Dimensions of matrix switches consisting of a series- and parallel-connection of numerous low-current contacts and requirements on their elements

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Abstract: This paper presents a new method for realizing switches in medium and high voltage systems with fast, low-current contacts. Naturally given effects of these contacts, such as the minimum voltage of a steady arc burning 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. It is studied how such matrices have to be arranged to realize current-limiting breakers, synchronous circuit breakers and dc breakers for various voltage levels. Basic experiments show how the properties of the switches and the parameter of the additional matrix elements influence the design of such matrices. Two problems affect the successful realization of such switches. First, a high number of contacts connected in series causes unacceptable nominal power losses. Secondly, the current commutation between the parallel paths during the switching operation can result in a current overflow in single paths. Thus, for a practicable realization of matrices for applications at high voltage levels, contact resistances in the sub-μΩ range and a variation of the opening times in the sub-μs range are necessary. These requirements cannot be reached by using switching elements of conventional technology. Apart from this, the studies show that the properties of fast, low-current contacts can be utilized to realize current-limiting breakers, synchronous circuit switches and dc breakers with the help of such matrix switches.

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.

Research on a potential current-limiting breaker technology that involve the use of a hybrid system [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. The contacts of such a matrix switch have low mass and a small gap distance and can so be separated very fast. A steady arc, burning after contact separation, has in any case a minimum voltage (cathode fall) between the open contacts of more than 15 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]. With a series connection of small contacts these naturally given effects can be utilized to reach a high breaking capacity. To achieve a higher current carrying capacity several such paths of small contacts in series have to be added in parallel to the so-called matrix switch.

To dimension such matrix switches for different applications (synchronous circuit breaker, current limiting breaker, dc breaker) it is necessary to know the switching properties of the switching elements (small, low-current switches) of the matrix. Therefore, in order to find out the switching properties of these small, low-current switches, experiments were carried out with a dc circuit which is interrupted by a series connection of these switches. The experiments show how the run of the voltage over the opening contacts and the dielectrical strength of the series connection can be determined. It is also pointed out how the contact parameters influence the switching behaviour of the elements of the matrix.

With help of the results of these basic experiments the dimensions of matrices used as synchronous circuit breakers, current limiting breakers and dc breakers are calculated for different voltage levels. The problems caused by the high number of contacts needed for current limiting breakers and dc breakers at high voltage levels and the resulting high thermal power losses are
discussed and leads to the idea of integrating this matrix switch in a hybrid system.

The findings of the basic experiments and the results of the calculations to estimate the size of matrix switches for different applications are presented in this paper.

2 SWITCHING PROPERTIES

To design a matrix switch for different applications and voltage levels it is necessary to know the switching properties of the switching elements of the matrix and how additional elements (resistances, coils) in the parallel paths of the matrix influence the switching behaviour. This behaviour was investigated for small, low-current switches with help of a dc test circuit.

2.1. DC Switching

To gather information on the switching behaviour of small, low-current switches a dc circuit has been set up as seen in fig. 1.

Fig. 1: Design of the dc test circuit interrupted by a matrix switch S.

The capacitor C has been charged to a voltage $U_C$. The value of current $I_S$ at the beginning of the switching operation is defined by $R_V$. The time constant ($\tau = R_V C$) of the circuit is high enough that switching is not influenced by the discharge of the capacitor C. With help of inductance L the slew rate of the current in the test circuit can be influenced during the switching process. The matrix switch S is realized with a different number of parallel paths, each path consisting of a different number of switches connected in series. Fig. 2 shows the realization of such a path.

The switches $S_n$ in the path are driven with a common drive circuit ($U_A$, $L_A$, $R_A$). It is possible to add inductances ($L_P$) in the parallel paths and capacitors ($C_{Pn}$) to each switch.

2.2. Arc voltage

Fig. 3 shows a typical voltage waveform for a matrix switch, made up of one path of ten small, low-current switches, interrupting a dc circuit.

Fig. 3: Typical voltage waveform of a series connection of ten opening switches with arcs burning after contact separation.

The opening command is given at time $= 0$ and the separation of the first contact pair occurs about 500 $\mu$s later. If a steady arc is burning at contact separation the voltage 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) [6]. So the steps of the voltage waveform of fig. 3 are a result of the scatter of the times of contact separation between the different switches of the path. The linear growth of the voltage is defined by the velocity of the opening switches.
The current $I_s$ of the dc circuit is suppressed by this growth of the voltage $U_s$ of the matrix switch and the interruption of the current occurs sharply when the current falls below $I_{s\text{min}}$ [7].

