Ultra fast switches – Basic elements for future medium voltage switchgear

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presented by
Walter HOLMUS
Dipl.-Ing., Vienna University of Technology, Austria
born on 24 December, 1972
citizen of Austria.

Accepted upon recommendation of
Prof. Dr. Klaus FRÖHLICH, examiner
Prof. Dr.-Ing. Jörg HUGEL, co-examiner
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Zurich, September 2001

Walter Holaus
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Abstract

The steadily increasing demand on electric energy and the continuing liberalization process of the electricity market raise the utilities' need for further reduction of operation costs, increased functionality and power quality. One possibility to do so is the use of fault current limiters. Although many solutions for fault current limiting devices at medium and high-voltage levels have been presented in literature, utilization of these limiters is restricted to particular installations due to missing economical feasibility. One specific hybrid system for current limiting using an assembly of three electro dynamically driven opening switches, power semiconductors and a pure wire resistor, was already proposed and successfully tested in this ongoing research project. This solution has a much better potential of being economical than previous ones but some features are still not satisfying.

Therefore, in the present work, investigations for medium-voltage fault current limiting devices were decided starting from a fundamental discussion on ultra fast-acting switches. As the basic element of these ultra fast switches, so-called "elementary switches" are defined which are only capable of carrying the nominal current when closed and withstanding the dimensioning voltage when open. The basic idea of the project was, to realize high power switchgear with a combination of such elementary switches using precise control of the operation instants. Elementary switches are not designed to withstand high-current arcing and they do not have facilities for forced arc cooling. Given this definition and using a repulsion drive, the vital characteristics of elementary switches using linear or rotational operation are derived as follows:

The moving mass in an elementary switch turns out to be around 1 g/MW dimensioning power, resulting in a drive energy requirement of several 100 J depending on design parameters. Linear operation requires up to 3 times the drive energy at rotational operation, especially if using air as switching medium. A generally applicable equation for calculating the resulting opening velocity as a function of design parameters is given. The results were compared to measured velocities and show good coincidence for linear and rotational operation up to 50 m/s.

With the use of several implementations of elementary switches, theoretical and experimental investigations of its switching performance were conducted. Elementary switches can also be closed using a repulsion drive, re-
sulting in an overall closing time down to 0.5 ms. The contact force required
to carry the nominal current is provided by the inertia of the moving part
and results in a 20 % decrease of opening velocity. Repetitive switching at a
repetition frequency above 10 Hz is not feasible due to bad drive efficiency.

Elementary switches are well suited for synchronous interruption of high ac
currents at medium voltage levels up to 24 kV. As the energy dissipated by
the arc at synchronous interruption is only around 1 J and the fast switch
noticeable increases its contact gap during rise of TRV, elementary switches
show a dielectric breakdown mechanism. The reignition voltage linearly in-
creases with time from current zero but shows at least minimum break-
down strength according to the instantaneous recovery.

The arc voltage of fast opened elementary switches is higher than the arc
voltage of free burning arcs but lower than the one of strongly cooled arcs.
This can be utilized to commutate high currents on a parallel resistor or ca-
pacitance. Both are treated theoretically and experimentally with an eye on
applications in a hybrid system.

Applications of elementary switches arise either from combinations of sev-
eral switches in series or in parallel with one common drive or by using the
switches in a hybrid system. Combinations of elementary switches in paral-
lel leads to a further reduction of dissipated arc energy in any single switch.
A combination of many elementary switches in series leads to a linearly in-
creasing gain of breakdown strength after synchronous interruption. The-
oretically, even the ability for transient recovery performance of a standard
vacuum switch is obtained by a combination of elementary switches using
air at 5 bar, 12 breaks in series and an opening velocity of 50 m/s. A hybrid
fault current limiting circuit breaker using three elementary switches or
combinations with many breaks in series and one pure-wire resistor is pro-
posed together with a trigger strategy to get low contact wear at load
switching. Successful tests in a medium voltage circuit were performed.
Feasibility of this system is given up to a rated voltage of 24 kV and a rated
current of 2...3 kA.

It is concluded from this work, that the given characteristics of ultra fast act-
ing switches have the potential to be the basic elements for future applica-
tions in medium voltage systems, such as fault current limiting circuit
breakers and dc breakers.
Kurzfassung


In der vorliegenden Arbeit wird ein wirtschaftliches System zur Strombegrenzung in der Mittelspannung ausgehend von einer grundlegenden Diskussion über sehr schnelle Schalter und ihrer Eigenschaften untersucht. Dazu werden sogenannte „elementare Schalter“ (elementary switches) definiert, welche im geschlossenen Zustand den Dimensionierungsstrom führen können und im offenen Zustand die Dimensionierungsspannung halten können. Es wird aber nicht gefordert, dass sie Lichtbogenbelastung ertragen können und sie haben keine Einrichtungen zur forcierten Lichtbogenkühlung. Leistungsschalter erhält man durch geeignete Kombination von elementaren Schaltern und exakter Steuerung. Für Schalter, welche nach dieser Definition konstruiert werden und welche elektrodynamisch angetrieben sind, wurde folgende charakteristische Eigenschaften für lineare- und rotierende Öffnungs- und Schliessbewegung gefunden:

Die bewegte Masse eines elementaren Schalters ergibt sich zu etwa 1 g/MW dimensionierte Leistung, wofür einige 100 J an Antriebsenergie abhängig von Designparametern benötigt werden. Lineare Bewegung benötigt bis zu 3 mal mehr Antriebsenergie als rotierende Bewegung, im besonderen, wenn ein schlechtes Schaltmedium wie Luft bei 1 bar verwendet wird. Eine allgemeine Formel zur Berechnung der resultierenden Öffnungs- und Schliessgeschwindigkeit als Funktion der Konstruktionsparameter wird angegeben und zeigt eine gute Übereinstimmung mit Messergebnissen für lineare- und rotierende Bewegung bis 50 m/s.

Verschiedene elementare Schalter wurden realisiert und damit und mit Hilfe theoretischer Überlegungen die Schalteigenschaften bestimmt:
Elementare Schalter können auch elektrodynamisch geschlossen werden, wobei Schliesszeiten bis zu 500 μs möglich sind. Die Kontaktkraft im geschlossenen Zustand wird durch die kinetische Energie des bewegten Kontaktstückes aufgebracht und verringert die Öffnungsgeschwindigkeit um etwa 20 %. Getaktetes Schalten mit einer Wiederholfrequenz über 10 Hz ist aufgrund des schlechten Antriebswirkungsgrades nicht sinnvoll.

Elementare Schalter sind sehr gut für die synchrone Stromunterbrechung auch bei hohen Strömen in der Mittelspannung geeignet. Die im Lichtbogen umgesetzte Energie beträgt dabei nur etwa 1 J und die Schalter erreichen eine deutliche Vergrösserung des Kontaktabstandes während des Anstiegs der wiederkehrenden Spannung. Die Schalter zeigen daher einen dielektrischen Wiederzündmechanismus, wobei die Wiederzündspannung linear mit der Zeit nach Stromnull ansteigt und grösser als die Sofortverfestigung ist.

Die Lichtbogenspannung elementarer Schalter ist aufgrund der schnellen Öffnung höher als die eines frei brennenden Lichtbogens aber niedriger als die eines stark gekühlten Bogens. Diese Eigenschaft wird benutzt, um hohe Ströme auf parallele Widerstände und Kapazitäten zu kommütieren. Dieser Vorgang wird analytisch beschrieben, vor allem im Hinblick auf einen Einsatz dieser Schalter in einem hybriden System.


Aus den Ergebnissen dieser Arbeit wird gefolgt, dass diese Schalter mit ihren spezifischen Eigenschaften das Potential besitzen, um als Basislemente für zukünftige Anwendungen wie etwa strombegrenzende Leistungsschalter und Gleichstromschalter in der Mittelspannung zu dienen.
1 Problem statement

The evolution of circuit breakers has led to the invention and utilization of various switching principles and optimized switchgear design; in each case switching principles are based on the specific characteristics of the electric arc.

Circuit breakers rely upon the characteristics of the electric arc
The electrical switching arc manifests the general conditions for understanding the possibilities and limitations of electromechanical power circuit breakers. One of the specific arc characteristics is an arc voltage in the range of some tens to some hundreds of volts per break. Another feature is the build-up of an instantaneous dielectric recovery in the range of some hundreds of volts after current interruption. For effective (fault) current limitation, the voltage drop across the limiting element has to be commensurate to the system voltage. Thus in low voltage systems, i.e., below one thousand volts, the arc itself is used for current limitation and for withstanding the transient recovery voltage after interruption. At higher voltage levels, the arc voltage is too small for effective current limitation even if a switch could be made to perform instantaneous triggering and opening.

Missing economically viable solutions for current limiting at high voltage
Fault current limitation reduces the mechanical stresses on components due to the high instantaneous currents of a faulted circuit. Mechanical forces are increasing with the square of short-circuit current. Therefore, many scientific attempts have been made searching for high voltage fault current limiters or fault current limiting circuit breakers, resulting in several technically feasible solutions. Anyhow, today’s solutions – semiconductor switches, hybrid systems, superconductor limiters, upgraded fuses – show economical feasibility only in very specific applications.

New switchgear technology based on fast switches
In the ongoing research project „New Switchgear Technology“ (NST), fault current limiting systems for the medium voltage range based on extremely fast-acting electro-dynamically driven switches are investigated. Steurer [42] describes one particular hybrid fault current limiting system, which was suc-
cessfully tested (at 10 kV, 11 kA). This hybrid system compiles the advantages of electromechanical switches (low losses if closed), semiconductor switches (no switching arc, immediate triggering) and a pure wire resistor (PTC-effect, high energy absorbing capacity). Although this solution provides a significant input to the difficult task of fault current limiter development, it still has disadvantages such as:

- No fast closing mechanism for the switches
- Expensive Semiconductors
- Complex hybrid arrangement

Considering these, it has to be questioned whether even better solutions could be available, in particular as the experience gained in the previous work on the fast commutation switch was very promising.

Therefore the present work was started in order to augment the knowledge on extremely fast-acting switches by theoretical and experimental investigations of single switches and continued by investigating how they can be utilized for better solutions for fault current limiters and possibly other type of switchgear.
2 State of the art

It is better to ask some of the questions than to know all the answers.
James Thurber (1894 - 1961)

In the first section, the principle of circuit interruption using today's electromechanical breakers is resumed for readers that are not familiar with this topic. Specific applications for high power breakers requiring very fast operation are reported in the second section. The third section deals with the specific characteristics of very fast-acting high power switches to give a starting point for the investigations in the present work.

2.1 A survey on circuit interruption

Generally, the attributes of electrical contacts, their physical and electrical properties and the characteristics of the switching arc together with its current switching capability have been summarized in many text books, amongst them are Holm [1], Flursheim [2] and recently a comprehensive work by Slade [3]. Focused either on the properties of the switching arc and contact materials (e.g. [4] - [6]), on the transients occurring during circuit interruption (e.g. [7] - [9]), or on switchgear technology (e.g. [10] - [15]), the topic of switching in electric power systems is well described in literature. Therefore, this survey will be focused on the items related to the present work on fast switches.

The need for increased switching capability in economical solutions has led to continuously improved and specialized switchgear. Today, electromechanical switches – circuit breakers, load switches, earthing switches, contactors, disconnectors – and semiconductor switching devices find applications in power systems.

For successful current interruption, a contact pair is separated, the resulting switching arc must lose conductivity at a following current zero, and finally the rate of rise of dielectric strength of the contact gap has to be faster than the rise of the transient recovery voltage (TRV) that is imposed across the contacts by the system. The principle of the interrupting process is fundamentally dependent on the system voltage level [3], [6], [16] and therefore switching principles will be discussed separately for low voltage
switching principles will be discussed separately for low voltage systems (standardized for rated voltages < 1000 volt [27]) and high voltage systems.

2.1.1 Low voltage breaking with fault current limitation

Circuit breakers must be able to switch normal currents, overload currents and short-circuit currents on and off.

Principle of modern low-voltage circuit breakers

In low-voltage circuit breaker, the arc is typically influenced by arc chutes as described by Lindmayer [16] to improve cooling of the arc column and thus raise the arc voltage. Modern designs mostly use the so-called deion-plates: The arc is “forced” by a magnetic blast field of a properly designed current loop into an arcing chamber, where it is split into several series arcs by a stack of insulated ferromagnetic conducting pieces separated by a distance of 1 mm. The formation of new anode and cathode fall regions on each segment leads to a higher arc voltage and to a multiplication of the so-called instantaneous recovery due to additional cathode sheets after current interruption. This type of circuit breaker is suitable for dc switching and current-limiting ac short circuit interruption as the arc voltage can be raised above the instantaneous system voltage. An overview of low voltage switching principles is e.g. given by Berger [26].

Besides having a sufficiently high arc voltage, triggering and contact separation of an effective fault current limiting breaker have to occur within 1 ms after fault inception [31]. This very short reaction and opening time is normally achieved by using the increasing fault current itself in the drive mechanism, utilizing the magnetic repulsion of anti-parallel and closely spaced current paths [3] p. 652 ff.

Electromechanical breaker and semiconductor devices for current limitation at low voltage are compared in [95]. It is shown, that the solutions using power semiconductor show several times higher on-state losses, several times higher price and have several times higher space requirements for realization compared to a mechanical breaker although they will show a higher electrical lifetime.

2.1.2 Circuit interruption in medium and high voltage systems

An up-to-date overview of the different types of high-voltage breakers and their qualities are given e.g. by Garzon [15] and Lindmayer [16].
Principle of current interruption in high-voltage ac systems

The principle of current interruption in high-voltage systems is briefly discussed following Greenwood [7] p.37ff to introduce the relevant parameters. Fig. 1 shows the waveforms typical for current interruption in an inductive ac-circuit with standard electromechanical switchgear. The circuit breaker (CB) is commanded to open at \( t_1 \). Separation of contacts and drawing of the switching arc occurs several ten milliseconds later at \( t_r \). The arc voltage \( U_a \) will range from some tens of volts (short arc) up to some kilovolts (strongly cooled, extended arc) but is normally negligible compared to the system voltage \( U_n \). The current is therefore practically unaffected by the arc. Interruption of the current is accomplished at one of the following current zero-crossings by forced cooling of the arc column, so that the arc loses conductivity. Immediately after current interruption, the transient recovery voltage (TRV) starts to rise across the gap. The interruption process is successful (as shown in Fig. 1) if no thermal breakdown during the first few microseconds after current zero and no dielectric breakdown around the TRV-maximum occur [6].

![Fig. 1: Example: Single-phase circuit diagram and typical current and voltage waveforms at interruption of an ac current \( i_a \) with a circuit breaker. The circuit is mainly inductive and has a rated voltage \( U_n \) much higher than the maximum arc voltage.](image)

The overall interruption time (\( t_0 - t_r \)) is two to three periods \( T \) of the power frequency (20 ms in a 50 Hz system) for modern CB-designs, but may last up to 100 ms for older designs or severe breaking conditions such as missing current zeros.

Transient recovery voltage as a function of system parameters and topology

Transients in power systems are fundamentally discussed in textbooks by Greenwood [7] and Rüdenberg [8] and specifically for circuit interruption by Slamecka [24], [25]. The transient recovery voltage \( U_s(t) \) and its transient frequency \( f_t \) are given in Fig. 1 by the system parameters \( Z_{\text{source}} = R_{\text{source}} + \)
2.1 A survey on circuit interruption

\[ j \omega \text{source} C_{\text{sys}}, U_n \] and the phase angle between \( i_s \) and \( U_n \). The TRV can be approximated by Eq. 1 (from [7] p.40) in a single-frequency circuit, which occurs for example when interrupting a terminal fault. Here, \( U_n(t) \) names the system voltage at the instant of current zero \( t_0 \).

\[ t > t_0: \quad U_5(t) = U_n(t) \cdot (1 - \cos(2\pi f_T \cdot (t - t_0))) \quad f_T = \frac{1}{2\pi \cdot \sqrt{\text{source} \cdot C_{\text{sys}}}} \quad \text{Eq. 1 (17)} \]

If interruption takes place in a system with two or more natural frequencies, the oscillation of TRV will become more complex than shown in Fig. 1. One of the most severe faults imposed on circuit breakers in high voltage systems is the so-called “short line fault” [6] p. 30ff. Here the TRV is composed of a source-side transient according to Fig. 1 and a load-side transient, which is of triangular shape due to wave-propagation phenomena on the line. This results in a much higher rate of TRV rise immediately after current zero in the thermal region.

**Gap recovery and the breaker design**

The recovery of the gap after current interruption in gas circuit breakers has been treated by *Ragaller* [6]. The reignition voltage depends on the rate of fall of circuit current at current zero, the quality of arc cooling, the switching medium, its pressure and the rate of rise of the TRV. Sample data for the limits of the recovery as a function of the rate of decrease of current shortly ahead of current zero is depicted in Fig. 2.

**2.1.3 Types of high-voltage circuit breakers**

In Fig. 2, the interruption performance of medium-voltage vacuum breakers, an air blast breaker and SF\(_6\) breakers are given for their according insulating and arc quenching media. Oil, vacuum and SF\(_6\) as switching medium are in use in today’s medium voltage circuit breakers. Oil, air and SF\(_6\) are in use in high-voltage circuit breakers; therefore the characteristics of these types of circuit breakers shall be briefly mentioned in the following section.

**Air blast and oil circuit breaker**

Air blast circuit breakers were once dominant in high voltage applications but have now been widely substituted by SF\(_6\) breakers [15].

In oil circuit breakers, the arc is drawn in oil, forming a bubble of mainly hydrogen by dissociation. Oil is used for insulation and as interruption medium in so-called bulk oil breakers. To minimize dimensions and reduce the oil volume, minimum oil breakers have been developed in the beginning of the century but vacuum breakers and SF\(_6\) breakers are also substituting them.
Vacuum circuit breakers: Radial field contacts and axial field contacts

Vacuum circuit breakers take advantage of the exceptional dielectric strength of vacuum at short gap distances, as is comprehensively discussed by Greenwood [18]. Vacuum as insulating and interrupting medium is mostly used in medium voltage circuit breakers at voltage ratings up to 36 kV [3] p. 663ff. There are two basic types of vacuum breakers in use. Breakers with radial field contacts force the constricted arc to rotate on the contacts in order to evenly distribute the arc energy across the entire contact surface. The magnetic force peripheral to the arc (burning in the axial direction) is provided by the radial magnetic field of the current path, proper shaped in the contacts. Breakers with axial field contacts keep the arc diffuse up to high current values due to an axial field formed by coil-like current paths in the contacts. Vacuum gaps possess an exceptionally fast recovery of dielectric strength within several microseconds after a diffuse vacuum arc, whereas the recovery is strongly influenced by the contact material [18] p. 72. Both vacuum switching principles are currently marketed and do not substantially differ in size and performance, see Fig. 2.

SF₆ circuit breakers

In particular modern high voltage circuit breakers utilize sulfur hexa-fluoride (SF₆) as an insulating and arc-quenching medium, see e.g. Ryan [17], as for
two reasons. Its dielectric strength is three times higher than that of air and it's maximum of thermal conductivity is with about 2000 °K rather low. Therefore, near current zero, when rapid cooling of the arc column is required, SF₆ is superior to other gases. A collection of SF₆ properties is given in [17] p. 8ff.

The pressure necessary for cooling the arc during interruption is either generated by mechanical compression of SF₆ by the drive (puffer principle) or by heating of the gas in an auxiliary volume by the arc itself during the high-current region (self-blast principle). The main advantage of the latter technology is a lower mechanical energy required for the drive [101]. Another advantage of the self-blast technology is, that small inductive currents are interrupted more smoothly, which reduces the dielectric stresses on the power system due to eventual current chopping.

**Drive systems of high voltage breakers**

After tripping of a circuit breaker, it must operate within several power frequency cycles (compare to Fig. 1), even after idling for months or years without operation. The high velocity (up to several m/s) required for the moving contacts in a circuit breaker requires high driving forces to be supplied by the operating mechanism through a mechanical coupling. The drive energy is stored in a mechanical spring or a compressed pneumatic volume. The energy transfer is performed by mechanical, hydraulic, or pneumatic systems [17], [18], [15].

### 2.2 Fast switchgear and their application

For synchronous interruption and for fault current limiting switching times much lower than one cycle (compare to Fig. 1) are required. Specific drive designs and/or other interrupting principles are therefore necessary. Some existing solutions and applications for very fast switches are reviewed in this section. With an eye on the focus of this work, the explanations will be restricted to medium- and high voltage applications rather than on low voltage principles.

#### 2.2.1 Synchronous circuit breakers

The basic idea for synchronous interruption is to trigger a very fast-acting switch shortly prior to current zero (see Fig. 1 with \( t_u - t_e \leq 1 \text{ ms} \)) in order to minimizing arcing time. A reduction of arc energy input and arc erosion results is the primary benefit [29]. Solutions of very fast opening synchronous
ac circuit breakers have been in existence for a long time [30], [29] but were for cost reasons never brought to a widely used product.

Requirements for synchronous circuit breakers

Kesselring [12] p. 193ff has given three requirements to be fulfilled by synchronous breakers:

- The drive has to operate the contacts within 1 ms. Contacts are to be opened shortly ahead of natural current zero.
- Contact distance at current zero has to be sufficient to withstand the transient recovery voltage.
- If the current cannot be interrupted, the contacts are to be immediately closed again. The next interrupting effort can be performed at the next zero crossing.

