text{open}} = 0$) until the moment of current interruption ($I_S < I_{\text{Smin}}$). $E_S$ in V/m can be calculated from the linear increase of the voltage $U_S$.

### 3. Current commutation to parallel path

As mentioned above one of the main tasks of such switches realized by a series connection of contacts is the current commutation in a hybrid system. The test circuit as shown in fig. 1 has been modified to investigate such behavior and to verify the model for the commutation process.

Fig. 4 shows the changes in the test circuit. There is an additional ohmic-inductive path parallel to the opening switch. Experiments are made with different values of $R_p$ and $L_p$ and the waveforms of $U_S$ and $I_F$ are measured.

In fig. 5 the model for the switch with the parallel path is shown together with a graphic where the influence of the different parameters to the calculated current waveform in the parallel path can be seen.

$$I_p (t) = I_{p_0} + (I_{p_0} - I_{p_\infty}) \cdot e^{-\frac{t}{\tau}}$$  \hspace{1cm} (2)

Contact separation occurs at $t = 0$ and the current in the parallel path increases as shown in fig. 5. $I_{p_0}$ considers a current flowing before contact separation. The values of the parameters $I_{p_0}$ and $\tau$ of the exponential curve can be calculated with help of the voltage $U_S$, the resistor $R_p$ and the inductor $L_p$. $I_{p_\infty}$ and $\tau$ characterize how fast the current commutates to the parallel path. The value of $U_S$ represents the voltage over the one opening switch of this test circuit. For a series connection of contacts, $U_S$ represents the voltage over all opening contacts.
If the arc current in the switching path falls below \( I_{S\text{min}} \) \((\rightarrow I_p = I_C - I_{S\text{min}})\), the arc is interrupted and the current in the parallel path swings (frequency is given by the inductivity of \( L_p \) and the capacitance of the open contact) into the current \( I_p \) of the circuit. In the diagram (fig. 5) this moment of arc interruption can be identified with help of the chain dotted line \((I_C - I_{S\text{min}})\). Fig. 6 and fig. 7 show two measured current waveforms of the current \( I_p \) in the parallel path for different values of \( I_C, R_p \) and \( L_p \). It can be seen that the position of the chain dotted line has a great influence to the curve form and velocity of the current commutation process.

Fig. 6: Measured current waveform of \( I_p \) in the parallel path \((I_C = 1.75 \text{ A}, I_{S\text{min}} = 0.35 \text{ A}, R_p = 10 \text{ }\Omega, L_C = 12 \text{ }\mu\text{H}, I_p = 1.3 \text{ A})\)

Fig. 6 shows that the measured waveform of the current \( I_p \) fits with the expected exponential characteristic. Only the upcoming voltage \((U_S \text{ is not constant})\) over the opening contact results in a linear increase in the waveform shortly before current interruption.

At \( I_{S\text{min}} = 0.35 \text{ A} \) \((I_C - I_{S\text{min}} = 1.4 \text{ A})\) the current in the switch is interrupted. Commutation of the current \( I_C \) to the parallel path happens in a few \( \mu\text{s} \) \((\tau = 1.2 \mu\text{s})\).

Fig. 7: Measured current waveform of \( I_p \) in the parallel path \((I_C = 1.4 \text{ A}, I_{S\text{min}} = 0.7 \text{ A}, R_p = 33 \text{ }\Omega, L_p = 12 \text{ }\mu\text{H}, I_p = 0.4 \text{ A})\)

If the chain dotted line in fig. 5 is above the line of \( I_{p\text{c}} \), \((I_C - I_{S\text{min}} > I_{p\text{c}})\) a complete different waveform for the commutation process (fig. 7) is measured. The current in the parallel path increases very fast \((\tau = 0.3 \mu\text{s})\) up to \( I_{p\text{c}} = 0.4 \text{ A}\). So only a part of \( I_C = 1.4 \text{ A} \) is commutated and the arc is still burning. The linear growth of \( I_p \) is now caused by the increase of \( U_S \) (opening switch). When the current in the path of the switch falls below \( I_{S\text{min}} = 0.7 \text{ A} \) the arc is interrupted and \( I_p \) swings into \( I_C = 1.4 \text{ A}\).