Fig. 4 shows that contrary to this discussed linear growth of the matrix voltage there is a non-linear increase of the voltage before current interruption.

This strong increase is caused by the negative voltage-current characteristic of the burning arcs. The reduction of the current in the test circuit causes a non-linear increase of the voltage near the interruption of the current. The result of this current interruption is a transient overvoltage of about 1300 V. The series connection of the open switches is able to withstand the voltage rise over the contacts. The frequency of this voltage waveform and the splitting of the voltage over the small switches can be influenced by the parallel capacitors.

If an arc is burning after contact separation the run of the matrix voltage can be characterized as follows:

- Voltage jumps at the time of contact separation of each switch in the range of the minimal arc voltage.
- Linear increase of the voltage for small contact gaps and no decrease of the current in test circuit (voltage over the matrix switch is not high enough to limit the current in the test circuit).
- Strong and non-linear increase of the voltage caused by the negative voltage-current characteristic of the burning arcs.

### 2.3. Electrical strength

If the current in the path is below $I_{s\text{min}}$ there is no stable arc burning at the time of contact separation and as fig. 5 shows there are multiple reignitions up to the moment where the open contacts are able to interrupt the test circuit.

Fig. 5 also shows that the gap withstand voltage is in the range of some hundreds of volts even for this small contact gap of some μm. With help of the series connection of the open contacts a high electrical strength for the matrix switch can be reached. The splitting of the voltage over the small switches connected in series is optimized by parallel capacitors. These capacitors also influence the increase of the voltage over the open contacts.

The dielectric strength of the contact gaps can be defined as follows:

- For small contact gaps (μm-range) and/or after arc extinction the electrical strength is in the range of some hundreds of volts.
- The dielectric strength of open switches is given by the contact gap and pressure of the isolating medium (Paschen’s Law).

### 2.4. Properties of the switches

The properties of the switches themselves influence the interruption process of the matrix switch.

The scatter of the times of contact separation influences the course of the arc voltage of the series connection of the contacts. This scatter means also different contact gaps and dielectrical strength of the switches during the interruption process.

The velocity of the contact separation influences the rising of the arc voltage of the opening contacts. At small contact gaps a high velocity can result in a bouncing of the switches.

The choice of the contact material defines the minimal arc voltage and minimal arc current. It also defines the contact resistance and the power losses of the closed contacts.
3 MATRIX DIMENSIONS

With the knowledge of the switching behaviour and the properties of the small switches it is now possible to define the number of switches \( n \times m \) of a matrix as shown in fig. 6.

![Diagram of a matrix switch](image)

Fig. 6: Matrix switch of \( n \) switches in series and \( m \) parallel paths.

Each path consists of \( n \) switches in series and additional to the switches, inductors and resistors can be connected in series. If the current capacity of the single switches is too low to carry the whole rated current of the circuit, the matrix switch has to be made up of several paths (\( m \)) in parallel. The problems caused by the current commutation between the parallel paths were discussed in [8].

3.1. Dimension parameters

The dimensions of a matrix are influenced by the system parameters (voltage and current levels of the circuit) and by the parameters of switching elements. So the calculations are made for different ratings in medium and high voltage levels as shown in tab. 1.

<table>
<thead>
<tr>
<th>Voltage levels</th>
<th>12 kV, 36 kV, 72.5 kV</th>
<th>145 kV, 245 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated current</td>
<td>800 A – 1250 A</td>
<td>1250 A – 2000 A</td>
</tr>
<tr>
<td>short-circuit current</td>
<td>16 kA, 20 kA, 25 kA</td>
<td>31.5 kA, 40 kA</td>
</tr>
</tbody>
</table>

Tab. 1: Voltage and current values for the calculation of the dimensions of a matrix.

For the switching elements of the matrix typical parameters of small, low-current switches have been taken:
- Ampacity: 2 A
- Basic Insulation level: 1800 V
- Arc voltage: 20 V (constant)
- Contact resistance: 1 mΩ

3.2. Number of switches for synchronous circuit breakers

The intention to realize current limiting breakers, dc breakers and synchronous circuit breakers with help of a matrix switch, results in different numbers of contacts for these applications. Fig. 7 shows the results of the calculations for synchronous circuit breakers.