The first requirement takes for granted that current zero occurrences are exactly known in advance. This requires an accurate and fast current zero detection algorithm, which in every switching case gives the correct signal for triggering the drive. Specific triggering units have been developed for this purpose [29]. Problems occurring during field tests of an ultra fast fault sensor due to transformer inrush currents and highly meshed systems are reported by Lee [32].

The second requirement is a vital requirement for all circuit breakers. For a synchronous switch this is significantly more crucial as there is less time for the contacts to reach sufficient gap distance.

The third requirement results from safety considerations. Synchronous breakers are designed for fast opening but are not designed to endure a high current arc (not even for one half period), because the absence of a high current arc is their main advantage. Thus, if interruption fails, arcing and destruction of the switch can be avoided only by an immediate reclosing of the switch. Interruption is then attempted again at the following zero crossing.

Synchronous interruption does not result in noticeable improvement of interrupting capacity as this, in a gaseous switching ambient, depends on the rate of current fall before current zero and the TRV, both of which are not affected by synchronous switching. [15] p. 321ff (also compare to Fig. 2). Some improvements in interruption capability may be expected if using synchronous interruption in vacuum, because the maximum arc current is much smaller than the peak current to be interrupted and the arc will remain in its diffuse mode [15] p. 336ff.
An electrodynamic repulsion drive for synchronous breakers

For fast reaction, the electrodynamic repulsion drive\textsuperscript{1} was found to be suitable, producing high repulsion forces at repeated operation [33]. The theory and design of such electrodynamic actuator systems are well described in literature [34], [35], [36], [37], [38], [39], [40] and are reviewed below, because this drive will be utilized for the fast switches investigated in the present work. A more detailed discussion of this drive is given by Steurer [42].

An electrodynamic repulsion drive transmits “drive energy” by means of an electromagnetic field, as shown in the schematic diagram in Fig. 3 [39], [40]. A capacitor $C_d$ is charged and connected to a drive coil with $N$ turns via a closing switch $T_1$ to complete a resonant circuit. A conducting disc is placed close to the drive coil. When $T_1$ is closed, a current $i_d$ energizes the drive coil and induces eddy currents within the skin depth of the conductor. $i_d$ and the induced eddy currents are nearly anti-parallel and thus repel each other. The supply impedances $R_o$ and $L_o$ are to be kept as low as possible for maximal efficiency.

![Fig. 3: Principle of a repulsion drive (Thomson drive).](image)

Thomson drives are triggerable with high accuracy by the closing switch $T_1$, which normally is a thyristor. They provide repulsion forces $F_{rep}$ up to several 10 kN, and multiple operation. Due to their low efficiency (less than 10 %) they are used only where such strong acceleration is required [35], [36] that cannot be achieved easily by other principles. Typical values of such drive systems given in literature are: $C_d = 100 \ \mu F$, $L_{drive} = 10 \ \mu H$, $U_d = 1 \ \text{kV}$.

Fig. 4 shows the equivalent circuit for a repulsion drive [39], [40], [35] with the drive capacitor $C_d$, the closing switch $T_1$, the supply impedances $R_o$ and $L_o$ and the impedances of the drive coil $L_v$, $R_v$ (per winding), which include the mutual inductances of the moving part.

\textsuperscript{1} synonyms are: Thomson drive, eddy current drive, electrodynamic actuator, repulsion drive
At low values of the series resistance $R_d = (R_o + N \cdot R_i) < 2 \cdot Z_w$, this circuit represents a resonant circuit with resonant frequency $f_d$, characteristic impedance $Z_w$, and damping time constant $\tau_d$ as given in Eq. 2 [29].

\[
\begin{align*}
L_d &= L_o + N^2 \cdot L_i \\
R_d &= R_o + N \cdot R_i \\
\omega_d &= \sqrt{\frac{1}{L_d \cdot C_d} - \left(rac{R_d}{2 \cdot L_d}\right)^2}, \quad f_d = \frac{\omega_d}{2\pi} \\
Z_w &= \sqrt{\frac{L_d}{C_d}} = \sqrt{\frac{(L_o + N^2 \cdot L_i)}{C_d}} \\
\tau_d &= 2 \cdot \frac{L_o + N^2 \cdot L_i}{R_o + N \cdot R_i} = 2 \cdot \frac{L_d}{R_d}
\end{align*}
\]

Eq. 2 (from [29])

The current of this damped resonant circuit $i_d(t)$ is dependent on the initial voltage $U_d$ of the drive capacitance $C_d$ as given in Eq. 3.

\[
i_d(t) = U_d \cdot e^{-\frac{t}{\tau_d}} \cdot \sin(\omega_d \cdot t)
\]

Eq. 3

Fig. 5 shows the sinusoidal waveform of a drive current having $N = 10$ turns. The first current peak reaches $i_{max} = 4$ kA within 80 $\mu$s. The resonant current $i_d$ is strongly damped since the series resistance $R_d$ is close to $Z_w/2$.

The repulsion force $F_{rep}$ of a repulsion drive can be calculated by the drive current $i_d(t)$, the induced eddy current $i_e(t)$ and the change of the mutual inductance $\frac{dM}{dx}$ between the drive coil and conductor with distance, according to Eq. 4 [12], [35].
\[ F_{\text{rep}}(t) = I_d(t) \cdot I_E(t) \cdot \frac{dM}{dx} = m_c \cdot a_c(t) \]  \hspace{1cm} \text{Eq. 4}

To obtain a high acceleration \( a_c \), high currents, a high change in mutual inductance and a small moving mass are necessary.

For drive frequencies \( f_d > 1 \text{ kHz} \), the repulsion force \( F_{\text{rep}} \) can be approximated according to Eq. 5, where \( K_d \) is a function of the coil diameter and its distance to the moving part [29].

\[ F_{\text{rep, max}}(t) = K_d \cdot N^2 \cdot I_{d,\text{max}}^2 \quad K_d = 10^{-5} \cdots 10^{-6} \left[ \frac{N}{A^2} \right] \]  \hspace{1cm} \text{Eq. 5}

**Applications of synchronous circuit breakers**

*Morita* [41] published a prototype design, featuring an opening velocity of \( v_k = 15 \text{ m/s} \) while moving a total mass of \( m_k = 1.1 \text{ kg} \) with a drive energy of \( E_d = 1.7 \text{ kJ} \). This resulted in a drive efficiency of \( \eta_d = 8 \% \) and an interruption time of \( t_o - t_i \leq 1.5 \text{ ms} \). A prototype synchronous breaker was installed by the American Electric Power utility and remained in service for 15 years but no series production of synchronous breakers was started [15] p. 335. A Japanese manufacturer announced a synchronous SF6 breaker in 1972 as mentioned in [39].

### 2.2.2 The basics of fault current limitation

Ideal fault current limiting devices (FCLD) show negligibly low impedance during normal operation and, in the event of a fault, instantaneously increase their impedance to limit the still rising short-circuit current before it reaches its first current peak [43]. *Steurer* [42], [44] recently has summarized the basics of fault current limitation and possible fault current limiting elements.

**Short-circuit currents in power systems**

To limit a fault current, its evolution after fault occurrence is first to be studied. The event of a short circuit in power systems can mathematically be represented as a turn-on instance as derived e.g. by [7] p. 32ff, see Eq. 6.

\[ I_{sc} = I_{sc} \cdot ( \sin(\omega \cdot t + \alpha) - \sin(\alpha) \cdot e^{-t/T_{sc}} ) \]  \hspace{1cm} \text{Eq. 6}

The short circuit current \( I_{sc}(t) \) depends on the source impedance which gives the peak short-circuit current \( I_{sc} \) and furthermore on the phase angle \( \alpha \) between system voltage and the instant of the fault. \( I_{sc} \) reaches its first peak \( I_{sc} \) within several milliseconds as calculated in Fig. 6 for \( \alpha = 0 \cdots -\pi \) and \( I_{sc} = 20 \) p.u., using a time constant \( \tau = 45 \text{ ms} \) for the dc component according to [100] p. 99 and \( I_{sc} = 1 \).
Fig. 6: Evolution of short-circuit current for various instants of fault occurrence calculated using Eq. 6 [7]. The prospective peak current in the symmetric case $i_{sc}$ is 1 p.u., the time constant was chosen to be $\tau = 45$ ms [100] p. 99.

The peak value of $i_{sc}$ is higher in the asymmetric case, but the current rate of rise within the first millisecond after short circuit inception is highest in the symmetric case. Fig. 6 also shows the evolution of the short-circuit current for various cases in between. The horizontal line is given at 0.3 pu, which might be a desirable value for the maximum let-through current of a fault current limiter. The two vertical lines represent $t = 1$ ms and $t = 2$ ms, respectively, what shows that this is the time window available for effective fault current limitation.

The switching time limit for effective fault current limiting was also given as 1 ms by Kesselring [12], and this is a very short time for any mechanical process in the devices discussed. For effective limitation, within this time interval, a short circuit has to be detected and a limitation element has to be inserted into the circuit. This element must then generate a voltage drop that is as high as the instant system voltage in order to prevent the current from further increase. The energy stored in system the inductances and that continuously delivered by the source has to be dissipated by this element.

**Electromechanical switches too slow for current limiting at high power**

Given the time limit of one millisecond for effective fault current limiting, it is to be questioned what switching elements are available today, and at what operating time and switching capability.

An overview of the switching capability for single semiconductor switching devices [45] and electromechanical switches is given in Fig. 7 to compare the
switching time and interrupting power of these elements. The interrupting power is calculated by rated voltage times prospective interruptible current.

Fig. 7: Overview on interrupting power and switching time of single semiconductor elements and electromechanical switches. Values for semiconductors are taken from [45].

Electromechanical switches have minimum interrupting times around one millisecond only at lower power levels, see Fig. 7. The highest interrupting power at switching times of around one millisecond is reached by the low-voltage circuit breakers following the magnet blast principle as mentioned in chapter 2.1.1 p. 14. These breakers utilize the short-circuit current itself in an electromagnet to increase opening speed at high prospective currents [3] p. 655.

At high (above 20 MW) interrupting power, which normally correlates with higher system voltage, the interruption time of circuit breakers increases to several tens of milliseconds; see i.e. interruption process in Fig. 1. For effective fault current limiting – even if the arc voltage could be raised above system voltage during this time – this is too slow, compare to Fig. 6.

**Semiconductor switches are fast enough for effective current limitation**

The values for semiconductor devices in Fig. 7 are given for single elements that can be turned on and off. In general, semiconductor switches show very fast switching times at reasonable interrupting power. Thyristors lose conductivity at a current zero if not triggered. Their switching time therefore depends on the method of forcing current through zero. Particularly the so-
called gate turn-off thyristor (GTO) or its successor, the integrated gate
commutating thyristor (IGCT) deserve attention here. IGCTs are thyristors
equipped with a gate unit that can provide a high counter-current pulse to
force a current zero and thus turn the element off. Hence, turn-off time de-
pends on the rise time of the counter current. The conductivity of transis-
tors can be gradually changed, which can be used for switching extremely
quickly (e.g., in integrated circuits) or any slow (e.g., in an amplifier). The
limiting value here is the power loss during switching. Therefore, the switch-
ing power is lower at long switching times as indicated in Fig. 7.

Needs and impacts of fault current limiting devices

Slade [46] published a survey on utilities’ needs for fault current limiting de-
vices (FCLD): The survey results imply that it would be most desirable to
have a FCLD which is able to limit a 20 kA fault current to half of its value in
a 15 kV circuit.

The technical and economical impacts of fault current limiters on power
systems were e.g. studied by Sjörström [103] with a focus on High-
Temperature super-conducting devices. It is concluded, that FCLD show a
great potential in a technically efficient manner, independent of the nomi-
nal power and for all voltage levels. From an economical point of view, the
most promising applications are found in 16 kV- and in industrial systems.
This is consistent with the conclusions from another study of the technical
and economical benefits of superconducting fault current limiters con-
ducted by Noe [107].

2.2.3 Hybrid systems for fault current limitation

In medium voltage (MV) and high voltage (HV) systems, up today it is not
feasible to raise arc voltage above the system voltage in particular not
within one millisecond. For fault current limitation it is therefore insufficient
to simply speed-up today's high power switches. Consequently, the basic
idea of HV-FCLD designs is to commutate the still rising fault current very
quickly onto a parallel path using the arc voltage drop as the commutation
voltage. This shifts the tasks of increasing the impedance and absorbing the
circuit energy to the element in the parallel path. If further subdividing the
latter two tasks, one arrives at a hybrid system as given e.g. by Okazaki [47],
which is shown in Fig. 8
So the tasks of short-circuit detection, current commutation, increasing impedance and energy absorption can be integrated either into one single element (e.g., a fuse) or they can be subdivided to different elements. The latter principle is then called a hybrid system.

**Specific tasks for the elements of a hybrid system**

As pointed out, in hybrid systems each element is designed for a specific task: The fast continuous current switch (FCCS) has to carry the load current during normal operation and thus is designed to show small losses. A triggering unit ([sc?]) in Fig. 8) has to monitor the current and, at the event of a fault, give a trigger signal to the FCCS. By opening, the arc voltage of the FCCS has to be high enough to commutate the still rising current onto the commutation element. The voltage drop across the commutation element has to be lower than the arc voltage of the FCCS for successful commutation. For effective limitation, the voltage drop $U_a$ across the absorber has to be as high as the system voltage. Therefore, the commutation element and the absorber together have to increase their impedance by the ratio of system voltage over arc voltage of FCCS. During limitation, huge amounts of power are to be dissipated by the absorber until the current is finally switched off by a series load switch (not shown in Fig. 8).

**A specific hybrid system for fault current limitation**

Steurer [42] describes a hybrid system for fault current limiting and interruption at the medium voltage level as shown in Fig. 9. This hybrid system is also essentially based on the structure given in Fig. 8. As the present work bases strongly on this approach, it is explained in the following in more de-

---

1 An example for this ratio: $U_N = 24$ kV, $U_{arc} = 100$ V: $\Rightarrow \frac{Z_{max}}{Z_{min}} = \frac{24}{\sqrt{2}}\frac{V}{100} = 340$

2 For example: $U_N = 24$ kV, $I_{lc}$ limited to 5 kA $\Rightarrow P_{abs} = 24 \cdot 5 = 120$ MW
tail. This will also show how selected elements are applied for specific tasks to be performed in this hybrid system.

![Hybrid System Diagram](image)

**Fig. 9:** A hybrid system for fault current limitation and interruption and simulation of an interruption sequence as given by Steurer [42].

In the concept of [42], an electro dynamically driven mechanical switch was chosen for the continuous current contacts, providing low losses in the closed position and an opening time not more than several 100 μs. A GTO in a diode bridge (to operate both current directions) with a metal-oxide varistor in parallel is utilized as a commutation aid. The fast disconnector (FD) in series to the GTO is opened several hundreds of microseconds after the GTO has switched off the current in path B. Therefore, the GTO and the diodes need not be designed to withstand the system voltage transients during limitation, which allows for a small number of semiconductors. An electro dynamically driven mechanical switch was also chosen for the FD. Additional information to this switch design will be given in section 2.3.2.

All this action takes place within the first millisecond after the triggering signal, which has to be provided by a short-circuit detection unit, see switching sequence in Fig. 9. Fast commutation requires low stray inductances $L_{ob}$ and $L_{oc}$ in the parallel paths.

A pure wire resistor [104], [105] with a high positive temperature coefficient (PTC) was chosen as the absorbing element, featuring a high energy absorbing capacity and a rise in resistance to seven times the cold resistance when heated to 1000 °C. This characteristic, together with the heating from the limited current, results into a moderate voltage rise across the limiter. The limited current is finally interrupted by a load switch (FLS), which is not explicitly specified. Since the phase angle between limited current and system voltage is small due to the ohmic PTC resistor, the interruption duty is not critical for this load switch compared to that of the inductive current shown.
in Fig. 1. If the limited current is to be interrupted at the first current zero after triggering as shown in Fig. 9, then this load switch has a window to operate of several milliseconds.

**Other fault current limiting devices**

Fault current limiting devices can be divided into active and passive devices as summarized by Steurer [44]. A passive device is simply additional impedance in the circuit, which does not change at fault occurrence e.g. a current limiting air coil. Passive devices are not considered in the following. An active device shows small impedance at nominal load, which rapidly increases at fault occurrence.

Numerous designs for active fault current limiting devices for the medium and high voltage level according to Fig. 8 are presented in literature [47], [50], [51], [52], [53], [54], [56], [57], [58]. For each system, specific elements are designed for their usefulness in coping with specific tasks. Not all possible systems are now mentioned, but for reasons of their current popularity, fault current limiters based on high-temperature superconductors shall be briefly discussed below.

**Fault current limiters based on high-temperature superconductors**

Within the last decade, various designs of FLCD based on high-temperature superconductors (HTSC) have been presented, which utilize the increase of resistivity at the transition from the superconducting state to the normal state as a “switching” event [59], [60], [61], [55]. HTSC fault current limiters are usually divided into resistive and inductive principles [106]. The challenge of FCLD design based on HTSC is the so-called “hot-spot” problem, inherent to all such systems, wherein strongly non-linear elements are connected in series: if, due to small (production, design, material) differences, one series part strongly increases its resistance whereas the others remain superconducting, then its voltage drop is not sufficiently high to limit the current. Therefore the unlimited current together with this voltage drop cause strong heating of this part, usually followed by destruction.

For superconductors (and other high power devices) the hot-spot problem is overcome by a low ohmic shunt, which is then essentially a division of tasks as shown in Fig. 8 for the commutation aid and the absorber [108]. The drawback of shunting is a lower overall resistance after quenching, typically resulting in “long” and “thin” designs, somehow comparable to the pure wire PTC used in Fig. 9 [42].
Consequently, the superconducting element in the FCLD is used in one of two ways: One way is in the continuous current path to provide low impedance, inherent triggering and therefore an increase in impedance by quenching at higher currents, as shown by Giese [59]. The second is a commutation aid, as discussed by Steurer [55] (compare to Fig. 8). The second possibility reduces the costs for cooling the ac losses, as the continuous current does not flow through the superconductor, but raises the need for an external triggering unit and a fast mechanical switch.

A comparison of superconducting fault limiter concepts for electric utility applications was carried out by Salasoo [106]. From the comparison of total costs, cryogenic costs and conventional system costs it is concluded, that a current limiting reactor based on High-Tc superconductors is the highest ranked approach.

An economic solution for a superconducting fault current limiter must have costs of only a few times the price of a standard circuit breaker [62]. This demand cannot be fulfilled with today’s superconducting systems.

An extensive discussion on the use of high-temperature superconductor materials for fault current limiting is given by Schubert [98]. According to ABB [63], a superconducting current limiter with a rated power of 6.4 MW will be ready to market in 2004.

**The \( I_1 \)-Limiter: a one-explosion fault current limiting breaker**

The only FCLD in commercial use for several decades in the medium voltage range is the so-called \( I_1 \)-Limiter, which consists of a metallic pipe filled with explosives (which works as the FCCS and commutation aid) and a medium voltage fuse in parallel as absorber and for interruption [64]. Of course, the pipe with explosives has to be replaced after operation. The price of an \( I_1 \)-Limiter is around three times the price of a circuit breaker with the same ratings.

**2.2.4 Semiconductor switchgear**

The use of semiconductor switchgear in medium and high voltage applications was economically restricted to specific applications due to noticeably higher nominal losses, higher price, higher volume and lower overload capacity. The evolving silicon carbide (SiC) device technology offers the potential to strongly decrease switching losses [65]. The main problems with SiC lie in material and process technology but might get resolved in future [25], [66], [67].

According to Stephani [65], the main advantages of semiconductor switchgear are the lack of moving parts, which enables immediate triggering (see
Fig. 7), and the absence of a switching arc so that no wear, welding and erosion occurs, and forced arc-cooling facilities are not necessary. There are perspectives for the application of SiC switches in low voltage systems [68].

The use of semiconductors for fault current limiting is self-evident due to their fast operation at reasonable power. Many fault current limiting devices based on semiconductors have therefore been proposed and in principle no major technological problems exist, see for example [69]. However, FCLDs based on semiconductors are not in use in medium and high voltage systems due to their lack of economical attractiveness.

2.3 Characteristics of fast-acting switches and actuators

The switching time of electromechanical switchgear varies from milliseconds to several seconds when performing both opening and closing operations, compare to Fig. 7. As the present work is concerned with extremely fast-operating electromechanical switches, today's limits for switching time (or opening velocity) using known switch designs and actuator systems shall be briefly discussed in this section. In addition, the characteristics of rapidly extended arcs and the cold recovery of gaps are briefly mentioned as these will also be studied in the present work using new switch designs.

2.3.1 Switching time limits using standard actuator systems

Some considerations of the switching time limits of electromechanical switches are given by Branston [70]. There, it is stated that the minimal moving mass for low voltage current limiting switchgear is higher than 100 mg and that switching times lower than one millisecond are not feasible in electromechanical breakers due to mechanical instability. With an eye on Fig. 7 and the fact that higher rated power needs larger contact cross-section or larger gaps or both, it can be presumed that for medium and high voltage switchgear these limits will be even higher.

Asche [71] describes experimental and simulation results for an electromagnetic actuator used in a percussion drill. With this drive, an armature with a mass of 159 g is accelerated to about 10 m/s within 9 ms, showing a dead time of only 3 ms. System efficiency, calculated by input energy over kinetic energy of the moving part, turns out to be smaller than 10 %.