4. Current commutation between parallel switching paths

If a path of series connected small contacts is not able to carry or to switch the overall current, several such paths have to be added in parallel, to a so-called matrix. As a result of the different times of contact separation there is also current commutation between the parallel paths. To prevent overload of single paths of such a matrix it is necessary to know the current distribution and the additional current load. To investigate switching with parallel paths the switch in the test circuit has been modified. The switch consists now of three parallel paths, each with a one pin wrap connection (arc voltage is described by \( U_S \)), driven together by a pneumatic actuator. Resistances and coils can be replaced in each parallel path. Fig. 8 shows the equivalent circuit diagram of this matrix switch.

Fig. 8: Equivalent circuit diagram of the switch with three parallel paths.

The value of \( R_p \) is given by the contact resistances and additional inserted resistances. The value of \( L_p \) is influenced by the geometry and additional added coils.

If contact separation occurs in one of the paths, the current of this path is commutated to the other parallel paths. The reduction of the current, starting from the value \( I_{p\text{c}} \) flowing at contact separation, can be described with an exponential decrease, the amount of the commutated current is characterized by \( \Delta I \) and the velocity by the time constant \( \tau \):

\[
\Delta I = \frac{U_S}{R_p + R_p} \quad \text{and} \quad \tau = \frac{L_p}{m - 1}
\]

with \( m \): number of parallel paths
Out of fig. 9 it can be seen that for $\Delta I > I_{P0} - I_{S\min}$ additional facts have to be mentioned for the calculation of the current distribution:

- Only the first part of the curve is important for the calculation. If the current in the path with the opening switch falls below $I_{S\min}$ the arc is interrupted and the current swings into zero.
- $I_{P0}$ instead of $\Delta I$ is commutated to the other parallel paths.
- If the whole current is commutated and the arc is interrupted, the number of parallel paths for the calculations has to be reduced by one.

Fig. 10 shows the measured current waveforms in the three parallel paths of the matrix:

Before starting the switching operation, the current is equally distributed in the parallel paths of the matrix. When the switch in one of the parallel paths is opened (1) the current decreases ($\Delta I = 0.78\, \text{A}, \, \tau = 1\, \mu\text{s}$) and is distributed equally to the other two paths. The same happens when the next switch in one of the other parallel paths opens (2). When the current in the path of the first contact separation falls below $I_{S\min}$ the arc is interrupted (3). Then the last switch opens (4) and after arc interruption (5) in one of the both current carrying paths, the other path has to interrupt the whole current (6).

So the amount of the commutated current is influenced by $U_S$ and the resistance $R_P$. The value of $U_S$ is given by the linear upcoming of the voltage, starting at $U_{min}$ over all contacts connected in series. By adequate choice of $R_P$ the current overload in the parallel paths of a matrix can be limited to uncritical values.

5. Conclusions

Realizing switches with a series and parallel connection of contacts fails when the current commutation between the parallel paths due to the jitter at contact separation is accelerated by switching in an area with a negative voltage-current characteristic of the burning arcs. The experiments show that this negative characteristic can be avoided, by using switches with contact gaps up to one mm and interrupting currents of some ampere. The arc voltage there is determined uniquely by the gap of the contacts. In a matrix, built up of these small low-current contacts, the current commutation is only caused by the different opening times of the contacts. The presented model and additional basic experiments show that this current overload can be limited to uncritical values. So these small low-current contacts are proper for realizing matrix switches for higher switching capacities. Further investigations are necessary to define the design of such matrices and if the requirements on the parameters result in practicable solutions.

References


Manfred Grader was born in Austria in 1971. He graduated in 2001 from the Vienna Technical University in Electrical Engineering and is currently a PhD-candidate at the Swiss Federal Institute of Technology in Zurich, Switzerland.