![Diagram of matrix switch dimensions for synchronous circuit breakers](image)

Fig. 7: Dimensions (\( n \times m \)) of matrix switches used as synchronous circuit breakers.

The required dielectrical strength for the open matrix switch and for the successful interruption at current zero can be obtained with \( n \) switches connected in series (multiplying the basic insulation level of the low-current switches). Fig. 7 shows the results for different voltage levels \( U_r \).

The short current (Isc) carrying capability of the low-current contacts defines the number \( m \) of the parallel paths.

3.3. Number of switches for dc breakers and current limiting breakers

Fig. 8 shows the results of the calculations for dc breakers and current limiting breakers.

![Diagram of matrix switch dimensions for dc breakers and current limiting breakers](image)

Fig. 8: Dimensions (\( n \times m \)) of matrix switches used as dc breakers and current limiting breakers.
For realizing dc breakers and current limitation breakers, the upcoming voltage over the opening contacts has to be in the range of the rated voltage. So the arc voltage of the single low-current contacts defines the number n of contacts connected in series that are necessary for an effective current limitation and dc switching.

Because of the short current limitation of such matrix switches the number m of parallel paths is given by the capability to carry the rated current $I_r$.

### 3.4. Power losses

Calculating the dimensions for different matrix switches, it can be seen that a high number of switches is needed for higher voltage levels, especially for dc breakers and current limiting breakers. This results in the problem of high power losses for such matrix switches. In fig. 9 the resulting power losses are compared for the discussed matrix switches.

![Fig. 9: Power losses relating to the rating current for the different applications of the matrix switch.](image)

The power losses are related to the rated current and calculated for different rated voltages. The comparison shows the high power losses of the dc breakers and current limiting breakers, a result of the high number of switches connected in series.

For $U_r = 72.5$ kV and $I_r = 1250$ A this results in nominal power losses of 140 W for a synchronous circuit breaker and 7.25 kW for a dc breaker or current limiting breaker.

To obtain acceptable power losses for these applications it is necessary to call for contact resistances in the sub-$\mu\Omega$ range. These values cannot be reached with conventional technologies for low-current switches.

### 3.5. Hybrid switch

Fig. 10 shows the required number of low-current switches (n x m) for realizing synchronous circuit breakers in comparison to short current limiters and dc breakers.

![Fig. 10: Comparison of the dimensions (n x m) of matrix switches for different applications.](image)

This comparison shows that the number of low-current switches can be reduced by integrating the matrix switch in a hybrid switch HS. In such a hybrid switch the short circuit current for a synchronous circuit breaker is carried by other elements of the hybrid system. For short current limiters and dc breakers the upcoming voltage over the series connection of the small switches is used to commutate the current in the parallel paths of such a hybrid system. So the number of switches (n x m) can be reduced as shown in fig. 10.

### 4 CONCLUSIONS

The basic experiments point out how the parameters of the small low-current switches influence the switching behaviour of such a series connection of switches and how they have to be mentioned when dimensioning the matrix switch for different applications. The appearance and extinguishing of an arc is given by the minimal arc current. If an arc is burning the run of the increasing matrix voltage is a result of the jumps to the minimal arc voltage at contact separation of each switch connected in series and the opening velocity of the switches. The voltage waveform shortly before current interruption is influenced by the negative voltage-current characteristic of the burning arcs. With help of a high withstand voltage of some hundreds of volts even for smallest contact gaps we can reach a high dielectrical strength for the series connection of the switches. The scatter of the contact separation influences not only the run of the voltage over the opening contacts; it also results in a current commutation between the parallel paths of the matrix switch.

Out of these findings the number of switches is calculated to realize synchronous circuit breakers, dc breakers and current limiting breakers for different voltage levels with help of the matrix switch. The calculations show the differences in the required number of switches for the different applications,
especially the high number of switches in series for dc breakers and current limiting breakers at high voltage levels results in the problematic of the high nominal power losses. Thus, for a practicable realization of matrices for applications at high voltage levels, contact resistances in the sub-μΩ range are necessary. This cannot be reached by using switching elements of conventional technology.

Apart from this, the studies show that the properties of fast, low-current switches can be utilized to realize current-limiting breakers, synchronous circuit breakers and dc breakers with the help of such matrix switches. To avoid the problems caused by the required high number of switches, a practicable solution will be to integrate this matrix switch in a hybrid system.

5 REFERENCES