A detailed comparison of drive mechanisms and switch designs for very fast acting electromechanical switchgear was performed by Bosselmann [72], also with a focus on low-voltage switchgear. He states, that from known drive principles only the repulsion drive offers the low dead-time necessary for effective fault current limitation. In [72], several designs for the use of
piezo-electrically driven switches are also presented and tested in low voltage circuits with switching times of less than 1 ms for currents up to 20 A. An example given for a piezo-drive allows an opening gap of 80 μm within 25 μs, showing a maximum opening velocity of 2 m/s. The use of combinations of many serial and parallel piezos for obtaining larger gaps and higher interrupting power is discussed. Finally, a piezo-drive for synchronous switching and for fault current limiting in low-voltage applications is proposed, although arcing problems remain untreated. No comments on the costs of such a switch are given but they may be estimated to be not competitive to standard low-voltage circuit breaker.

2.3.2 Switching time limits using the repulsion drive

As discussed in the previous section, the repulsion drive shows the highest potential for use in fast switches. Therefore, further details on this drive principle are now discussed.

Opening velocity as a function of efficiency, drive energy and inertia

The switching time of electromechanical switches in general is dependent on the drive energy, its efficiency and the mechanical inertia. This is, of course, also true for the electrodynamic repulsion drive which was found to be the most promising drive system for fast-acting high power switches and repeated operation [40], [34], [42].

Morita [41] gives the final opening (or closing) velocity \( v_k \) of an electro-dynamically driven switch from the energy \( E_d \) stored in the drive Capacitor \( C_d \) by introducing a drive efficiency \( \eta_d \), whereas \( U_d \) is the charge voltage of \( C_d \), see Eq. 7

\[
v_k = \sqrt{\frac{2 \cdot \eta_d \cdot E_d}{m_c}} = U_d \cdot \sqrt{\frac{\eta_d \cdot C_d}{m_c}} \tag{7} [41]
\]

Considering Eq. 7, the potential to increase opening velocity when using an electrodynamic repulsion drive is threefold:

- Increase stored energy in the capacitor \( E_d \)
- Low mechanical inertia (moving mass) \( m_c \)
- Increase the drive efficiency \( \eta_d \)

Increasing the stored energy \( E_d \) is mainly a question of cost and space requirements. The other two potentials are affected by the design of the contact system, the overall switch, and the drive. Given the vast knowledge of high-power switchgear and the many years of continuous improvement of each component, it is not very likely to find a way of deriving a greatly improved switch design or drive system. Thus, in order to lowering the switching time one has to find an essentially different approach.
Fast opening switches due to reduced requirements

On approach for the implementation of switches with noticeable higher opening velocity is based on the division of tasks in a hybrid system (compare to chapter 2.2.3). Here the switch is designed to carry the nominal current, to fast open, and to quickly commutate the instantaneous current onto a low-ohmic parallel path. However, it need not to have a high power interruption capability.

Such a fast opening switch design, using the repulsion drive, is described in several publications by Steurer [52], [42], [55] and shown in Fig. 10. In this axially-symmetric design, the continuous current flows radially across a movable contact ring. The drive coil for repulsion is located below this ring and pushes the ring upward for opening.

![Diagram of fast opening switch](image)

**Fig. 10:** Side view of an electro-dynamically driven fast switch used in a hybrid system [42].

The sum of arcing voltage of the two arcs drawn on the inner and outer contact surface of the ring on opening commutates the current onto the parallel path, which causes the arc to extinguish on this opening contact. An opening velocity of $v_{\text{open}} = 16 \text{ m/s}$, moving a total mass of $m = 60 \text{ g}$ is reported for an implemented switch at a continuous current of 2 kA, showing a dead-time of $100 \mu s$ and a final contact gap of $s_k = 7 \text{ mm}$. The dielectric breakdown strength during opening was calculated by using the streamer-breakdown criteria [23]. The drive efficiency was reported to be lower than 10% [42].

Similar designs for a fast-opening switch were published by Meyer [69] and Rufer [73] for a rated voltage of $U_h = 2.5 \text{ kV}$ and a maximum commutated current of 5 kA. Here a maximum opening velocity around 7 m/s and a dead-time of $150 \mu \text{s}$ is measured. In parallel to this switch, an IGCT and varistor in a diode bridge have been arranged, compare Fig. 9 p.27.

Fastest opening velocity in the literature is found for an electrodynamically driven disconnector used in a hybrid system presented by Jungblut [74]. An extremely high opening velocity of $60 \text{ m/s}$ is reported for a ring-shaped contact system according to Fig. 10, featuring a dead time of less than $20 \mu \text{s}$. The time delay from triggering this switch to contact separation depends on the
drive current and can be lowered to 50 μs. An aluminium ring with a mass of around 1 g was used as the moving part. No problems due to mechanical instability of the ring at such high acceleration are reported. Despite the extreme opening velocity, drive efficiency is lower than 1 %.

Closing by standard drives

The above-mentioned fast-opening switches have to be closed again for repeated operation. For use in a hybrid system under fault current limiting applications, only the very fast opening property is needed. Hence, the authors implemented standard closing actuators. For example, in the implementation of the hybrid system discussed in [42], a pneumatic closing drive was utilized. Closing of the fast disconnector [74] was performed manually.

2.3.3 Characteristics of rapidly increased arcing gaps

In fast switches utilized in hybrid systems for fault current limitation, a rapid extension of arcs followed by gap recovery will appear after current commutation. If using fast switches as disconnector, the cold recovery of the opening gap has to be known. Therefore, the few data found in literature to these topics are reviewed in this chapter.

The impact of the rapid extension of dc arcs on the arcing voltage has been described in literature for opening velocities of up to 4 m/s by Rieder [75]. Based on the voltage-current characteristic of stable burning arcs, the arcing voltage of rapidly extended arcs was modeled by adding a voltage drop depending on current, velocity and circuit parameters. For calculation of the arc voltage, several empirically gained functions and constants have been used.

No experimental data for non-cooled high current arcs, which are extended with opening velocities of up to several 10 m/s, could be found in the literature.

Steurer [42] calculated the cold recovery of a fast-opened gap for a model switch by using the Streamer-breakdown criteria. The calculations have been compared to measured values and show a linear increase in reignition voltage with a contact gap of up to several millimeters. This is in agreement with the linear region of the Paschen curve, that is $p[\text{bar}] \times [\text{mm}] > 10^4$ [23].
Seite Leer / Blank leaf
3 Research goal

There are two favorable time ranges for to operate high power switching devices (compare to Fig. 7, p. 24): Semiconductor switches can operate in the highest power ratings only in the time range of $1...10$ $\mu$s. The highest power ratings of electromechanical switches are possible only at switching times of down to $10...100$ ms. Unfortunately, the switching time of electromechanical switches at the highest rated power is not fast enough for fault current limiting, and semiconductor switches are expensive and show high nominal losses. Therefore, various questions are to be answered in the present work.

A new switch design based on changing requirements

The question to be addressed is whether there are unexplored possibilities and economical attractive solutions for electromechanical high-power switches with switching times in a time range of $\leq 1$ ms besides the solutions given in [42]. Given the comprehensive knowledge and application on physics of modern high power switching devices, it is highly unlikely that a feasible and economical solution can be found without considering a major change in the switching approach. A design separate from standard breakers to achieve a medium-voltage fault current limiter was shown by Steurer [42] using simple but fast electromechanical switches in a hybrid system. The simplicity directly arises from the relaxed requirements of the hybrid system components due to the split into single tasks.

To what extend does the arc determine switch design?

In the present work, this idea will be further extended. Eq. 7 shows, that the moving mass is crucial to the opening velocity. However, no concise theory about the theoretically minimal (possible) moving mass in a high power switch could be found in the literature. Presumably, there are two major reasons for this. First, the existence of the switching arc, its contact erosion and its cooling facilities has always been the major determining factor for switch design and selection of contact material. However, the switching arc itself will have less impact on the switch design if the arcing time can be drastically reduced by very fast and precise switching. Second, mechanical
stability, drive energy transfer and required space for energy storage are limiting factors.

Therefore in the present work and based on [42], the approach for new fast-acting medium voltage switches is to neglect the switching arc's impact on design in the first place and to minimize the number of moving parts. This approach results in elementary switches with one moving part only, which is driven by electrodynamic repulsion. These switches will show very high opening velocity and an opening or closing time around 1 ms (compare to Fig. 7, p. 24). As the impact of the switching arc on the design has been neglected, the interrupting capability of single elementary switches has to be studied; however, its high-power interruption performance will be low compared to standard breaker. But for applications in hybrid systems for fault current limitation, its synchronous interruption capability and the capability to commutate high currents on parallel impedance are investigated.

**What are appropriate applications for these switches?**

The elementary design of fast switches and omitting forced arc cooling facilities implies that the switching capability of single switches will be low compared to modern breaker. However, the short trigger and opening times allow several operations within a power system half-cycle. It has to be investigated how efficient an arrangement of fast switches in a hybrid system according to Fig. 8 p. 26 therefore could be. Several combinations of fast switches and applications in a hybrid system are to be studied. The goal of any hybrid system is to obtain high power switchgear with current limiting function or superior functionality over standard circuit breakers.
4 Fundamental analysis of fast switches

In order to answer the question on achievable contact speed and mass in this chapter, a kinematical analysis for very fast acting high power switches is first carried out. This analysis is started with a definition of "elementary switches". It is continued with a comparison of linearly and rotationally operated switches in terms of rated values and kinetic energy. Some guidelines on the design of elementary switches is then given to obtain highest opening and closing velocity. A generally applicable equation for the opening velocity as a function of design parameters is the goal.

4.1 How to use elementary switches in MV-applications

4.1.1 What is an elementary switch?
While considering a new design of an electromechanical switch, one might start with the well-known elementary functionality of switchgear or circuit breaker, as stated e.g. by Flurscheim [2]:

*The function of a circuit breaker is then to possess two stable conditions: 'close' in which it has ideally zero, and in practice a very small impedance; and 'open' in which it has ideally an infinite and practically an extremely high impedance. The circuit breaker must be able to change from either condition to the other when so instructed,...'*

From this statement, three irreducible requirements for an electric switch can be derived. In the present work, a switch is termed an "elementary switch", if it only fulfils these three requirements:

- Withstand the "design voltage" if open
- Carry the "design current" if closed
- Performing mechanical opening and closing operations.

The terms "design voltage" and "design current" are given to distinguish from rated values for circuit breaker. They will be specifically explained and

1 Quotation from Flurscheim [2] p. 2
defined in chapter 4.2.1 p. 42 below. It is obvious that, according to the third postulate, there has to be at least one movable part to perform an opening or closing operation.

**High opening velocity due to simplicity**

Having in mind the current limiting functionality and Fig. 7, the basic goal of a new switch design in the present work is **high opening velocity**. Hence, the accelerated mass (= inertia) is to be minimized (from Eq. 7 p. 31) and the operating mechanism has to be as simple as possible. Both is achieved, if the moving mechanism part is the one and only moving part (MP) in the switch. This part in general can be moved linearly or rotationally as shown in a principle sketch in Fig. 11 with FC1 and FC2 being the fixed contacts.

![Diagram](image)

**Fig. 11: Basic geometry of elementary switches with linear and rotational movement and only one moving part MP. FC1 and FC2 name the fixed contacts. No drive system is shown.**

The moving part forms a contact bridge between the fixed contacts and provides a double-break if moved in the direction shown. The remaining contact gap after fully opening (respectively turning by 90 °) is $s_k$. This operation theoretically can take place in a gaseous switching medium, in vacuum or in liquids. Liquids appear to be impracticable due to high flow resistance.

A switch cannot be operated without having a drive system, but any chosen drive system should not add inertia to the moving part. This advises the use of a repulsion drive, because it transmits drive energy via the electromagnetic field. Therefore, no other moved parts are necessary, if the one moved part is at the same time used as the eddy current conductor for the repulsion drive (see Fig. 3 p. 20).
4.1.2 A repulsion drive to open and close an elementary switch  
As summarized in chapter 2.3.2 p. 31ff, the multiple use of the moving part as  
contact bridge and as eddy current loop at the same time is described in  
several patents [76], [77], [78], [79], [80] and for opening switches with linear  
movement in the work of Jungblut [74] and Steurer [42]; both using a ring-  
shaped moving part. The implication of this idea on the minimization of  
inertia in an elementary switch shall be fundamentally discussed in this  
section.

Linear operation of elementary switches using a repulsion drive  
As an extension to the solutions given in literature, a solution was worked  
out which is suitable for opening and closing elementary switches with linear  
movement. This is feasible, if the drive coils are collocated to the moving  
part according to Fig. 12.

![Diagram of repulsion drive](image)

**Fig. 12:** Applying a repulsion drive for opening and closing a linearly operated elementary switch. The moving part MP carries the load current and the eddy current for the drive at the same time, but both currents are perpendicular to each other.

Discharging $C_d$ to the drive coil 1 by triggering the thyristor $T_1$ gives a current $i_e$ that induces anti-parallel eddy currents $i_e$ in the moving part. Thus, a repulsion force to the moving part is generated according to Eq. 4 p. 22, which pushes the moving part away from the drive coil. Slowing down of the fast moving part is done by friction on the walls of the narrowing gap. Closing the switch can is achieved the same way, using coil 2. Note that the linear operated switch is ring-shaped, because this best fit to the shape of the drive coils and thus results in highest magnetic interaction [39], [74], [42]. However, the principle is not restricted to the ring-shape.

Rotational operation of elementary switches using a repulsion drive  
Another feasible design is derived by applying the repulsion drive to the ba- 
sic geometry for rotational operation in Fig. 11. The basic design for opening
and closing elementary switches with rotational movement is given in Fig. 13.

Fig. 13: Applying a repulsion drive for opening and closing a rotationally operated elementary switch. The moving part MP carries the load current and the eddy current for the drive at the same time.

The moving part is of cuboids shape and its centre of rotation has to be fixed on both ends.

For linear and rotational design, the drive coils (1: opening, 2: closing) have to be as close as possible to the moving part for high efficiency but insulated properly to the fixed contacts FC1 and FC2 [40]. The load current (linear: in radial direction) and the eddy current i_E induced by the drive coil during opening (linear: in azimuthally direction) are sharing the same volume of the moving part, but are perpendicular to each other. Attention has to be paid to avoid eddy currents in the fixed contacts FC1 and FC2, as this will reduce efficiency.

The applicability of the repulsion drive for opening and closing linearly and rotationally operated switches is demonstrated in detail in several master thesis works [81], [82], [83], [86]. Its characteristics are summarized in the following chapter.

Characteristics of elementary switches with repulsion drive

Some key characteristics of the elementary switch design with electrodynamic repulsion drive as shown in Fig. 12 are:

- Linear and rotational operation is possible.
- Opening and closing is done by repulsion.
- Only one moving part. This allows very low inertia (see below, Eq. 11 or Eq. 12 p. 47), simple mechanical design and fast action as no mechanical energy transfer takes place.
• No galvanic connection between drive circuit and main circuit. Thus, main circuit and drive circuit may operate at different potential levels.
• No highly sophisticated manufacturing process for the main parts necessary.
• Simple design rules in a wider range of design current and voltage values (see below Eq. 8 p. 44).
• Uniform distribution of the repulsion force on the moving part. This minimizes mechanical stress on the lightweight moving part.
• The principle works in gaseous switching media and in vacuum.
• One particularity of the elementary switches presented in Fig. 12 and Fig. 13 is, that they are not equipped with arc cooling facilities. Therefore, compared to standard circuit breaker, they will show faster operation but lower current interruption capability.
A discussion on the appropriate use of these switches as high power switchgear follows.

4.1.3 High power breakers composed of elementary switches
In the above sections, the fundamental features of elementary switches with repulsion drive were defined. Due to missing arc cooling facilities, randomly triggered single elementary switches will not be capable of high power switching for voltages higher than several 100 V even though they provide very high opening velocity (see for example chapter 2.3.2 p. 31).
Therefore, additional elements are to be arranged for these switches to work as high power switchgear. Fig. 14 shows the elementary switch design providing a single moving contact bridge with low mass, having a repulsion drive. The repulsion drive offers immediate triggering and high driving forces. Therefore, as a key feature, the operation time from trigger to full open position of these switches will be much less than one ms, which is essentially less than one half cycle of the power frequency. As will be shown in chapter 5.3.2 p. 78f, the elementary design can be adapted so to have many breaks in series.
To finally obtain high power switchgear, these fast switches are to be arranged in a hybrid system together with other suitable elements in parallel paths. A precise control for all elements in the hybrid system is essential (see also chapter 2.2.3). For current limiters and dc breaker an energy absorbing element as discussed in Fig. 8 is required. Based on previous work ([74], [42]) and following the steps given in Fig. 14, it is possible to operate each fast switch in such a way, that the arcing time is always less than one millisecond and the arc extinguishes without forced arc cooling. The feedback-loop
4.2 Dimensioning guidelines for elementary switches

In Fig. 14 confirms the usefulness of the elementary switch design, which has no facilities implemented for forced arc cooling.

Fig. 14: The way from an elementary switch design to high power switchgear.

The power range of the resulting switchgear is discussed at the end of this work based on experimental results on the switching capabilities.

4.2 Dimensioning guidelines for elementary switches

Based on the fundamental considerations made above, dimensioning guidelines for elementary switches according to Fig. 12 are derived for given design values of voltage and current. The theoretical minimum for the moving mass of a switch is calculated and compared for linear and rotational movement. Finally, some comparisons on the kinetic energy for linear and rotational movement are given.

4.2.1 Design values and definitions for elementary switches

The design values of voltage $U_{\text{dim}}$ and current $I_{\text{dim}}$ will give the main dimensions of the elementary switch and thus the dimensions of the moving part. As the moving part is at the same time the eddy-current loop (see Fig. 12) a strong interdependence between circuit, drive and design is to be expected as shown Fig. 15.

Strong interaction between circuit, drive and design

For high drive efficiency the drive coil has to be placed close to the moving part. It has to be insulated from the main circuit because of different voltage levels so the distance between coil and moving contact has a lower limit [42]. Moreover, coil insulation and the electrostatic field in the contact gap are playing a major role.
Fig. 15: Impact of circuit, drive and design factors on the opening velocity of switches with elementary design and electrodynamic repulsion drive

The shape of the drive coil and the thickness b (see Fig. 11) of the moving part are interacting via the magnetic field of the drive current. Therefore, drive frequency $f_d$ (correlated to skin depth) and thickness b (correlated to length) will influence the drive efficiency [40], [34]. Finally, the drive coil for opening has to be placed in the contact gap. Thus, space limitations are given for the cross section of the coil, requiring a limited number of turns and limited cross section of each turn.

Fig. 15 shows the interdependences of the various parameters. They are now to be discussed individually to find the design criteria for high opening velocity. With an eye on a wide applicability, it is tried to reduce to integral (measurable) values like energy, efficiency and opening velocity for the optimisations in the following section. This, instead of deducing from spatial distributions of local values (eddy current density, magnetic flux density, forces) as has been done in literature [40], [34], [74] (without strictly following the elementary switch design).

In the following chapter, it is therefore tried to give analytic expressions for design rules, using physics and generalizing from experimental results. Additionally, field calculations for a detailed optimisation of a rough design approach are employed [36].
Definitions for design values of elementary switches

In chapter 4.1.1, the first postulate for the elementary switch in the “open” position was to withstand the “design voltage”. For a circuit breaker with given ratings, its design values such as rated voltage, basic insulation level,... are strictly given by the standards (e.g. IEC 56). As was emphasized in chapter 2 p. 13ff, the fast switches will be applied only in specific hybrid systems. Therefore, the values given by the standards are to be applied to the overall hybrid system and not to the elementary switch. Hence, a different definition for the design values for elementary switches is necessary and thus given below:

- The “design voltage” $U_{\text{dim}}$ is the breakdown voltage of an elementary switch in the fully OPEN position.
- The “design current” $I_{\text{dim}}$ is the continuous thermal limiting current through the elementary switch in the CLOSE position.
- The “average breakdown field strength” $E_{\text{avg}}$ is given by the ratio of $U_{\text{dim}}$ over contact gap $s_c$ for a given switching medium and pressure.
- The “average contact current density” $J_{\text{avg}}$ is given by the ratio $I_{\text{dim}}$ over the cross section of the moving part $A_c$ (see Fig. 11).
- The “average breakdown field strength” of the coil insulation material $E_{\text{iso}}$.

These definitions are used in the following for calculation of the basic dimensions of an elementary switch. The connection between these here defined values and the ratings of a circuit breaker given by standards will be given for applications in chapter 6.4.5 p. 121f.

4.2.2 Calculation of the minimum required contact gap

As done by [74] and [42], a dielectric breakdown mechanism is assumed to calculate the minimum contact gap for a given design voltage $U_{\text{dim}}$. Therefore, the minimum contact gap $s_k$ in fully open position results from Eq. 8 with the design voltage $U_{\text{dim}}$, the average breakdown field strength of the utilized switching medium $E_{\text{avg}}$ and a safety factor $k_{\text{safe}}$ compared to the geometry in Fig. 11.

$$s_k = \frac{U_{\text{dim}} \cdot k_{\text{safe}}}{E_{\text{avg}}} \quad \text{Eq. 8}$$

The safety factor $k_{\text{safe}} > 1$ is necessary, because $U_{\text{dim}}$ is defined as breakdown voltage. As the contact gap does not show a homogeneous electric field, $E_{\text{avg}}$ is understood to be an average value, which can be derived from field calculations or from experimental data for a specified geometry.
According to Eq. 8, an increasing contact gap leads to a linearly increase of the breakdown voltage. However, the inherent necessity of having the drive coil close to the contact gap gives a field distortion in the gap as for example shown in Fig. 16 [83].

Due to the field distortion with an increase of the contact gap $s_v$ the breakdown voltage will rise slightly less than linear. Therefore, Eq. 8 is valid over limited ranges of $s_v$ only. The increase of withstand voltage over a range for $s_v$ from several mm up to 35 mm was measured to be in good accordance with Eq. 8 [42] p. 64. In the present work, gaps over 35 mm are out of focus. Hence, the dependency of the contact gap as a function of design voltage given by Eq. 8 will be used for the following fundamental considerations as a quick and adequate tool.

4.2.3 Calculation of the minimum necessary contact cross section

Corresponding considerations as given for the contact gap are now applicable for a calculation of the minimum contact cross section of an elementary switch.

**Dimensioning current defines the cross section**

The cross section $A_c$ of the moving part is given by Eq. 9, where $I_{dim}$ is the dimensioning current and $I_{avg}$ is the average contact current density applicable (see definitions in chapter 4.2.1 p. 42).

$$A_c = l \cdot b = \frac{I_{dim}}{I_{avg}}$$  \hspace{2cm} \text{Eq. 9}

Eq. 9 gives the necessary cross section $A_c$ in the moving part while assuming a homogenous distribution of current. This disregards the constriction of the current path at the contact points as sketched in Fig. 17.
The constriction resistance is inversely proportional to contact force and decreases with the number of contact points \([5], [1], [16]\). Therefore, by applying Eq. 9, it is assumed that contact force, the number of contact points and the mass of the fixed contacts can be chosen sufficiently high so that the thermal limit for the contact region is not exceeded for a current density equal or smaller than \(J_{\text{avg}}\). These assumptions are included in the definition for \(J_{\text{avg}}\) in section 4.2.1, p. 42 and it is therefore to question, whether the contact design can be chosen such as to fulfil these assumptions. This will be done in the following by comparing the calculated contact cross section (Eq. 9) with values provided by a manufacturer of high-current multi-contact lamellas [84].

**Current carrying capability of a lamella limits thickness of moving part**

When using standard high current multi-contact connectors for fixed contacts, the maximum continuous current per lamella \(i_t\) is given in the data book [84] together with the distance \(t\) between two lamellas. For a moving part with a small thickness \(b\) and a given current density \(J_{\text{avg}}\), the rated current per lamella \(i_t\) is higher than the maximum current allowed in the cross section \(A_c = b \cdot t\), of the moving part. For a high thickness \(b\), the limitation will result from the maximum current \(i_t\) per lamella. Hence, Eq. 9 will be applicable up to a maximum thickness \(b_{\text{max}}\), which is calculated by Eq. 10.

\[
J_{\text{avg}} = \frac{i_t}{A_{c1}} = \frac{i_t}{b \cdot t_1}, \quad b_{\text{max}} = \frac{i_t}{J_{\text{avg}} \cdot t_1} \quad \text{Eq. 10}
\]

For example: With the values given in [84] for multi-contact lamellas LAOPG (Cu-Be, silver coated), the maximum thickness results to \(b_{\text{max}} = 4\) mm \((t_1 = 2.5\) mm, \(i_t = 40\) A and \(J_{\text{avg}} = 4\) A/mm\(^2\). Contact force is \(F_t = 7\) N per lamella.

\(b_{\text{max}}\) gives an upper limit for the contact thickness. This looks like a rigid restriction for the use of this dimensioning method for elementary switches at a first glance. However, it is not that rigid, because Eq. 9 defines the cross section of the moving part but not its length 1 and thickness \(b\) separately.
Hence, there are possibilities for optimisation although there’s an upper limit for b. This optimisation is addressed in chapter 4.2.7 p. 57.

4.2.4 The minimal moving mass for elementary switches

In the above chapters, the minimum contact gap as a function of design voltage and the minimum contact cross section as a function of design current were derived. Based on these minima’s, the theoretical minimum for the moving mass of a switch is now given and compared for linear and rotational operation.

The theoretical minimum for the moving mass

Given the contact gap $s_k$ and its cross section $A_c$, the theoretical minimum for the moving mass $m_c$ of a linearly moving part can be obtained by Eq. 11, whereas $\rho_c$ is the mass density of the moving part.

$$m_c = \rho_c \cdot A_c \cdot s_k = \frac{\rho_c \cdot k_{safe}}{E_{avg} \cdot j_{avg}} \cdot U_{dim} \cdot l_{dim}$$  \hspace{1cm} \text{Eq. 11}

When using a rotationally operated switch according to Fig. 11 p. 38 then the moving part remains between the fixed contacts after a 90° turn. Consequently, the contact gap has to be increased to $s_k + b$. Therefore, the theoretical minimum of moving mass of rotationally operated switches $m_{rot}$ is higher than at linear motion and shows more dependency on the dimensioning current; see Eq. 12. The values for $s_k$ and $b$ are taken from Eq. 8 and Eq. 9 respectively, $l$ is the length of the moving part.

$$m_{rot} = \rho_c \cdot A_c \cdot (s_k + b) = \frac{\rho_c \cdot k_{safe}}{E_{avg} \cdot j_{avg}} \cdot U_{dim} \cdot l_{dim} + \frac{1}{l} \left( \frac{l_{dim}}{j_{avg}} \right)^2$$  \hspace{1cm} \text{Eq. 12}

To show what values result for this minimal moving mass, Fig. 18 gives $m_c$ (Eq. 11) calculated as a function of $U_{dim} \cdot l_{dim}$ for copper and aluminium and various field strengths with the parameters for $k_{safe}$ and $j_{avg}$ given on the chart. It can be seen, that – using $E_{avg} = 15 \, \text{kV/mm}$, e.g., air at 1 bar; $j_{avg} = 2 \, \text{A/mm}^2$ which are typical values, see e.g. [26] p. 644 f – the theoretical minimum for the mass of a moving part out of aluminium is $m_c \approx 1 \, \text{g/MW}$. 


The values for $m_{rot}$ (Eq. 12) are nearly identical to $m_c$ in the given range and are therefore not shown in Fig. 18.

![Diagram](image)

**Fig. 18: Theoretical minimum of moving mass in an elementary switch as a function of $U_{\text{dim}}$-$I_{\text{dim}}$ according to Eq. 11 (parameter given on the chart).**

The mass calculated in Eq. 11 and Eq. 12 only contains the mass of the moving part itself, based on the definitions and the approximative dimensioning formula given above. Neither drive components (springs, hydraulic oil, valves, gear lever...) nor additional mass for contacting, mounting or contact coating is contained herein. All additional functional, - dielectric, -drive, -material, -contact and arcing requirements related to high power switches will add mass to this theoretical minimum. For that, $m_c$ and $m_{rot}$ are defined to be the minimal (possible) moving mass.

Aluminium was chosen as bulk material for the moving part in the experiments conducted in this work as it was done for switches with repulsion drive in literature [74]. The values using copper are given for comparison. As already mentioned, the moving part has to be coated at the contact points.

**Switching power is not the dimensioning power**

An elementary switch having a “design power” $U_{\text{dim}}$-$I_{\text{dim}}$ (as given in Fig. 18) is essentially not capable of interrupting this power. It is albeit assumed, that this (very small) mass $m_c$ in combination with a repulsion drive leads to high contact separation velocity. It is then the high opening and closing velocity, which will be the key parameter to study the switching capability. It is also the high opening velocity (short opening time), which is the basic requirement for applications in a hybrid system (see i.e. Fig. 8 p. 26 or Fig. 14 p. 42) to further boost the switching capability.
Opening velocities of several 10 m/s are feasible with $m = 50$ g. Given the theoretical minimum for the moving mass, some fundamental considerations on the kinetic energy and the kind of motion are carried out. The linear switch design with a repulsion drive presented in Fig. 12 is identical to the opening switches presented in [42] except that there is a second drive coil for closing. Therefore, one can also assume drive efficiency to be around 5 % [42]. This is now used to estimate the resulting opening velocity of an example switch with a moving mass of $m_c = 50$ g, see also Fig. 18. For given values for the repulsion drive of $C_d = 100$ μF and $U_d = 2$ kV and an estimated drive efficiency of $\eta_d = 5 \%$, an opening velocity of $v_k = 20$ m/s results from Eq. 7. This is in the same range than the values found in literature in chapter 2.3.2.

It is now to discuss, whether the principle of rotational movement, which has not been treated in literature, has advantages over the linear movement.

4.2.5 Kinetic energy at linear and rotational movement

The question whether linear or rotational movement better fits for fast acting electromechanical switches is first discussed by calculating the kinetic energy needed for operating the moving part MP. Based on the theoretical minimum of moving mass given in Eq. 11 and Eq. 12 the kinetic energy is calculated with reference to Fig. 19. This requires first the calculation of the contact speed as follows.

![Diagram of linear and rotational switch geometry](image)

Fig. 19: Geometry of linearly and rotationally operated switches with the terms used for calculating the kinetic energy. Switches are shown in the OPEN position.

Opening velocity is calculated from the minimum required gap at “open”

An elementary switch is defined to be “open” if the distance between fixed contacts and moving contact is larger than between the fixed contacts. Then, the required way $x$ (angle $\alpha$) to move is given by Eq. 13:
4.2 Dimensioning guidelines for elementary switches

a) linear: \( x \geq \frac{s_k + b}{2} \)
b) rotational: \( \alpha \geq 1 + 2 \cdot \sin \left( \frac{b}{s_k + b} \right) \)  \( \text{Eq. 13} \)

The opening gap \( x \) (on each side) has to be larger than half of the maximal contact gap increased by the thickness of the moving part. The same holds true for rotational operation.

Given an opening time \( t_o \) and the opening gap \( x \) calculated by Eq. 13, the necessary velocity \( v_k \) (\( \omega \) if rotationally operated) for fully opening the contacts within \( t_o \) can be calculated with Eq. 14. Here, it is assumed that \( v_k \) and \( \omega \) are constant during opening which indeed was measured and simulated [74] for a repulsion drive.

\[
\begin{align*}
\text{a)} \quad & v_k = \frac{x}{t_o} = \frac{s_k + b}{t_o} = \text{konst.} \\
\text{b)} \quad & \omega = \frac{\alpha}{t_o} = \frac{1 + 2 \cdot \sin \left( \frac{b}{s_k + b} \right)}{t_o} = \text{konst.} 
\end{align*}
\]

\( \text{Eq. 14} \)

The required opening velocity therefore is a function of the switch parameters \( s_k \) and \( b \) and it is inversely proportional to the required opening time.

**The kinetic energy of the moving part during opening**

Eq. 11 and Eq. 14a lead to the kinetic energy \( W_{\text{lin}} \) of linearly opened switches as a function of the opening time as given in Eq. 15. Note that the cross section \( A_c = l \cdot b \) from Eq. 11. The kinetic energy \( W_{\text{lin}} \) strongly depends on \( l \), \( b \) and \( s_k \), but contact length \( l \) and thickness \( b \) are not separately determined, which gives possibilities for optimisation to be discussed in chapter 4.2.7 p. 57.

\[
W_{\text{lin}} = \frac{m_c \cdot v_k^2}{2} = \rho_c \cdot l \cdot b \cdot s_k \left( \frac{s_k + b}{2} \right)^2 
\]

\( \text{Eq. 15} \)

For rotationally operated switches, the moving part is approximated by a cuboid and the moment of inertia \( J_c \) of cuboids is given in Eq. 16 [19], analogous to \( m_c \) in Eq. 11.

\[
J_c = \frac{m_{\text{rot}}}{12} \cdot \left( (s_k + b)^2 + 2b^2 \right) = \frac{\rho_c}{12} \cdot l \cdot b \cdot (s_k + b) \cdot \left( (s_k + b)^3 + b^2 \right) 
\]

\( \text{Eq. 16} \)

Thus, the kinetic energy \( W_{\text{rot}} \) results from Eq. 17; mainly depending on contact gap \( s_k \) and contact thickness \( b \).
\[ W_{\text{rot}} = J_c \cdot \frac{a^2}{2} = \rho_c \cdot l \cdot b \cdot (s_k + b) \left( \frac{b}{s_k + b} \right)^2 \left( 1 + 2 \cdot \sin \left( \frac{b}{s_k + b} \right) \right)^2 \]

\text{Eq. 17}

\( W_{\text{lin}} \) and \( W_{\text{rot}} \) are both functions of the design values of the switch and inversely proportional to the square of the required opening time.

**Comparison of linear and rotational movement**

For comparing linear or rotational operation, the kinetic energy of both principles is to be compared. Fig. 20 shows the absolute values of \( W_{\text{lin}} \) and \( W_{\text{rot}} \) (computed using Eq. 15 and Eq. 17) as a function of the contact distance \( s_k \) for an opening time of \( t_o = 0.5 \text{ ms} \) while varying the contact thickness \( b \). The contact cross section was chosen to \( A_c = 20 \text{ cm}^2 \), which is suitable for currents in the kA-range.

![Graph showing kinetic energy comparison](image)

**Fig. 20:** Kinetic energy of the moving part during opening as a function of contact distance \( s_k \) when opened within \( t_o = 0.5 \text{ ms} \). Parameter is the thickness \( b \) of the moving part, which is of aluminum for both linear and rotational operation.

From Fig. 20 it can be drawn, that the kinetic energy of linearly moving contacts is noticeable higher at high contact gaps \( s_k \), for all values of mass density and opening time. At small contact gaps, there is small difference between the kinetic energy for linear and for rotational movement. The resulting values of kinetic energy are within several 10 J. Using copper instead of
aluminium for the moving part would lead to three times higher energy values due to higher mass density.

**Calculation of the ratio: kinetic energy for linear over rotational movement**

Using Eq. 15 and Eq. 17, the ratio \( N_{lr} = \frac{W_{lin}}{W_{rot}} \) can be easily calculated. As can be seen from Eq. 18, it varies with contact distance \( s_k \) and contact thickness \( b \).

\[
N_{lr} = \frac{W_{lin}}{W_{rot}} = \frac{12 \cdot s_k \left( \frac{s_k + b}{2} \right)^2}{(s_k + b) \left( (s_k + b)^2 + b^2 \right) \left( 1 + 2 \cdot \sin \left( \frac{b}{s_k + b} \right) \right)^2}
\]

EQ. 18

\( b = 0 : N_{lr} = 3 \quad b = s_k : N_{lr} = 0.7 \quad b = 5/8 \cdot s_k : N_{lr} = 1 \)

Extreme values for \( N_{lr} \) are \( b = 0 \), \( b = s_k \) and \( b = 5/8 \cdot s_k \); however, these values will be impractical for implemented switches; see the upper limit for \( b \) in chapter 4.2.3, p. 45.

Fig. 21 shows \( N_{lr} \) (Eq. 18) as a function of the contact gap \( s_k \) with thickness \( b \) as parameter. This curves confirm the fact, that a linearly operated switch requires higher kinetic energy than a rotationally operated one for the same design values, although the given energy ratio is < 3 for any design. This holds true for the medium voltage level and for contact a thickness in the mm-range.

![Fig. 21: Ratio \( N_{lr} \) of kinetic energy of linearly and rotationally operated switches for various geometries.](https://example.com/fig21)

The result from this comparison for the design of elementary switches from an energy point of view is:

- the thinner the moving part is, the superior is the rotational movement compared to linear movement
- if contact thickness \( b \) is above \( 5/8 \cdot s_k \), than rotational operation requires higher kinetic energy
- the ratio is not depending on contact material, length and opening time.
Given this ratio and keeping in mind, that the cross section $A_c$ but not $l$ and $b$ individually are determined by Eq. 8, there are possibilities for design optimisations, which will be discussed in chapter 4.2.7 p. 57.

4.2.6 Required drive energy as a function of design voltage

In the previous chapter, the kinetic energy of the moving part during operation was calculated. The energy to be provided by the drive capacitor has to be significantly higher than that of the moving part due to low efficiency of the repulsion drive. The dependency of drive efficiency on system- and design parameters and the effects on the required drive energy are analysed below.

Drive efficiency as a function of contact thickness and skin depth

For the thickness $b$ of the moving part, an upper limit $b_{\text{max}}$ was derived in chapter 4.2.3 p. 45. A method to calculate the loss of accelerating force on the moving part for low values of $b$ was given by Zieve [35]. Hence, there has to be an optimum for $b$ in between these two. The force generated on the moving part is a function of thickness $b$ and skin depth $\delta_d$. The latter is given by Eq. 19.

$$\delta_d = \sqrt{\frac{2}{\omega_d \cdot \mu_0 \cdot \gamma_{alu}}} = \sqrt{\frac{1}{\pi \cdot f_d \cdot H_0 \cdot \gamma_{alu}}}$$  \hspace{1cm} \text{Eq. 19}$$

The skin depth $\delta_d$ is a function of the frequency of the drive current $\omega_d$, the permeability $\mu_0$ and conductivity $\gamma_{alu}$ of the moving part. Typical values for $\delta_d$ for aluminium and copper are some mm (see e.g. Fig. 25 below). The dependence of the efficiency $\eta_o$ from skin depth $\delta_d$ and $b$ is given in Eq. 20 [35].

$$\eta_o = \eta_{\text{inf}} \cdot \left(1 - e^{-\frac{b}{\delta_d}}\right)^2$$  \hspace{1cm} \text{Eq. 20}$$

$\eta_{\text{inf}}$ is a theoretical maximum drive efficiency that would result for a very high thickness $b$. $\eta_o$ can be measured for a given switch and drive ($b$ and $\delta_d$ are then determined).

Drive efficiency exponentially decreases with coil insulation thickness

The drive efficiency is not only influenced by the thickness and the skin depth, but also by the thickness of the coil insulation. Therefore, Eq. 20 has to be extended in order to obtain dependence from all relevant parameters.

In [39] it was found, that drive efficiency decreases with insulation thickness $s_i$ of the drive coil. The drive efficiency is given in [39] as a polynomial function ($g^{th}$ order) of $s_i$. The influence of distance between drive coil and moving part on the efficiency $\eta_d = f(\eta_o, s_i)$ was also experimentally investigated by
Popelka [83], using the linear design given in Fig. 12. The results are given in Fig. 22.

![Graph showing measured values: aluminum, b = 2 mm and exponential approximation](image)

Fig. 22: Measured drive efficiency of a linear moving switch as a function of the thickness of the coil insulation and exponential approximation

The opening velocity \( v_s \) was measured as a function of \( s_i \) and \( \eta_d \) calculated by rearranging Eq. 7. The results of these measurements (Fig. 22) show an exponential decrease of the drive efficiency with \( s_i \). The drive parameters for these measurements were: \( N = 10 \) turns, \( b = 2 \text{ mm} \), \( s_x = 17 \text{ mm} \), \( \delta_d = 1.4 \text{ mm} \) and a moving part of aluminum. The measured efficiency is less than \( \eta_o = 8\% \) and can be described by Eq. 21, using \( s_i \) in [m].

\[
\eta_d = \eta_o \cdot e^{-\frac{b}{\delta_d}} = \eta_{inf} \left(1 - e^{-\frac{b}{\delta_d}}\right) \cdot e^{-\frac{b}{\delta_d}} \approx 8\% \quad \text{Eq. 21}
\]

Using an insulation with \( s_i = 2 \text{ mm} \) will therefore reduce efficiency down to \( \eta_d = 5\% \).

**Calculation of coil insulation thickness \( s_i \) from its dielectric strength**

The measurements given in Fig. 22 show the drive efficiency as a function of distance \( s_i \) between coil and moving part. In a switch, \( s_i \) is given by the necessary coil insulation thickness, which has to be chosen according to the system voltage. As already done with the dielectric strength of the contact gap, an average dielectric strength of the insulation \( E_{iso} \) is introduced to get an approximate value for \( s_i \) without exact field calculation; see also definitions in 4.2.1, p. 42. Accordingly, the necessary coil insulation thickness \( s_i \) can be approximated by Eq. 22. \( E_{iso} \) has to be looked up in insulation material data books and will be in the range of several 10 kV/mm, see for example Kind [20] p. 173ff.

\[
s_i > \frac{U_{dim}}{E_{iso}} \quad \text{Eq. 22}
\]
Eq. 22 is a rather rough dimensioning formula. However, it will be used further on as it suitably describes the dependency of the insulation thickness from the design voltage.

**System voltage influences required drive energy**

From the above given dependence of drive efficiency from system voltage, the required drive energy $W_{\text{Dlin}}$ from Eq. 15, Eq. 21 and Eq. 22 can be calculated, taking into account the system voltage. This is done in Eq. 23 for linear operation, and the drive energy is equated to the drive parameters $C_d$, $U_d$.

$$W_{\text{Dlin}} = \frac{W_{\text{lin}}}{\eta_d} = \rho_c \cdot l \cdot b \cdot s_k \left( \frac{s_k + b}{2} \right)^2 \cdot \frac{U_{\text{dim}}}{t_o^2} \cdot e^{200 \cdot \frac{U_{\text{dim}}}{E_{\text{ua}}} \cdot \frac{C_d \cdot U_d^2}{2}}$$  \hspace{1cm} \text{Eq. 23}

Accordingly, the required drive energy for rotational operation is given in Eq. 24 with $J_c$ from Eq. 16 and $W_{\text{rot}}$ from Eq. 17.

$$W_{\text{Drot}} = \frac{W_{\text{rot}}}{\eta_d} = \rho_c \cdot l \cdot b \cdot (s_k + b) \cdot \left( \frac{(s_k + b)^2 + b^2}{2} \right) \cdot \frac{1 + 2 \cdot \sin \left( \frac{b}{s_k + b} \right)}{24 \cdot \eta_d \cdot t_o^2} \cdot \left( 1 + 2 \cdot \sin \left( \frac{b}{s_k + b} \right) \right)^2$$  \hspace{1cm} \text{Eq. 24}

$W_{\text{Dlin}}$ and $W_{\text{Drot}}$ are both functions of $U_{\text{dim}}$ and $l_{\text{dim}}$, the geometry parameters $l$, $b$, $s_k$ and inversely proportional to drive efficiency $\eta_d$ and the square of the opening time $t_o$.

**Comparison of drive energy for linear and rotational operation**

The values of $W_{\text{Dlin}}$ and $W_{\text{Drot}}$ (Eq. 23, Eq. 24) are given in Fig. 23 as a function of system voltage $U_{\text{dim}}$ with varying the pressure $p$ of the switching medium as parameter. $s_k$ was calculated from Eq. 8 p. 44 with $E_{\text{avg}} = p \cdot E_o$ (the pressure $p$ of the switching medium is assumed to give linear rise to the maximum applicable dielectric strength, see i.e. Paschen-curves in Kind [20] p. 168, or [23]). The pressure of the switching medium has been varied from 1 to 5 bar ($E_o = 15$ kV-cm$^{-1}$-bar$^{-1}$). Approximate values for the required drive energy of standard gas-blast breaker technology are added to the chart for comparison. This curves are calculated using values for drive energy over rated power of $W_o = 100$ J/MW for self-blast technology and $W_o = 700$ J/MW for puffer-breaker technology [101]. For this comparison, $U_{\text{dim}}$ was assumed to be equal to the rated insulation level of standard breaker (see also chapter 6.4.5 p. 121f) and only $1/3$rd of the breaker-values have been taken to compare to a single-phase elementary switch. The necessary drive energy for linear movement is higher than for rotational movement in the medium voltage range and above in accordance with Fig. 21.
For comparison: Drive energy for puffer-breaker (approx.)

Self-blast technology (approx.)

Lin. 1 bar
Rot. 1 bar
Lin. 3 bar
Rot. 3 bar
Lin. 5 bar
Rot. 5 bar

Fig. 23: Required drive energy as a function of dimensioning voltage for linear and rotational movement. Parameter for calculation: $E_{\text{iss}} = 50 \text{ kV/mm}$, $E_0 = 12.5 \text{ kV/cm}$, $\eta_0 = 5\%$, $b = 2 \text{ mm}$, $l = 250 \text{ mm}$, $t_{\text{open}} = 1 \text{ ms}$, $I_{\text{dim}} = 2 \text{ kA}$, Self-blast: $100 \text{ J/MW}$, Puffer-breaker: $700 \text{ J/MW}$ from [101].

The drive energy can be drastically reduced by using higher pressure of the switching medium. In Fig. 24, the ratio $W_{\text{Dlin}}$ over $W_{\text{Drot}}$ is shown as a function of design voltage with the pressure of the switching medium as parameter. While assuming the same drive efficiency for both principles, it has not changed from Fig. 21 (Eq. 18) as efficiency cancels down.

Fig. 24: Ratio of required drive energy of linear over rotational movement. Parameter is the pressure of the switching medium

It can be seen, that higher pressure (or equivalent, a better insulation medium) leads to a smaller ratio. The contact thickness is $b = 2 \text{ mm}$, the cross
section of the moving part is $A_c = 600 \text{ mm}^2$, resulting in a design current of 2400 A.

Thus, some general conclusions for switches with minimal mass can be derived:

1) Rotational moved contacts require less drive energy than linear operated ones at medium voltage levels and above (Fig. 23). The lower the dielectric strength of the switching medium and the higher the system voltage, the better is rotational (Fig. 24).

2) For switching with minimal mass switches with repulsion drive at higher voltage levels, it makes sound sense to increase the dielectric strength of the utilized switching medium rather than drive energy (Fig. 23). This can be done by increasing pressure or using a switching medium with higher dielectric strength, as $SF_6$.

3) For an implementation, best insulation materials and optimal dielectric design are to be applied for the insulation between drive coil and contacts. This strongly increases opening velocity and reduces drive energy.

The drive energy is one design parameter that can be chosen for a realization and the given comparison will help to choosing the right operating principle and switching ambient.

4.2.7 Opening velocity as a function of design parameters

In this section, the opening velocity is calculated as a function of drive energy and switch parameters. The requirement for continuous current determines the cross section $A_c$ of the moving part but not length $l$ and thickness $b$ individually, see Eq. 9 p. 45. Consequently, one of the variables $l$ or $b$ can be chosen to optimise drive efficiency (Eq. 21) and therefore achieve high opening velocity.

The opening velocity of an elementary switch can be calculated from the drive energy (Eq. 23) and drive efficiency (Eq. 21). This shows the influence of contact geometry, thickness, material and drive parameters at linear movement, see Eq. 25.

$$v_{k,lin} = \sqrt{\frac{2 \cdot W_{lin}}{m_c}} = \sqrt{\frac{2 \cdot \eta_{mlf} \cdot W_{Dlin} \cdot e^{-100 \cdot \delta}}{\rho_c \cdot l \cdot s_k \cdot b \cdot \left(1 - e^{-\frac{b}{\delta}}\right)}}$$

Eq. 25

Corresponding considerations (Eq. 24 and Eq. 21) lead to the opening velocity as a function of drive energy at rotational operation, see Eq. 26.
4.2 Dimensioning guidelines for elementary switches

\[ v_{k,\text{rot}} = \sqrt{\frac{6 \cdot \eta_0 \cdot W_{\text{Drot}} \cdot (s_k + b)}{\rho_c \cdot l \cdot b \cdot \left( \frac{b + s_k}{2} \right)^2 \cdot e^{-100 \cdot s_0}} \cdot \left( 1 - e^{-\frac{b}{\delta_d}} \right)} \]

Eq. 26

Knowing the dependence of the opening velocity on switch parameters, one now can optimise switch design. To give an example, the opening velocity is calculated as a function of thickness \( b \) and material of the moving part to compare to a realized switch, see Fig. 25. This diagram shows the velocity calculated with Eq. 25 and Eq. 26, using aluminium, magnesium and copper and the same drive energy for both operating principles: \( W_{\text{Dlin}} = W_{\text{Drot}} = W_{\text{D}} = 210 \) J.

![Graph showing calculated opening velocity of elementary switches with repulsion drive as a function of contact thickness. Linearly- and rotationally operated switches of Al, Mg and Cu are shown in comparison to measured values.](image)

**Fig. 25:** Calculated opening velocity of elementary switches with repulsion drive as a function of contact thickness. Linearly- and rotationally operated switches of Al, Mg and Cu are shown in comparison to measured values.

**Optimum thickness of the moving part:** \( b_{\text{opt}} = (0.5 \ldots 2) \cdot \delta_d \)

From Fig. 25 it can be seen, that the optimum contact thickness \( b \) to get highest velocity is in the range of some mm for all three materials. The opening velocity shows a flattish optimum at a thickness \( b \) which is little larger than the skin depth \( \delta_d \) and thus depends on the drive frequency \( f_d \), see Eq. 19. In general, the optimal contact thickness \( b \) is within \( b_{\text{opt}} = (0.5 \ldots 2) \cdot \delta_d \) for linear and rotational movement; thus the optimum thickness if using copper is slightly smaller.
In Fig. 25, also the measured opening velocities for \( b = 2 \) mm of an implemented switch with the given parameters and equipped with a copper, respectively an aluminum moving contact are given for comparison (values from [83]). The measurements are in good agreement with the calculated values. A comparison of the measured opening velocity of an rotationally operated switch to Eq. 26 for a wide range of drive energy is given in Fig. 26.

![Image of graph comparing measured and calculated velocities](image)

**Fig. 26: Comparison of measured opening velocity with calculated values from Eq. 26 for a rotationally operated switch. Measured values are taken from [82]**

The parameters of these switch are: \( s_k = 26 \) mm, \( l = 90 \) mm, \( b = 2 \) mm, \( m_c = 10.5 \) g, \( J_e = 59 \times 10^{-6} \) kg·m\(^2\), \( C_d = 270 \) μF. The measured values are taken from Magri [82] and show good agreement with Eq. 26 at high drive energy. For lower values of the drive energy, the contact force in the closed position strongly affects the opening velocity, as then the repulsion forces are much lower, compare to Eq. 3, Eq. 5 p. 22. Therefore the measured values are lower than the calculated ones at low drive energy (see also chapter 5.1.4 p. 68f).

**Implications of the material of the moving part in elementary switches**

The design rules (Eq. 8, Eq. 9 p. 45) are defining the volume but not the mass \( m_c \) of the moving part. Thus, mass density is one factor to be chosen for the moving part (Eq. 23, Eq. 24). A second factor is its conductivity, as this affects the skin depth \( \delta_e \) (Eq. 19). Fig. 27 shows the value of resistivity and mass density for particular contact materials; both are to be low for getting high velocity. In literature, mostly aluminium was chosen as material for the moving part, see [39], [74], [42].

The results given in Fig. 25 show, that the use of aluminium results in a nearly 60% higher maximum velocity than if using copper. However, it also shows, that a moving part made of magnesium results in even higher velocities than aluminium at larger thickness \( b \). This is due to the lower mass density of magnesium and its higher skin depth.
Fig. 27: Specific resistance and mass density for particular materials.

Aluminium and magnesium are not used as a contact material as they show some bad attributes: low melting point (and thus high contact wear), the immediate formation of an isolating aluminium-oxide and lower electrical and thermal conductivity than copper [3], [10]. Hence, for elementary switches with repulsion drive, the moving part should be of aluminium or magnesium to get high opening velocity, but must be coated at the contact points to get best electrical contact performance. Of course, the erosion of this coating by arcing has to be avoided; however this was one of the presumptions for high power switchgear made of elementary switches, compare to Fig. 14 p. 42. Additional material data and guidelines for the use of magnesium in a variety of applications are given by Busk [21].

Due to the many design parameters included in Eq. 25 and Eq. 26, these equations are suitable to calculate the resulting opening velocity for a variety of designs. Therefore, they are useful for optimising a given concept with respect to opening velocity in a simple manner.

4.3 Summary: fundamentals of elementary switches

Based on the presumption that the design voltage only determines contact gap and the design current only determines the cross section of the moving part, a design guideline for the so-called "elementary switches" with repulsion drive was given. Based on the definitions for design voltage and design current, the minimal moving mass of a mechanical switch was calculated. The kinetic energy of a linearly operated switch turns out to be noticeably higher for most geometry's than that of rotationally operated ones.

The efficiency of the repulsion drive is lower than $\eta_d = 8\%$ and exponentially decreases with increasing system voltage. The drive needs less than 1 kJ energy to be stored in the drive capacitor for contact velocities up to 50 m/s.
Rotationally operated switches need less drive energy than linear operated ones. Rotational movement is so much the better, the lower the dielectric strength of the switching medium, the lower the design current and the higher the design voltage.

The optimum thickness of the moving part is 0.5 to 2 times the skin depth for linear and rotational movement, but there's an upper limit at a thickness of \( b_{\text{max}} = 4 \ldots 5 \) mm. With regard to low drive energy and high contact velocity, aluminium and magnesium are the most suitable materials for the moving part but both are worse contact materials. They are to be coated with a suitable contact material.

A widely applicable equation for calculating the opening velocity of elementary switches as a function of switch design, drive values and contact material was given. This equation can be used as an optimisation tool for a quick check on the dimensions for a specific rating.
4.3 Summary: fundamentals of elementary switches

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5 Mechanical and electrical performance of fast switches

Based upon the theoretical considerations in the previous chapters, an experimental setup was installed which enables analysis of practical designs for verifications. The focus for the experiments was the use of these fast elementary switches in hybrid systems. Several test switches were designed and assembled for these tests, which should come as close as possible to realistic designs applied in practical use. So in the following chapter many practical aspects for the use of elementary switches are covered. The electric power switching capability is treated for current interruption and for current commutation on parallel impedance.

5.1 Operation aspects of real elementary switches

The data points given in Fig. 26 p. 59 are calculated from the measured opening time and the opening gap as average opening velocity of a rotationally operated switch. This calculation implies, that the velocity of a switch remains constant during opening, which copes with measurements and simulations found in [74]. Nevertheless, this was to be proved experimentally.

5.1.1 Measurement of an opening process

Fig. 28 shows the cross section of a test switch as it was realized for a linearly operated type for experimental proof (see also Fig. 12 p. 39). Fig. 28 gives the corresponding travel curve $x(t)$ for the moving contact measured during opening for different drive voltages $U_d$. The movement starts at $t = 200 \mu s$ after triggering. Then the ring moves with a nearly constant velocity $(dx/dt)$ for all drive voltages. At the lower end of the gap ($x = -14.5 \text{ mm}$) the ring is decelerated by friction at the wall, finally bashing against the end of the gap. The position of an opening gap calculated with a constant velocity of $v_k = 20 \text{ m/s}$ is also given in Fig. 28 for comparison. This comparison shows that the assumption of a constant opening velocity is a good approximation even for lower drive voltages.
The remaining distance from the lower end varies from 0.1 mm up to 3 mm. Here, the design of the mechanism for slowing down the moving part has to be improved, as discussed in the following section.

![Diagram of a linear actuator with opening and closing coils.](image)

**Fig. 28**: Measured travel curves of the moving part during opening a linear operated switch at various drive voltages $U_d$, which are given on the chart. The position was measured optically with a resolution of 0.1 mm.

No measured curves for the opening gap of rotationally operated switches are available as no suitable travel sensor could be found. However, the use of the repulsion drive for rotational movement and having comparable moving mass and geometry implies that the travel behaviour of the opening gap will be very similar to the one for linear movement.

### 5.1.2 Deceleration of the moving part while opening

In the basic design of elementary switches (Fig. 12 p. 39), linearly and rotationally operated switches have a narrowing gap to slow down the moving part and keep it then in open position by friction. This is the simplest method for doing so and it works well as shown in Fig. 28. The details of this deceleration method are analysed below.

**Fast slowing down but no rebound**

A general problem for all kind of switching devices is rebounding of the moving parts when reaching their end position. In the present case, the kinetic energy of the moving part is within several 10 J (compare to Fig. 20, p 51), which is a small amount of energy, although the moving part moves very fast. An immediate slowing down (e.g., by bashing against a wall) will cause
a rebound and significant mechanical stress on the moving part. Rebounding is crucial, as closing is also done by repulsion and drive efficiency strongly decreases with the distance from the drive coil, compare to Fig. 22. However, gentle slowing down takes too much time and additional gap, and this gap has to be covered again at closing. For instance: Given \( v_k = 50 \text{ m/s} = 5 \text{ mm/100 } \mu \text{s} \). Then a deceleration time of 100 \( \mu \text{s} \) would require additional gap of \( x = 2.5 \text{ mm} \).

**Parameters affecting the deceleration**

The following parameters are significant for deceleration:

- turbulent flow of the switching medium
- compression of the switching medium in the narrowing gap (see Fig. 12)
- gravitation
- friction on the gap walls

These effects are correlated by a differential equation in Eq. 27, which gives an equilibrium of forces. The initial conditions for \( v_k \) and \( x \) are also given. The geometry parameters such as length \( l \) and contact gap \( s_k \) are given by the switch design. The shape and material of the narrowing gap determines the value of friction \( F_f \) on the walls.

\[
-m_c \frac{d^2 x}{dt^2} - \rho_{\text{air}} \cdot c_w \cdot l \cdot s_k \frac{(dx)^2}{dt} - p(x) \cdot l \cdot s_k - m_c \cdot g - F_f = 0
\]

**Eq. 27**

\[
\frac{d^2 x}{dt^2} \bigg|_{t=0} = 0, \quad \frac{dx}{dt} \bigg|_{t=0} = v_k, \quad x \bigg|_{t=0} = 0
\]

The motion of the ring in the gaseous medium in the gap decelerates the ring and is a depending on mass density \( \rho_{\text{air}} \) of the medium, the shape of the moving part, which determines the air-drag coefficient \( c_w \) and its instant velocity. To study the impact of these parameters, turbulent flow calculations in a gap with given geometry have to be carried out.

Therefore, it is not feasible to give a general solution for Eq. 27 without having a specified geometry. Anyhow, the impact of gravitation \( (m_c g) \) may be neglected in most cases, as also stated by [83] based on experimental results. The impact of the mass density of the switching medium \( (\rho_{\text{air}}) \) on the opening velocity was experimentally studied with a rotationally operated switch by Sartori [81] as shown in Fig. 29.
In the experiment the switch was operated with increasing drive voltage in steps in an air ambient with \( p = 1 \text{ bar} \) or \( p = 5 \text{ bar} \). From this experiment, the opening velocity turns out to be around 10% higher at \( p = 1 \text{ bar} \) than at \( p = 5 \text{ bar} \).

5.1.3 The closing function

To use the repulsion drive for closing elementary switches is self-evident, if already used one for opening and because of the elementariness of the repulsion drive. A high closing velocity is not necessarily the main requirement in most applications. The vital requirement for the closing mechanism is to provide a sufficient number of contact points in the closed position, each with sufficient contact force for the continuous current to flow. In the following, this subject is illuminated.

High closing velocity necessary for sufficient contact force

Depending on the frequency of the drive current (see Eq. 2, p. 21), the accelerating force impulse for closing will typically last for some 100 µs only \([83], [81], [82], [74], [69]\). Then, there is only the inertia of the moving part (which is apprehended to be as low as possible) to force the moving ring into a set of contact springs, which finally provide the contact force for the individual contact points. To check on the feasibility of such a system, a simulation using data from a manufacturer of multi-contact high current lamellas \([84]\) was carried out.

The results from this simulation are given in Fig. 30. They show the maximum continuous current that can be carried by an elementary switch in the closed position for a given closing velocity. The latter, in combination with the ring's mass, is finally responsible for the contact force which can be provided and thus for the capability to carry the continuous current.
The maximum current is calculated for four different multi-contact connectors (the corporate names of the connectors are given on the chart), having differences according to [84] in:

- contact force,
- current per lamella and
- distance between two lamellas.

The continuous current derived from acceptable current density of $J_{\text{avg}} = 4 \text{ A/mm}^2$ (Eq. 9) is also given for comparison. It turns out that for the connector LA-CU, a closing velocity of 10 m/s is sufficient to get a contact force high enough to carry the continuous current calculated by Eq. 9. Connector LAI 0.50 needs a closing velocity of 25 m/s to reach this limit. The results from this simulation can be summarized as follows:

- a repulsion drive is suitable for closing elementary switches.
- the required closing velocity depends on the lamellas used as fixed contacts
- the closing velocity provided by the repulsion drive has to be higher than given by the intersection of the curve for a given lamella with the values calculated by Eq. 9

The conclusion from these considerations is that closing velocities in the range of 8 ... 25 m/s are necessary to get the required contact force, if closing of elementary switches is done by repulsion. The challenge is to optimise contact force and number of parallel contacts for the fixed contacts such as to get high current carrying capability in the closed position but no rebound while closing.
5.1.4 Influence of the contact force on the opening velocity

As pointed out, the fixed contacts have to provide the necessary number of contact points and contact force to carry the normal current of an elementary switch. This contact force causes friction on the moving part while opening. The coefficient of friction for multi-contact lamellas is given by the manufacturer as $\mu = 0.15$ [84]. Therefore, the withdrawal force can be calculated by multiplying the contact force with the friction coefficient. The withdrawal force tends to slow down the moving part at opening. Some basic measurements for studying the impact of the contact force on the opening velocity were carried out by Muminovic [86]. The results for the opening velocity as a function of drive voltage for experiments with and without using fixed contacts are shown in Fig. 31.

The opening velocity linearly increases with drive voltage as indicated by the trend lines (and shown in Fig. 29). If using no fixed contacts, the average opening velocity is around 20% higher than with fixed contacts. Unfortunately, for the experiment no quantitative figures for the contact force and thus the friction were available. Therefore, a quantitative link to the commercially given values is missing. However, this rough experiments show that the impact of contact force on the opening velocity may not be neglected and will be even more significant for very high rated currents.

5.1.5 Repetitive switching with elementary switches

Being within a 1-millisecond range, the switching time of elementary switches is 10...100 times lower than that of conventional high power switches (but still by a factor 1000 higher than that of semiconductor switches, see Fig. 7 p. 24). Therefore, switching with repetition rates of 500 Hz in principle would be possible with elementary switches. However, the limiting factors for repetitive switching are:
• Charging of the drive capacitor.
• Small efficiency. Thus, the moving part is heated by the losses of the drive.

For example: The switch with an opening velocity of 50 m/s shown in Fig. 26 requires a drive energy of \( W_d = 200 \text{ J} \) for each operation and shows a drive efficiency of less than \( \eta_d = 5 \% \). Therefore, around 95% of this energy is heating the drive coil and the moving part. Given a repetition frequency of \( f_{\text{rep}} = 100 \text{ Hz} \), this will lead to a thermal power input of \( P_{\text{rep}} = (1 - \eta_d) W_d f_{\text{rep}} = 19 \text{ kW} \) into the moving part. This would also require a charging unit for the drive capacitor with a rated power higher than 20 kW.

From this considerations it can be concluded, that repetitive switching is possible, but it is not reasonable at repetition frequencies of > 10 Hz. Simple switching sequences as for example required for high-power circuit breakers by standards (O-300ms-CO) seem to be no problem.

### 5.2 Closing characteristic of fast turn-on switches

As was discussed in chapter 5.1.3, the use of a repulsion drive together with the low inertia of elementary switches (compare to Fig. 18 p. 48) results in a reasonable high closing velocity. For some applications, the closing time (including pre-strike of the contact) is more essential rather than the velocity itself. Therefore, in this section, focus is laid on the closing time.

![Diagram of closing characteristic](image)

**Fig. 32:** Measured position of the moving part during closing a linear operated switch at various drive voltages \( U_d \), which are given on the chart. The position was measured optically with a resolution of 0.1 mm.
It is investigated, what closing times can be achieved with elementary switches and what are uses for these switches. As an example, Fig. 32 shows the measured closing travel curve of the contact for various values of the drive voltage $U_d$. The switch stays closed only at highest drive voltages. The opening velocity measured at a drive voltage of $U_d = 1110$ V is nearly constant at $v_k = 17$ m/s. The closing time is 1.1 ms for this experiment.

The closing time of a rotationally operated switch was measured by Sartori [81] as a function of the drive voltage as shown in Fig. 33. The total gap of this switch in the open position was $s_k = 26$ mm, resulting in an average closing velocity of $v_k = 50$ m/s at highest drive voltage (see also Fig. 12 p. 39).

It can be concluded from these measurements, that the overall closing time can be lowered to 500 $\mu$s using the rotational switch design and reasonable drive- and design values.

**Calculation of the prestrike-time**

The measurements given in Fig. 33 have not been performed in a high-voltage circuit and therefore, no pre-strike occurred. An estimation of the pre-strike-time as a function of closing velocity is given in Fig. 34. This pre-strike time was calculated for a gap with $s_k = 20$ mm in air while closing with a double break switch at a voltage of $U_s = 20 \text{ kV}_{\text{peak}}$ across the switch. Parameter is the air pressure; the breakdown voltage is derived from the paschen-curve for air [20] p 168, assuming a homogenous field in the contact gap.
It can be seen from the estimation that the pre-strike time strongly decreases with closing velocity and with ambient pressure. It is within several 10 µs and it will be even shorter, if using a switching medium with higher dielectric strength, i.e. SF₆.

### 5.3 Interruption behaviour at very short arcing time

In a first approach for elementary switches, the switching arc was considered not to determine the design (Fig. 14, p. 42). This assumption does not make sense, if arcing appears to an extend as it occurs in standard mechanical switchgear. Therefore, switching with elementary switches is possible only in applications, where the switching arc occurs only for a very short arcing time (less than 1 ms). One of these applications would be the so-called synchronous interruption as discussed in 2.2.1 p. 18f.

It is now investigated, how the fast action and high velocity of the elementary switch fits for synchronous interruption in the medium voltage range. According to the nature of these switches, the investigations are conducted without having forced arc-cooling facilities applied to the elementary switches.

#### 5.3.1 The current interruption capability

The current interruption capability of very fast acting switches is studied based on a principle interruption process as shown in Fig. 35.

The influence of the following parameters on the gap recovery is to be investigated:

- Opening velocity $v_k$
- Circuit current and its rate of change $\frac{di}{dt}$
- Arcing time $t_{arc}$
- TRV and the rate of rise of recovery voltage (RRRV)
5.3 Interruption behaviour at very short arcing time

- Instantaneous recovery
- Number of series breaks

The investigations are based on experimental results rather than on the physics of the switching arc. This approach was chosen due to the complex arc phenomena and the many boundary conditions, which are to be considered while theoretically studying the arc.

![Diagram of current interruption principle and typical waveforms]

**Fig. 35: Principal of current interruption using fast switches.**

The goal of these investigations is to deliver basic insight on the influence of the above-mentioned parameters on the interruption process in a parameter-range, which is suitable for power switching at medium voltage levels.

**Example: Interruption sequence and typical waveforms**

Experimental investigations have been conducted in a medium-voltage resonant circuit as shown in Fig. 36. Before coming into details of the interruption process, an interruption sequence and typical waveforms are given in this subsection.

![Resonant circuit diagram]

**Fig. 36: Resonant circuit for studying synchronous interruption in the medium voltage range.**

The storage capacitor $C_s$ together with the circuit inductance $L_s$ forms the resonant circuit, which is described by the equations given in Eq. 3 and Eq. 2.
p. 21. The test switch is used to close and open the resonant circuit. The capacitance $C_p$ in parallel to the test switch defines frequency and the TRV according to Eq. 1 after current interruption at current zero. Typical waveforms of current $i(t)$ and voltage $U_s(t)$ for synchronous interruption in this resonant circuit are shown in Fig. 37. The fast switch was closed and opened again within the first half sine wave of the circuit current $i_s(t)$ at a resonant frequency of 500 Hz. The voltage $U_s$ collapses at the instant of contact closing and the parallel capacitance $C_p$ discharges through the switch, resulting in some short time high current spikes. Opening of the switch was triggered 100 μs ahead of current zero at this experiment.

![Graph showing current and voltage waveforms](image)

**Fig. 37:** Typical current and voltage waveforms at synchronous current interruption tests with an elementary switch in a medium voltage resonant circuit (Fig. 36).

At the instant of contact parting (shortly after 1.2 ms in Fig. 37) an arc is drawn. Arc voltage is in the range of 20 – 150 V (double break switch) and thus can hardly be seen on this voltage scale. The circuit impresses the TRV across the switch after current zero. The peak current was 590 A at this test, the rate of decline at current zero was $\frac{di}{dt} = i_{peak} \omega = 1.85$ A/μs and the maximum of TRV peak = 3780 V, reached 140 μs after current zero which corresponds to a TRV-frequency of $f_{TRV} = 3450$ Hz. This test was performed with a rotationally operated switch in air at ambient pressure with an opening velocity of $v_k = 35$ m/s.
Dependence of recovery from time after current zero and opening velocity

In order to obtain information on the gap recovery after current zero, the amplitude of the TRV was increased until reignitions occurred. The latter giving the so-called load characteristic, see Fig. 38. This is a zoom in the current zero-period compared to Fig. 37. The time scale (given in milliseconds) of each experiment has been shifted, so that current zero occurs at $t = 0$.

![Graph showing TRV and recovery voltage](image)

$v_k = 35\, \text{m/s}$

$f_{TRV} = 5\, \text{kHz}, 3.6\, \text{kHz}$

$f_{rev} = 700\, \text{Hz}$

$I_{peak} = 300...700\, \text{A}$

rotational operation,
air, 1 bar, double break

$u [\text{V}]$

Fig. 38: A collection of transient recovery voltages of several successful and non-successful synchronous interruption tests. Opening velocity was $v_k = 35\, \text{m/s}$.

The black points mark the reignition voltages for the non-successful interruptions. The tests were performed in air at ambient pressure at an opening velocity of $v_k = 35\, \text{m/s}$, see parameters given on the diagram. Arcing time was not constant for all experiments but was less than 40 $\mu\text{s}$. A parallel capacitance $C_p$ was connected across the switch, but no capacitance was used for voltage grading across the two series breaks.

From these experiments, some basic insights into interruption with fast opening contacts at short arcing times can be derived:

- The reignition voltage for non-successful interruptions is higher than the theoretical "instantaneous recovery", which is around 300 V for copper and silver contacts at interrupting currents of several 100 A (see [3] p. 641).

- The reignition voltage linearly increases with time from current zero.
The breakdown process is very fast, which indicates a dielectric breakdown of the gaps. This is confirmed by results in [42] p. 94f.

To study the influence of the opening velocity on the interruption limits, the TRV-values given in Fig. 38 for an opening velocity of $v_k = 35$ m/s are compared to values measured at an opening velocity of $v_k = 17$ m/s in Fig. 39.

Fig. 39: Comparison of reignition voltages of several synchronous interruption tests at opening velocities of $v_k = 35$ m/s and $v_k = 17$ m/s. The values for the instantaneous recovery from [3] p. 641 and from [42] p. 92 are given for comparison.

The straight lines in Fig. 39 are given to indicate the linear dependence of the reignition voltages with time (see Eq. 28 below). The values for the instantaneous recovery from [3] p. 641 and from [42] p. 92 (measured at 15 m/s, $i_s = 2.1$ kA and $t_{arc} = 50$ $\mu$s) are also given for comparison. The moving parts of the elementary switches utilized for these measurements were of aluminum coated with 50 $\mu$m silver. If a breakdown occurred at these measurements, the arc eroded the coating and the contact were to be replaced. Therefore, the number of tests with reignitions was limited.

**Instantaneous recovery shortly after current zero**

To compare instantaneous recovery known from literature with the reignition voltage of the elementary switches at fast opening, a more detailed investigation of the synchronous interruption process very shortly after current zero was conducted. The results are shown in Fig. 40 for a constant
opening velocity of $v_a = 12$ m/s. Note that the time scale has changed from Fig. 38! An example TRV curve is shown together with a set of 37 reignition voltages at different time from current zero. The frequency of TRV was changed by connecting capacitors $C_p$ with increasing capacitance in parallel to the switch. The five points showing a rise time of less than one $\mu$s resulted from measurements without a parallel capacitance. These measurements are compared to the values for instantaneous recovery ([3] p. 641) and the values calculated for a dielectric breakdown for single break (SB) and double break (DB). The arcing time prior to current zero was kept constant at $t_{arc} = 135$ $\mu$s.

![TRV example graph](image)

**Parameter:**
- $v_a = 12$ m/s
- Linear operation, air, 1 bar, double break
- $f_{frv} = 16$ kHz ... 1 MHz
- $t_{arc} = 135$ $\mu$s,
- $dV/dt = 2$ ... 2.9 A/\mu$s

**Calculated:**
- $e_{fr} = 0.5$, $E_a = 25$ kV/cm
- 10% vertical spread

**Fig. 40:** Comparison of reignition voltages at opening velocities of $v_a = 12$ m/s with values for instantaneous recovery of single- and double break switches calculated for a dielectric breakdown.

The measured values of the reignition voltage are mostly in between the instantaneous recovery values for a single- and a double break switch but are varying from 250 V to 600 V within the first 10 $\mu$s. At time instants higher than 20 $\mu$s, the reignition voltage starts to increase according to the values calculated for a dielectric breakdown for a double break switch.

The following conclusion can be drawn from this investigation:

- The breakdown strength of an elementary switch immediately after current zero is as high or higher as the instantaneous recovery of one single-break switch.
This is the first step for describing the recovery of the opening gap. The next step to be discussed according to Fig. 35 is the breakdown mechanism and a description of the gap recovery.

**Dielectric breakdown mechanism after interruption**

The linear increase of reignition voltage with time from current zero and with opening velocity in Fig. 39, Fig. 40 and [42] p. 92 already indicates a dielectric breakdown mechanism. Another evidence for a dielectric breakdown mechanism 50 μs after current zero is given in Fig. 41, which shows a successful interruption after one reignition during interruption. The rate of decline of current was \( \frac{di}{dt} = 0.6 \text{ A/μs} \), the TRV-frequency was \( f_r = 4.8 \text{ kHz} \) and opening velocity \( v_k = 11 \text{ m/s} \). Opening of the switch was triggered 200 μs ahead of current zero, arcing time was \( t_{arc} = 100 \text{ μs} \) and the arc voltage reached \( U_{arc} = 100 \text{ V} \). The straight line shows the dielectric strength of the opening gap, calculated using \( \eta_f = 0.5, E_o = 25 \text{ kV/cm} \) and \( v_k = 11 \text{ m/s} \) which gives \( \frac{dU_p}{dt} = 13.7 \text{ V/μs} \).

![Dielectric strength diagram](image)

**Fig. 41:** Measured waveforms of \( U_p(t) \) and \( i_p(t) \) around current zero at synchronous interrupting with an arcing time of 120 μs. Opening velocity \( v_k \) was 11 m/s.

The TRV-rate of rise was higher than the gap recovery. Thus, a reignition of the opening gap occurred at 50 μs after current zero. This put a spark energy of \( E_b = C_p U_p^2/2 = 0.5 \text{ J} \) into the still opening gap but did not lead to continuous current flow. The gap again gained dielectric strength and finally showed a successful current interruption. Note that the overall current \( i_s \) was measured and not the current through the switch (see Fig. 36 p. 72). Therefore, the current spike at the breakdown of the gap cannot be seen in Fig. 41 but the residual current through the parallel capacitance \( C_p \).
Analytical approximation for the gap recovery

From the instantaneous recovery (Fig. 40) and the assumption of a dielectric breakdown mechanism (Fig. 41), an analytical description of the gap recovery after current interruption can be given.

The reignition voltage $U_b$ in a gaseous switching medium linearly increases with gap and pressure in the linear region of paschen’s law, that is $p\text{[bar]} \cdot x\text{[mm]} > 10^3$ [20] p. 168. It can be calculated from the homogeneous breakdown field $E_o$ by introducing a field inhomogeneity factor $\eta_r$. This factor can be derived from comparison of a given geometry with known configurations [20] p. 169ff. Therefore, the reignition voltage $U_b(t)$ is calculated as a function of opening velocity $v_k$ and time from current zero as given in Eq. 28.

$$U_b(t) = x(t) \cdot \eta_r \cdot p \cdot E_o = v_k \cdot t \cdot \eta_r \cdot p \cdot E_o, \quad U_b(t) > U_{ir} = 260V$$  \hspace{1cm} \text{Eq. 28}

The calculated reignition voltage was already given in Fig. 39 and Fig. 40 for comparison with the measured values using $\eta_r = 0.5, E_o = 25$ kV/cm for air at ambient pressure and a 10% vertical spread. The measured values are well within the range of the calculation. As Eq. 28 results into reignition voltage of a single gap but the results coincide with the measurements on a double break switch, it can be concluded that voltage is not evenly distributed between the two series contacts without adding a grading capacitance.

With an eye on Fig. 35 p. 72 one can see, that Eq. 28 describes the gap recovery equal to the no-load recovery of the switch but shifted by $(t_{arc} = t_o - t_c)$.

5.3.2 Current interruption with many breaks in series

The use of single elementary switches for synchronous interruption in a medium voltage resonant circuit was investigated in the above chapter. This has led to Eq. 28, which describes a linear increase of reignition voltage with time from current zero and opening velocity but also gives a minimum reignition voltage of around 260 V according to the instantaneous recovery with good coincidence to literature.

Apparently, the interruption performance will be improved when using many breaks in series and opening all of them at the same instant. In this section, a realization of a switch with many series breaks is presented and the results from current interruption experiments are discussed. Additional information to the design with many series breaks is given in chapter 6.3 p. 104ff below.

Recovery as a function of the number of series breaks

To study current interruption with many series breaks, a switch arrangement was designed by Muminovic [86] as shown in Fig. 42 from a top view. A
rectangular shape of the moving part was chosen to get straight contacts on both sides. The rectangular shaped eddy current loop is insulated and the moving bridging pieces are clamped on both sides. Fixed contacts and moving bridging pieces are made of copper with a 50 μm silver coating. Grading capacitors can be connected across each double-break as shown on the left side. The overall mass of the moving parts was 25 g and its maximum opening velocity was 20 m/s when using drive energy of 200 J. At most, 32 breaks can be connected in series in this switch. The distance between two fixed contacts was chosen to 5 mm according to an arc radius in the kA range.

The experiments have been conducted in a medium voltage resonant circuit as already introduced in Fig. 36 p. 72. The results are given in Fig. 43. The results given in Fig. 43 were measured with an opening velocity of 12 m/s. Across each double break, grading capacitors were connected not only for grading but also to adjust the TRV-frequency. The dots mark the reignition voltages. The circles mark peak voltage and peak time of successfully interruptions. Several TRV-examples, the values for instantaneous recovery and the calculated reignition voltage by Eq. 28 are plotted for comparison. Note that the time scale is given in μs.

What can be seen from Fig. 43 is the following:

- The minimum reignition voltage results higher than 800 V. This is 3 times the instantaneous recovery of a single gap, which indicates a linear increase with the number of double-breaks in series.
- The minimum reignition voltage determines the breakdown-limit during the first 10 μs after current zero.
- For later than \( t = 10 \, \mu s \), the reignition voltage can be approximated by multiplying the results of Eq. 28 p. 78 with the real number of gaps in series.
Fig. 42: Top view (photo) of a rectangular-shaped linearly operated elementary switch having at most 32 breaks in series.

Fig. 43: Measured reignition voltages at synchronous interruption using 6 breaks in series. TRV-frequency was adjusted with the grading capacitors.
Most "non-successfully" experiments show a partial reignition of one or two series gaps only. Therefore, interruption still took place but with limited recovery, see e.g. dots marked with P. Further insights are derived from measurements with 12 breaks (=12 gaps or 6 double breaks) in series using the same switch. These are presented in Fig. 44.

**Fig. 44: Measured reignition voltages at current interruption with 12 breaks in series. TRV-frequency was adjusted with the grading capacitors.**

The very difference to the experiments with only 6 breaks in series is, that not all breaks are located on one side of the moving part, compare to the current path sketched in Fig. 42 above. After each experiment shown in Fig. 44 it was found, that the grading capacitors weren't equally charged, i.e. the instant of contact separation of each series breaks has varied and therefore degrading occurs. The results from this experiments and its comparison to the calculated values can be summarized as follows:

- The reignition voltage within the first 10 μs is up to twice the values if using only 6 breaks in series but they show a larger scatter than in Fig. 43. It is assumed that this is caused by variations in the instant of contact separation, which mechanically differs in the μs-range. This assumption follows from the non-equally charged grading capacitors and from the arrangement of the series breaks on two sides of the moving part.
The TRV shows a partial reignition of one or several gaps even if current interruption finally takes place. This is also due to degradation. These results from Fig. 43 and Fig. 44 are compiled in Eq. 29 which adds the impact of the number of series breaks \( n_k \) on instantaneous recovery \( U_{ir} \) and rise of reignition voltage \( U_b(t) \) to Eq. 28. For these experiments the instantaneous recovery results to \( U_{ir} = 260 \text{ V} \).

\[
U_b(t) = n_k \cdot v_k \cdot t \cdot \eta_F \cdot p \cdot E_0, \quad U_b(t) > \frac{n_k}{2} \cdot U_{ir} = \frac{n_k}{2} \cdot 260 \text{V} \tag{29}
\]

This is a crucial result for the application of elementary switches with regard to two aspects:

- First, according to Eq. 29, the reignition limits can be linearly scaled with pressure of the switching medium, with opening velocity and with dielectric strength of the switching medium.
- Second, the fast switches can hold a very steep initial TRV with a rise time in the \( \mu \text{s}-\text{range} \) can by using sufficient breaks in series.

Additional experiments using 24 breaks in series were performed. The results are in good agreement with Eq. 29.

Some pictures during the interruption process while interrupting a current with \( \frac{di}{dt} = 0.6 \text{ kA} \), which corresponds to a peak current of 2 kA @ 50 Hz, are shown in the following sequence. The photos were taken by a high-speed video camera (2000 frames per second) and are therefore of bad quality (see Fig. 42 for details).

Fig. 45: Pictures of a high-speed video sequence taken during interruption of a current with \( \frac{di}{dt} = 0.6 \text{ kA} \) showing several series arcs. The switch was opened with 12 m/s in air with 24 breaks in series.

These photos show the linear motion of the moving part and an overall arcing time lower than 500 \( \mu \text{s} \).

**Comparison of interruption capability to standard circuit breaker**

From the experiments shown in Fig. 43 and Fig. 44 above, the \( \frac{di}{dt} \) prior to current zero was also measured. Therefore, the interruption performance of the fast switches is shown in Fig. 46 in the same plot with data for standard
breaker (see Fig. 2 p. 17). This is to show the relation only, because it does consider the RRRV but not the absolute values for the rated voltage.

Fig. 46: Measured gap recovery as a function of $\frac{dU}{dt}$ prior to current zero. Parameter is the number of serial breaks. The values for circuit breaker from Fig. 2 and for standards for a 24 kV breaker [100] p. 49 are given for comparison.

This comparison shows, that for the elementary switches operated in air at 1 bar the values for RRRV is around $1/10^4$ the limits given for medium voltage circuit breaker, if using 24 breaks in series. According to Eq. 29 the reignition voltage is not depending on the $\frac{dU}{dt}$ prior to current zero.

To reach the values given for a vacuum breaker (AMF), an elementary switch having 12 breaks in series and operating in air at 5 bar with 50 m/s is required according to Eq. 29 as the extrapolation in Fig. 46 shows.

Some comments to the presented results:

- The comparison of interruption limits between standard circuit breaker and elementary switches was undertaken to show, that it is reasonable to use elementary switches for high power switching at medium voltage level. Of course, this comparison is valid only, if a circuit breaker made of elementary switches would be manufactured and pass the required type tests. This was not done in present work, and the utilized prototype switches would not pass any type test.

- As already mentioned, the design for elementary switches with many breaks in series is not intended to carry high continuous currents. Therefore, if looking for applications, such switches will be best suited to oper-
5.3 Interruption behaviour at very short arcing time

ate in hybrid systems in parallel to the continuous current path, see also chapter 6.4 p. 112 below.

A simple model for to calculate the necessary opening velocity

For successful interruption, the reignition voltage has, at any time, to be higher than the TRV $U_r(t)$. For a single-frequency circuit, the TRV is given by Eq. 1 p. 16. For an application, the TRV and the RRRV have to be taken from standards (e.g. [100] p. 49f). By comparing the rise of reignition voltage of the opening gap (Eq. 28) to the RRRV, the required opening velocity for successful interruption can be estimated, see Eq. 30.

$$\frac{dU_g(t)}{dt} > \frac{dU_r(t)}{dt} \Rightarrow v_{k,\text{min}} = \frac{4 \cdot U_n \cdot f_r}{n_k \cdot \eta_F \cdot E_o} = \frac{2 \cdot \text{RRRV}}{n_k \cdot \eta_F \cdot E_o} \quad \text{Eq. 30}$$

The $(1-\cos(\omega t))$ function of a single frequency circuit, or the time delay specified by standards which is around several $\mu$s, provides a safety margin to Eq. 30. This requirement for the opening velocity gives the very limits for the use of elementary switches in medium- and high voltage systems.

For instance: Suppose an interruption of an inductive current in a 24 kV circuit (as shown in Fig. 1). The standards require $\text{RRRV} = 0.47 \text{ V/} \mu\text{s}$ [100] p. 49. Assuming, an elementary switch (double break) operates in air at a pressure of 5 bar. From this, the required opening velocity results to $v_{k,\text{min}} = 75$ m/s according to Eq. 30. This is a rather high opening velocity even for elementary switches. Using $\text{SF}_6$ instead of air as switching medium would result in $v_{k,\text{min}} = 25$ m/s which is reasonable.

This minimum requirement for the opening velocity imposes a severe restriction on the use of single elementary switches for current interruption in high-voltage systems. However, it will be discussed in chapter 6 p. 101 below, how this interruption performance of single elementary switches is amplified by utilizing well-designed hybrid systems; see also chapter 2.2.3 p. 25. A second possibility to extend the use of elementary switches is to increase the number of serial breaks (Fig. 46), which is useful in a hybrid system, see 6.4 p. 112ff.

Influence of very short and very long arcing time on the gap recovery

The arcing time in a fast switch will affect the recovery after current interruption in two ways:

- For a very short arcing time and if using many breaks in series, the gap recovery may be smaller than calculated by Eq. 29 due to variations in the instant of contact separation which leads to different gaps distances.
A very long arcing time will change the interruption mechanism according to the one of standard breaker. Therefore, the assumption of a dielectric breakdown of the opening gap will no more be valid. The influence of a very short and a very long arcing time are discussed below.

Fig. 47: A zoom in measured current and voltage waveforms of two interruptions. Experiment a) was conducted with an extremely short arcing time, experiment b) with an arcing time of 50 μs. The parallel capacitance was \( C_p = 2 \ \mu \text{F} \).

A detailed view to the current zero region at very short arcing time is given in Fig. 47 for two different interruption processes. This shows the waveforms of voltage across the switch \( U_s(t) \), overall current \( i(t) \) and the current through the switch \( i_{swi}(t) \) at interruption of an ac-current with \( \frac{di}{dt} = 1.5 \ \text{A} / \mu \text{s} \). This corresponds to a peak current of 4.7 kA at 50 Hz. Contact separation was triggered exactly at current zero in experiment a) and 50 μs prior to current zero in experiment b. Both experiments showed a successful interruption at \( v_s = 35 \ \text{m/s} \) (a) respectively 40 m/s (b), a TRV-frequency of 3450 Hz and TRV-peak of 3400 V.

In experiment a) of Fig. 47 the arc voltage cannot be distinguished from the noise level of the voltage probe. The current through the switch \( i_{swi} \) coincides with the overall current \( i_s \) exactly till the zero crossing and is then interrupted. The overall current is then equal to the current through \( C_p \).
In experiment b) the arc voltage shows a steep rise 50 μs ahead of current zero, causing a decrease of current through the switch. The switch current becomes zero 30 μs prior to the overall current. TRV starts to rise at current zero of the overall current; therefore, the arc plasma in the gap can cool off during this pause.

Additionally, for an opening velocities of \( v_k = 40 \) m/s it was found by Magri [82], that the optimal arcing time is around \( t_{arc} \leq 20 \) μs, which is rather short and corresponds to < 5 % of the overall opening time. This was measured while using only 2 breaks in series.

The following conclusions are drawn from these experiments:

- It is not the contact distance at the instant of current zero what is decisive for the gap recovery. This coincides with Eq. 29 as it is also not dependent on the arcing time.
- A high opening velocity lowers the scatter in the instant of contact separation. Thus, the higher the opening velocity and the lower the number of series breaks, the shorter is the optimal arcing time. As a rule of thumb, the optimal arcing time is around 5 % of the overall opening time.

In order to learn on the influence of a longer arcing time, measurements were conducted, keeping frequency and amplitude of the transient recovery voltage constant and varying arcing time from 30...300 μs. Successful interruptions and reignitions are shown in the diagram of Fig. 48.

![Diagram of arcing time and reignition voltage](image-url)

**Fig. 48: Measured reignition voltage at interruption as a function of arcing time prior to current zero. The switch was opened at \( v_k = 12 \) m/s at a TRV - frequency of \( f_{TRV} = 50 \) kHz.**
Test object was an elementary switch with 24 breaks in series. Details to the geometry of this switch with multiple breaks were given in Fig. 42 p. 80. Compared to the switch used in Fig. 47, this switch has less than $1/3$rd of opening velocity and 12 times as many breaks. The arcing time was adjusted by closing the resonant circuit at a predefined time-delay prior to contact separation of the test switch. The optimal arcing time for fast switches with only 2 series breaks derived above is given for comparison. For this switch, the reignition voltages are highest at arcing times of $t_{\text{arc}} = 100...200$ µs, which is nearly 20% of the overall opening time. When further increasing the arcing time, the reignition voltage is decreasing as indicated by the trend line. The result from these experiment is, that the optimal arcing time is around 20% of the overall opening time, if using many breaks in series and an opening velocity < 20 m/s.

5.3.3 Some details of the arc during current interruption

The current interruption performance was investigated in the above chapter with focus on the characteristic of the gap recovery. In particular for the use as a commutation switch and a current limiting function, also the values of the arc voltage at high opening velocity are of essential interest, thus investigated in the following.

**Measured peak arc voltage while opening with 12 m/s**

In the interruption experiments (e.g. Fig. 40), also the maximum arc voltage prior to current zero was measured. The result is shown in Fig. 49 for an opening velocity of $v_k = 12$ m/s and an arcing time of $t_{\text{arc}} = 135$ µs. The experiments are also conducted in air at 1 bar using aluminum contacts coated with 50 µm silver.

![Fig. 49: Measured peak arc voltage at current interruption with an opening velocity of $v_k = 12$ m/s, an arcing time of $t_{\text{arc}} = 135$ µs and a double break.](image-url)
The values of a free-burning arc at low currents with a gap of 1.5 mm are shown for comparison (from [3] p.464), as the length of the arc at an opening speed of \( v_k = 12 \text{ m/s} \) and an arcing time of \( t_{\text{arc}} = 135 \mu \text{s} \) is 1.6 mm. The resulting arc voltage is around 75 V with a 20 % scatter, which is comparable to the free-burning arc voltage but is nearly 3 times higher than the minimum arc voltage for silver contacts, which is 24 V (double break, see [3] p.464). The large scatter in the measured arc voltage indicates, that there is a scatter in the instant of contact separation. Therefore, arcing time and maximum arc length was not precisely constant for these experiments due to mechanical scatter in the opening process of the elementary switch.

It can be concluded from these measurements, that the arc voltage of a short arc is not significantly higher than the one of a free-burning arc if opening with 12 m/s.

**Measured arc voltage for opening velocities up to 50 m/s**

As the velocity of the contacts may be varied in a wide range up to 50 m/s it is of essential interest how speed influences the arc behavior and in particular the arc voltage. Therefore, according measurements on the arc voltage were performed using a rotationally operated switch in a low-voltage resonant circuit (compare to Fig. 36 p. 72). The circuit parameters are \( C_s = 90 \text{ mF} \) and \( L_s = 100 \mu \text{H} \), with resonant frequency \( f_r = 35 \text{ Hz} \). No parallel capacitance \( C_p \) was used. The arc current was \( i_{\text{arc}} < 450 \text{ A} \) in air at ambient pressure, see Fig. 50. The time scale of each experiment was shifted, so that contact separation occurs at \( t = 0 \).

![Graph](image)

**Fig. 50:** Measured arc current and arc voltage for different opening velocities in a low voltage resonant circuit.
Various voltage- and current waveforms from these tests are compiled in Fig. 50 for opening velocities up to 47 m/s. The results from these tests can be summarized as follows:

- the arc voltage is strongly increasing with opening velocity
- the initial jump of arc voltage is about 30 V and not dependent on velocity

The initial jump in arc voltage is due to anode- and cathode fall of the double break switch and was measured to be at $U_{kr} = 30$ V, see flat line in Fig. 50. This is in good match to the minimal arc voltage of copper (13 V) and aluminium (11.2 V) contacts of a single break [3] p.464.

Each experiment produced heavy erosion of the contacts; therefore, a good statistical approach was impossible. However, the measurements give a good idea on the dependency of the arc voltage on opening velocity.

Taking the measured arc voltage $U_a(t)$, $v_k$ and $U_{kr}$, the field gradient of the arc column $E_{arc}$ can be calculated using the known gap distance, see Eq. 31.

$$E_{arc} = \frac{1}{v_k} \frac{U_{max} - U_{kr}}{2 \cdot t_{arc}} = k_v \cdot v_k \quad \text{Eq. 31}$$

If the values for $E_{arc}$ are plotted in a diagram $E_{arc}$ as a function of $v_k$ then a linear relationship becomes clear (Fig. 51) and a value of $k_v = 128$ Vs/m² can be derived.

![Fig. 51: Arc column field gradient as a function of the opening velocity. Calculated with data from Fig. 50 used in Eq. 31. Data for a free burning arc and a strongly cooled arc from [16] p. 3.](image)

The measured values are noticeable higher than the column gradient of a free-burning arc [16] p. 3.

The following conclusions can be derived from these measurements:

- The arc column gradient is several times higher at very fast prolongation than the one of a free burning arc.
- The arc column gradient linearly increases with opening velocity if the latter is higher than 15 m/s (see also comparison of arc voltages in Fig. 49). It then can be approximated by Eq. 31 using $k_v = 128$ Vs/m².
- Eq. 31 certainly may be used only with limits for inter- and extrapolation.
From the values for the arc column gradient, the overall arc voltage can be calculated from the opening velocity $v_k$.

**Influence of number of interrupting gaps on the arc voltage**

As the investigated switches are mainly thought as basic elements in hybrid systems, it is of essential interest to know their behavior when being connected in series. Therefore, in the following it was investigated how their overall arc voltage develops for a number of gaps in series connection. For the moment, basic experimental results from measuring the arc voltage as a function of serial breaks are given. How to design elementary switches having many breaks in series will be shown later in chapter 6.2 p. 103ff.

For $v_k = 12$ m/s and $t_{arc} = 135$ μs a varying number of breaks was setup. Voltage control was achieved by grading capacitors across each double break. The interrupted current showed a rate of decrease in between $di/dt = 2.5 \ldots 9$ A/μs and was not constant. The physical distance between two proximate series arcs was 5 mm. Fig. 52 shows the peak arc voltage $U_{max}$ over the number of series breaks.

![Graph showing the relationship between maximum arc voltage and number of serial breaks.](image)

**Fig. 52: Measured maximum arc voltage at synchronous interruption with an opening velocity of $v_k = 12$ m/s and an arcing time of $t_{arc} = 135$ μs as a function of the number of serial breaks.**

As the figure show, the maximum arc voltage increases linear with the number of serial breaks. For 24 series breaks, a remarkable scatter occurs. This is assumed to originate from short-circuiting of single arcs, which are too close together, therefore reducing the overall arc voltage, compare to Fig. 42. Based on Eq. 31, the arc voltage $U_a(t)$ as a function of opening velocity $v_k$ and number of serial breaks $n_s$ for current interruption with elementary switches now can be estimated using Eq. 32 and $k_v = 128$ Vs/m².
\[ t > 0: \quad U_a(t) = n_k \cdot (U_{KF} + v_k \cdot t \cdot E_{arc}(v_k)) = n_k \cdot (U_{KF} + v_k^2 \cdot t \cdot k_v) \quad \text{Eq. 32} \]

This description of the arc voltage does not take into account a likely dependence on the arc current. It is based only on the measurements in Fig. 51 and Eq. 31. Therefore, Eq. 32 may not be generally applicable, especially not for very small currents < 10 A. However, this is out of the focus of the present work. The arcing voltage will be used to calculate the commutation capability on parallel impedance, see 5.4 p. 92ff.

**Dissipated arc energy**

For the calculation of the reignition voltage in Eq. 28 it was assumed, that there is a dielectric breakdown of the opening gap. The very difference to the interruption process in standard breaker is the short duration of the arc and therefore a small amount of dissipated arc energy. The influence of arcing time and interrupting current on the actual values of dissipated arc energy is studied in this subsection.

During arcing, the energy dissipated is given by Eq. 33, with the arc voltage \( U_a(t) \), the arc current \( i_{\text{peak}} \cdot \sin(\omega t) \) and the arcing time \( t_{\text{arc}} = t_o - t_c \).

\[ E_{\text{arc}} = \int_{t_c}^{t_o} U_a(t) \cdot i_{\text{peak}} \cdot \sin(\omega t) \cdot dt \quad \text{Eq. 33} \]

Reducing the arcing time \( t_{\text{arc}} = t_o - t_c \) therefore reduces the arc energy input into the contact gap, what essentially is the principle of synchronous interruption.

![Fig. 53: Calculated energy dissipated by a short-time arc as a function of the interrupting peak ac-current for different arcing times (\( U_{\text{arc}} = 100 V = \text{const.} \) see Eq. 33)](image_url)
In Fig. 53, the arc energy dissipated at synchronous interruption is calculated using Eq. 33 as a function of interrupted 50 Hz peak current. Parameter is the arcing time, which is varied from 10 \(\mu\)s to 2 half cycles while assuming a constant arc voltage of \(U_a(t) = 100\) V. These calculated values are compared to values from various synchronous interruption experiments. It can be seen, that the arc energy dissipated is reduced by six orders of magnitude compared to a 2 half cycle circuit breaker, if the switching arc is burning for only \(t_{\text{arc}} = 10\) \(\mu\)s. The total arc energy dissipated is below \(E_{\text{arc}} = 10\) J up to very high currents if arcing time is below 300 \(\mu\)s. The measured values for the arc energy are around \(E_{\text{arc}} = 1\) J and show a dielectric breakdown mechanism.

### 5.4 Current commutation on a parallel impedance

It was discussed in the literature survey (chapter 2.2.3 p. 25) that hybrid systems are necessary to achieve fault current limitation in high voltage systems. Hybrid systems are composed of one or more current path’s in parallel to a continuous current path. The opening switch in the continuous current path has to commutate the rising fault current onto a parallel path within one millisecond, see Fig. 9 p. 27 and its description by Steurer [42].

Elementary switches can be designed to carry continuous current and to open within several 10 \(\mu\)s; therefore it is to question to what extend they can be applied as opening switches for fast commutation. Commutation of high currents onto a parallel path by utilizing the switching arc requires low parallel impedance, as the arc voltage is limited to several 10 \(\ldots\) 100 V per break, see Fig. 50 and Fig. 52.

The main topic to be dealt with in this section therefore is the influence of low parallel impedance on the commutation capability of elementary opening switches.

#### 5.4.1 Current commutation on a parallel resistor

If commutating a current on a parallel resistor, the arc voltage of the opening elementary switch has to be higher than the voltage drop \(U_a\) across the parallel path, see equivalent circuit in Fig. 54. \(R_p\) is the parallel resistor and \(L_o\) represents the stray inductance of the resistor and its connections.
The condition for successful commutation is given in Eq. 34.

\[ U_{\text{arc}}(t) > R_p \cdot i_p(t) + L_o \cdot \frac{di_p(t)}{dt} \]  

**Eq. 34**

The arc voltage \( U_{\text{arc}}(t) \) may be calculated by Eq. 32 as a function of the number of serial breaks \( n_s \) and the opening velocity \( v_o \). Typical measures for the time constant of the parallel path \( \tau_p = L_o / R_p \) will be the \( \mu s \)-range. Therefore, the settling time is much lower than the half period of a power cycle. A minimum criterion for successful commutation of an instant current on a parallel resistor therefore is given by Eq. 35, where \( U_{\text{KF}} \) is the initial arc voltage and \( n_s \) the number of serial breaks.

\[ i_{p,\text{min}} = \frac{n_s \cdot U_{\text{KF}}}{R_p} \]  

**Eq. 35**

For instance: Supposed \( U_{\text{KF}} = 15 \) V (see Fig. 50) and \( n_s = 2 \) for an elementary switch, an instant current of \( i_{p,\text{min}} = 60 \) A can be commutated onto a parallel resistance of \( R_p = 0.5 \) \( \Omega \), see also Fig. 55.
However, considering the increase of arc voltage during opening, the maximum current to be commutated is reasonably higher than given by Eq. 35. This is shown for example in Fig. 55 for an opening velocity of 20 m/s. Contact separation is triggered at $t = 1$ ms after current inception followed by a jump in arc voltage and a rise of $I_p$ to 60 A within $5\tau_p = 10$ $\mu$s. The still rising arc voltage leads to a further increase of current in the parallel path until the commutation is finished and the arc extinguishes at $\Delta t = 1.4$ ms after contact separation.

For an application of elementary switches it is to question, whether an arcing time in the millisecond range as in Fig. 55 can be tolerated. If yes, than the limit for the current to be commutated on a parallel resistor is given by the rate of rise of the overall current as given in Eq. 36.

$$\frac{di_p(t)}{dt} < n_k \cdot k_v \cdot v_k^2$$

Eq. 36

Of course, this limit is restrictive only during rise of the overall current. For the example shown in Fig. 55, this limit results to $di_p/dt = 200$ A/ms what correlates to a peak current of 650 A at 50 Hz.

The results from this discussion can be summarized as follows:
- The maximum current, which can be commutated on a parallel resistor by opening an elementary switch, linearly decreases with parallel resistance.
- The maximum current that can be commutated increases with the opening velocity squared.
- To commutate currents in the kA-range, the parallel resistance has to be in the m$\Omega$-range.

It should be noted, that these results are derived from the above calculations, which are based on an arc voltage as measured in Fig. 50 respectively given in Eq. 32. A similar discussion on the commutation capability of elementary switches onto a parallel capacitance is given in the following section.

**5.4.2 Current commutation on a parallel capacitor**

The above discussion on the commutation capability of elementary switches on parallel resistance yields rather restrictive limits for the maximum current which can be commutated. It is therefore to question, whether a capacitance in parallel results in reasonably higher commutation capability. This question is also related to other topics to be dealt with in this work:
• For the use of elementary switches in hybrid systems, a single capacitor can be utilized as a commutation aid, see principle in Fig. 8 p. 26.

• When using elementary switches for (synchronous) current interruption, the current is commutated on a parallel capacitance, which may be stray capacitances only, compare to Fig. 47 p. 85.

Therefore, this topic is discussed in detail in the following section. It should also be mentioned here, that the parallel capacitance is understood to be permanently connected to the switch. This implies that it remains discharged while the switch is closed.

**Equivalent circuit for the commutation process**

Fig. 56 shows an equivalent circuit for discussing the commutation process with $C_p$, $R_p$ and $L_p$ being the impedances of the parallel current path including the stray values of the switch and its connections.

![Fig. 56: Equivalent circuit for the commutation of an arc current onto a parallel path with a capacitor. $R_p$ and $L_p$ are representing the stray values of $C_p$, the switch and its connections.](image)

The parallel capacitor $C_p$ remains uncharged as long as the switch is closed and the overall current $i_s$ entirely flows through the switch. When opening the switch, commutation of the current is successful, if the arc current $i_s$ entirely commutates on $C_p$ and the transient recovery voltage due to charging of $C_p$ by $i_p(t)$ is at any time lower than the reignition voltage of the gap.

**A resonant circuit excited by the arc voltage**

The commutation process using an elementary opening switch is now discussed: From the instant of contact separation, the arc voltage is again calculated by Eq. 32 and the current in the parallel path is given by a differential equation of second order (two energy storages $C_p$, $L_p$) as shown in Eq. 37 in an integral (above) and derived form (below). The initial value of $i_p$ at $t = 0$ is stated to be zero.

$$U_o(t) = U_c(t) + R_p \cdot i_p(t) + L_p \frac{di_p}{dt} = n_k \cdot (U_{kr} + v_k^2 \cdot k_v \cdot t)$$

$$i_p(t) + R_p \frac{di_p}{dt} + L_p \frac{d^2i_p}{dt^2} = n_k \cdot v_k^2 \cdot k_v \quad i_p(t)_{t=0} = 0$$  \hspace{1cm} \text{Eq. 37}

At low values of the series resistance $R_p < 2 \cdot Z_p$, the elements in the parallel path form a resonant circuit. The solution of Eq. 37 is given in Eq. 38, describing $i_p$ as a damped sine wave.
$$i_p(t) = \frac{U_{kr} \cdot n_k}{L_p \cdot \omega_p} \cdot e^{-\frac{t}{\tau_p}} \sin(\omega_p t) + \frac{V_k^2 \cdot n_k \cdot k_v}{L_p \cdot \omega_p^2} \left(1 - e^{-\frac{t}{\tau_p}} \cos(\omega_p t)\right)$$  \hspace{1cm} \text{Eq. 38}$$

The values for the resonant frequency $f_p$, $\omega_p$, characteristic impedance $Z_p$ and damping time constant $\tau_p$ are calculated from $R_p$, $L_p$, $C_p$ with the equations given in Eq. 3 and Eq. 2 p. 21. The particular solution (second term) is given as an approximation for $\omega_p \tau_p \gg 1$.

**The first peak gives the maximum current to be commutated**

Assuming a constant overall current $i_s$ during commutation and equating it to $i_p$ at $t = 1/(4f_p)$ leads to the maximum current, that can be commutated on the parallel capacitor by the switch as given in Eq. 39.

$$i_{p,\text{max}} = \frac{V_k^2 \cdot n_k \cdot k_v + U_{kr} \cdot \omega_p \cdot n_k \cdot e^{-\frac{t}{\tau_p}}}{L_p \cdot \omega_p^2}$$  \hspace{1cm} \text{Eq. 39}$$

The first addend of the sum in Eq. 39 gives the influence of the opening velocity on the maximum current, the second one the influence of the initial jump of arc voltage due to anode and cathode fall. This limit for the current that can be commutated on a (large) parallel capacitance is now to be compared to measured limits. Fig. 57 shows two example current waveforms measured through an elementary switch which was opened at $v_e = 38$ m/s close to the current peak in a resonant circuit.

Commutation of an instant value of $i_s = 830$ A was successful (a) but an instant value of $i_s = 930$ A could not be commutated on the large parallel capacitance $C_p = 800$ $\mu$F (b). The sinusoidal shape of $i_p$ calculated in Eq. 38 shows up, if no successful commutation occurs (Fig. 57b). The theory presented above assumes the first peak of $i_p$ being higher than the instant value of $i_s(t)$. This is the case in the result from Fig. 57 a but not for b. The resonant frequency measured at a not successful experiment can be taken to verify the stray values for $L_p$, $R_p$. 
Fig. 57: Current waveforms at a successful (a) and not successful (b) commutation by an elementary switch opened with $v_b = 38$ m/s on a parallel capacitor of $C_p = 800$ µF. Stray values were $L_p = 0.8$ µH, $R_p = 10$ mΩ.

Comparison between measurement and calculation

A comparison between measured (Fig. 57 for example) and calculated (Eq. 39) limits for current commutation capability on a parallel capacitance $C_p = 800$ µF is shown in Fig. 58 for two different elementary switches operated at various opening velocities. As the connections of the two switches were of different length, the measured stray values $R_p$, $L_p$ given on the chart varied for both switches.

The measured values show a high scatter, which may be due to small variations in opening velocity and instant of contact separation. However, they are in good match to the calculated values ($U_{xf} = 11$ V, $K = 128$ Vs/m² from Eq. 31). Therefore, Eq. 39 is found to be suitable to calculate the limits of elementary switches for commutation on a parallel capacitance. Given the usefulness of Eq. 39 for calculating the maximum current to be commutated, one can now do simulations for various applications. A significant from the above investigations is, that the resulting values for $C_p$ to commutate currents in the kA-range are in the mF-range. This will lead to large capacitor volumes, especially if considering applications in the medium voltage range.

If for example in a hybrid system a commutation capability of $i_{p,\text{max}} = 4$ kA is
requested, than the necessary capacitance value is up to \( C_p = 10 \ \text{mF} \) if opening at 15 m/s, see Fig. 59.

\[ \text{Fig. 58: Comparison of calculated (Eq. 39) and measured values for commutation with two different switches on a parallel capacitance of } C_p = 800 \ \mu\text{F}. \]

\[ \text{Required capacitance to commutate a given current} \]

The volume of a capacitor featuring the capacitance given in Fig. 59 is calculated in with an energy density of \( k_f = 2 \ \text{mlJ} \) for a rated capacitor voltage of \( U_c = 2 \ \text{kV} \), value taken from [91].

\[ \text{Fig. 59: Necessary capacitance parallel to the opening switch for successfully commutating various instant current values. Stray values: } L_p = 0.6 \ \mu\text{H}, R_p = 14 \ \text{m}\Omega. \]
Capacitance and thus volume of the parallel capacitor needed for successful commutation is strongly decreasing with increasing opening velocity. The volume given in Fig. 59 is calculated for a rated capacitor voltage of 2 kV. Of course, volume will increase for higher rated voltages. Two conclusions can be drawn from this simulation:

- A high opening velocity for commutation affects an economy of capacitance and space requirements.
- For higher rated capacitor voltage higher than several kV, it is not reasonable to commutate currents in the kA-range onto this non-charged parallel capacitance.

**High parallel capacitance limits TRV-rate of rise**

After successful commutation, the overall current \( i_s \) charges \( C_p \), resulting in a continuously increase of voltage. The increasing voltage across \( C_p \) has to be lower than the reignition voltage of the opening gap as calculated by Eq. 28 to avoid reignition. Equating Eq. 28 to the capacitor voltage \( U_s \) and solving for opening velocity gives the lower limit of the opening velocity for the switch to withstand the TRV after commutation as given in Eq. 40.

\[
V_{k,\text{min}} > \frac{i_p}{C_p \cdot \eta_f \cdot E_o}
\]

Eq. 40

For example: A switch opening at \( V_k = 50 \text{ m/s} \) requires \( C_p = 1.5 \text{ mF} \) to successfully commutate \( i_p = 2 \text{ kA} \), see Fig. 59. In air at 1 bar (\( \eta_f = 0.5 \), \( E_o = 25 \text{ kV/cm} \)) the minimum opening velocity according to Eq. 40 results to \( V_{k,\text{min}} = 1 \text{ m/s} \). Therefore, due to the high value of \( C_p \) required for successful commutation, the gap recovery is not even in air an additional restriction for the maximum current to be commutated.

**5.5 Summary: Performance of elementary switches**

The performance of elementary switches was studied theoretically and experimentally for opening- and closing velocities in the range of (10 – 100) m/s.

Opening and closing can be done by repulsion and yields a constant opening velocity which is linearly increasing with drive voltage. A narrowing gap can be applied to decelerate the moving part. A fivefold increase in ambient pressure results in a 10% lower opening velocity. The minimum closing velocity has to be higher than 10 m/s and depends on the utilized continuous
current contacts. The contact force of the contacts lowers opening velocity by 20%. Repetitive switching at repetition rates higher than 10 Hz is possible but not reasonable.

Elementary switches can be applied as closing switches to protect sensitive devices from over current in medium voltage applications. An overall closing time of 500 μs was measured for a rotationally operated switch. Prestrike time is lowered to 10 μs if closing with 50 m/s in air at 5 bar. Compared to single thyristors, elementary switches show higher withstand voltage.

Elementary switches can also be applied for synchronous interruption without forced arc cooling. For the first 10 μs after current zero, the instantaneous recovery gives the limit for the reignition voltage. Then, the reignition voltage linearly increases with time and opening velocity and indicates a dielectric breakdown mechanism. The optimal arcing time is around 5% of the overall opening time and decreases with opening velocity. Arc voltage at synchronous interruption is comparable to the arc voltage of a free burning arc in air up to an opening velocity of 12 m/s. At higher opening velocity, the arc voltage was measured at currents up to 400 A to be proportional to the square of opening velocity. The interruption mechanism is affected by the low arc energy input and the parallel capacitance which provides a current pause in the switch ahead of current zero.

Elementary switches can be used for fast current commutation on a parallel resistor or capacitor. The commutation capability on a parallel resistor increases with the opening velocity squared. To commutate high currents on a parallel resistor, its resistance has to be in the mΩ-range.

The commutation process on a parallel capacitance can be described by a resonant circuit, which is excited by the arc voltage. Increasing the opening velocity to 50 m/s doubles the commutation capability compared to slowly opening. To commutate currents in the kA-range, parallel capacitance of several mF is required but this can be lowered by one order of magnitude, if velocity is raised to 70 m/s.
6 Applications of elementary switches

In the preceding chapters, elementary design and performance of fast switches with repulsion drive was treated. For applications in high power switching, the switching capability of a single elementary switch normally is not sufficient. Therefore, combinations of single elementary switches and applications of elementary switches forming hybrid systems are discussed in this chapter, as this is the major innovation of the present work.

6.1 General considerations

The principle idea how to obtain power switchgear from single elementary switches was pointed out in Fig. 14 p. 42. Some applications mentioned in Fig. 14 are rather simple to implement with the elementary switch design, as for example the fast turn-on switch, which has already been treated in chapter 5.2 p. 69. Others are rather complex hybrid systems as for example the fault current limiting device (FCLD) or a fault current limiting circuit breaker (FCLB). An example for such a system was given in the state of the art, chapter 2.2.3 p. 25.

Why hybrid systems made of elementary switches?

From a technical point of view, it is to question whether a specific functionality (i.e. fault current limiting in high voltage) can be achieved by combining elementary switches with elements suitable for commutation and energy absorption. In general, hybrid systems tend to be complex, difficult to control and expensive compared to a standard circuit breaker. This is mainly the reason, why many hybrid systems with superior functionality to standard breakers were presented in the past, but are not in commercial use. Therefore, when it comes to a product, not only feasibility but also application aspects and economical constraints are to be treated.

What is most promising for the use of the presented fast acting switches with elementary design is its astonishing mechanical and technological simplicity. This results from using only one moving part and applying no
forced arc cooling facilities (compare to Fig. 12 or see photos in Fig. 42 p. 80 or implemented switches in the appendix, chapter 10.1 p. 139ff).

A basic question to be answered is:

What combinations of fast elementary switches or what hybrid systems are useful, what are their capabilities and where are the economical limits?

Why not low voltage and highest voltage levels?

In low voltage systems, fault current limiting circuit breakers are state of the art, at least in Europe. They have been continuously optimised and are manufactured in mass production, featuring already a switching time around 1 ms, see Fig. 7 and chapter 2.1.1 p. 14. Here, it is implausible that the use of the elementary switch design and the repulsion drive yields superior functionality or better profitability.

In high voltage systems (above 100 kV), standards require a basic insulation level for circuit breaker in the open position, which is several times higher than the rated voltage [100] p. 49. Given the definitions in chapter 4.2.1 p. 42, this insulation level is comparable to the design voltage of elementary switches. As shown in Fig. 23 p. 56, the required drive energy for elementary switches exponentially increases with design voltage due to thicker coil insulation, lower drive efficiency and larger contact gaps. Therefore, elementary switches for highest voltage would still be simple but would require a huge drive capacitance. Additional limits for the upper voltage level will be discussed for fault current limiters in chapter 6.4.5 p. 121ff.

Therefore, the most promising voltage range for technical and economical feasible applications is the medium voltage range. Consequently, the continuing discussion is focused on medium-voltage applications.
6.2 Elementary switches as closing devices

It was shown in Fig. 33 p. 70 that the overall closing time of elementary switches can be lowered down to 0.5 ms. The pre-strike time was given in Fig. 34 to be as low as 10 μs. A possible application for elementary switches as fast turn-on devices is discussed in this section.

The fast turn-on switching function is useful for the protection of sensitive devices (DTP = device to protect) as sketched in Fig. 60. In this application, the elementary switch is “open” during normal operation. At the event of a fault, i, will start to rise according to the simulation given in Fig. 6 p. 23. There has to be a fault detection unit, which triggers the switch to close.

![Diagram of elementary switch protection and typical waveforms](image)

**Fig. 60:** Application of a fast switch for the protection of sensitive devices (DTP) by short-circuiting this device (left) and typical waveforms (right)

The closing time of an elementary switch is much lower than the rise time of the short circuit current in power systems (compare time values in Fig. 33 p. 70 to Fig. 6 p. 23). After closing the fast switch, the fault current will flow (mostly) through the closed switch what prevents the sensitive device DTP from carrying high fault currents.

Hence, the design rules for elementary switches can be applied for designing fast closing switches in the medium voltage range. For implementation, a comparison of design values for elementary switches (chapter 4.2.1 p. 42f) to rated values given by standards [100] p. 49 is given in chapter 6.4.5 p. 121f.

**Comparison of elementary turn-on switches with thyristors**

Using the fast closing functionality, the elementary switch competes with other closing devices, such as semiconductor switches. Therefore, the characteristics of elementary switches are confronted with the characteristics of a thyristor below.
Table 1: Features of fast acting turn-on switches compared with a single thyristor unit. (n.s.=not specified, ev.=eventually)

<table>
<thead>
<tr>
<th>Feature</th>
<th>fast closing switch</th>
<th>Thyristor</th>
</tr>
</thead>
<tbody>
<tr>
<td>max. voltage/unit</td>
<td>$&lt; 150 \text{ kV}$ ?</td>
<td>$&lt; 5 \text{ kV}$</td>
</tr>
<tr>
<td>peak current/unit</td>
<td>$= 10 \text{ kA}$ ?</td>
<td>$= 10 \text{ kA}$</td>
</tr>
<tr>
<td>turn-on time</td>
<td>$&lt; 1 \text{ ms}$</td>
<td>$&lt; 1 \mu\text{s}$</td>
</tr>
<tr>
<td>repetitive</td>
<td>$&lt; 10 \text{ Hz}$</td>
<td>yes</td>
</tr>
<tr>
<td>arcing</td>
<td>during prestrike</td>
<td>no</td>
</tr>
<tr>
<td>reliability</td>
<td>n.s.</td>
<td>high</td>
</tr>
<tr>
<td>on overvoltage:</td>
<td>sparc</td>
<td>broken</td>
</tr>
<tr>
<td>on overcurrent:</td>
<td>heating</td>
<td>heating</td>
</tr>
<tr>
<td>drive energy</td>
<td>$&lt; \text{kJ}$</td>
<td>$&lt; \text{mJ}$</td>
</tr>
<tr>
<td>drive triggering</td>
<td>discharge</td>
<td>signal</td>
</tr>
<tr>
<td>losses</td>
<td>$R_{\text{ON}} &lt; 1 \text{ m}\Omega$ ?</td>
<td>$U_{\text{ON}} = 1 \text{ V}$</td>
</tr>
</tbody>
</table>

Table 1 gives an overview on the specific features of thyristors compared to fast acting elementary turn-on switches for applications in the medium voltage range. The values given with question mark are depending on the actual implementation. From this, the following conclusions can be drawn:

- Elementary switches are to be preferred for high voltage ratings, high peak current carrying capability and where no repetitive use is required.
- As the withstand voltage of an elementary switch can be chosen much higher than that of a single thyristor unit, there is also less need for series connection and voltage control at higher voltage levels.

6.3 Combinations of elementary switches

The design of fast elementary switches led to simple but fast, linearly or rotationally operated switches with two serial breaks, compare design in Fig. 12 and velocity in Fig. 26 p. 59. In this section, further combinations of elementary switches having many breaks in series and/or parallel are discussed. The switching capability of elementary switches with many breaks in series has already been discussed in section 5.3.2 p. 78ff.

6.3.1 Consequences and possible designs

The vital feature of elementary switches is fast operation. This also implies, that the scatter of the instant of contact separation is small (in the $\mu\text{s}$-range or 1 % of the overall opening time for example, compare to Fig. 33 p. 70).

Consequences from series and parallel combinations of switches

A combination of elementary switches, which are all operated simultaneously, therefore will provide a contact gap at each switch at nearly the same instant. This can be used to:
• get high arc voltage by series connection of elementary switches, compare to Fig. 52 p. 90
• get faster recovery after current zero by series connection, compare to e.g. Fig. 44 p. 81.
• draw arcs in parallel path’s

The impact on the arc voltage and current interruption of having many breaks in series has already been treated in this work. If having several breaks in parallel, simultaneously sparking of the arcs in parallel current path’s is a temporary phenomenon only due to the negative non-linearity of the arc characteristic. However, measurements by [42] p. 85 using a fast linearly opened switch showed, that 6 parallel arcs with 1 kA each could be established for 200 μs. As this is already more than the optimal arcing time shown in Fig. 48 p. 86, it is to question how parallel path’s are affecting the interruption process.

Principle solutions for combining fast switches with one common drive

Starting at the basic design given for elementary switches, it is a small step for designs with a common repulsion drive operating simultaneously many breaks in series or in parallel, see Fig. 61. The design options are given for linear and rotational movement and compared to the elementary design in the first line. As a rule, opening and closing is done by repulsion but the required drive coils are occasionally not shown in the drawings to focus on the principle.

Doubling the number of serial breaks by arranging a moving part on both sides of the drive coil as shown in the second line, is an obvious extension for the use of the repulsion drive. An implementation using linear movement was tested by [83]. It was measured, that the opening velocity of both moving parts is nearly half of the opening velocity of the basic design when using the same drive energy. This means, an equal contact gap results in the same time interval, but four arcs are connected in series. Therefore, the doubling design is not useful for high opening velocities or better drive efficiency, but it is useful to get higher arc voltage. No measurements are available for the rotational doubled design, but a comparable behaviour can be expected.

A further extension of elementary switches for a higher number of serial breaks is shown in Fig. 61 in the third line and in Fig. 62. Here, the continuous current path is arranged such as to have multiple transitions from fixed contacts onto moving bridging pieces and back. The eddy current loop, its insulation and the moving bridging pieces are accelerated when triggering the common drive. This draws an arc at every serial break at the same instant.
This works for both, linear and rotational operation and the bridging pieces can be connected on each side of the insulation or across the eddy current loop.

<table>
<thead>
<tr>
<th>Basic design</th>
<th>Linear movement</th>
<th>Rotational movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Diagram]</td>
<td>[Diagram]</td>
<td>[Diagram]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Doubling the number of series breaks</th>
<th>Linear movement</th>
<th>Rotational movement</th>
</tr>
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<tbody>
<tr>
<td>[Diagram]</td>
<td>[Diagram]</td>
<td>[Diagram]</td>
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</table>

<table>
<thead>
<tr>
<th>Many breaks in series (see also Fig. 62)</th>
<th>Linear movement</th>
<th>Rotational movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Diagram]</td>
<td>[Diagram]</td>
<td>[Diagram]</td>
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</table>

<table>
<thead>
<tr>
<th>Many breaks in parallel</th>
<th>Linear movement</th>
<th>Rotational movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Diagram]</td>
<td>[Diagram]</td>
<td>[Diagram]</td>
</tr>
</tbody>
</table>

Fig. 61: Principle designs of many elementary switches in series or parallel with a common repulsion drive. Drive coils for opening and closing and insulation parts (as shown for the basic design) are occasionally omitted to focus on the principle.

Many breaks in series with but one common drive

Of course, the moving part carrying the eddy currents for repulsion has to be insulated from the main current path to avoid short-circuiting of the serial breaks. This increases the moving mass and thus reduces opening velocity. Obviously, this design of a fast switch is not suitable for carrying high continuous currents. The distance between two serial breaks has to be larger than the maximum arc diameter, so that no shortening of serial breaks by the arc column will appear.
a) Moving bridging pieces on each side of the eddy current loop  
b) Moving bridging pieces across the eddy current loop

Fig. 62: Elementary switches with many breaks in series and a common repulsion drive. The moving bridging pieces, the insulation and the eddy current loop are to be accelerated by the repulsion drive.

The measurements and results for the current interruption performance with many breaks in series given in section 5.3.2 p. 78 resulted from the design in Fig. 62a. Further applications of switches with many breaks in series in a hybrid system are given in section 6.4 p. 112ff below.

6.3.2 Many switches in parallel with one common drive

The switches shown in Fig. 61 in the fourth line with many breaks in parallel seem to be not very different to the basic elementary design. This is, because parallel current path's are evident for any switch or circuit breaker with distinguished number of fixed contacts. However, elementary switches with a common repulsion drive feature a small jitter of the instant of contact separation and they can be used only, when the overall arcing time is very short, because this was the basic assumption for the design of elementary switches, compare to Fig. 14 p. 42.

It has to be investigated, if the overall arcing time is of the same order of magnitude as the commutation time from the distributed partial currents to the final arcing path. If yes, than contact wear and arc energy dissipated in the final arcing path is further reduced for the last remaining path. If no, is it possible to extend the commutation time by inserting grading inductivities in the partial current path's? Therefore, the question to be answered for elementary switches connected in parallel is as follows: Is the overall arcing time for current interruption by elementary switches of the same order of magnitude as the commutation time from the distributed partial currents to the final arcing path? For an investigation of this question, current commutation on parallel path's with one common drive in an elementary switch is now discussed using results from simulations.
Principle and impacts on the commutation process
The principle of current commutation between parallel paths is explained with the help of a photo of an implemented switch. Fig. 63 shows a ring-shaped linearly operated elementary switch with distinguished fixed contacts. Depending on the individual contact force of each fixed contact in the closed position, the overall current is unequally distributed on the contacts. At the instant of opening, the partial currents will commutate on a last arcing path very fast due to the low inductivity between the parallel paths.

Fig. 63: Photo of a linearly operated elementary switch with distinguished fixed contacts. No additional inductivity is inserted in the partial current path's.

Considering a closed switch with distinguished parallel current paths, the overall current is unequally distributed between the paths as sketched in Fig. 64. Each path has a small but existing self- and mutual inductance and a path resistance that is dominated by the contact resistance.

Fig. 64: Principle and schematic drawing of opening an elementary switch with distinguished parallel current paths. The unequally distributed current will commutate on one last current path at opening due to the negative arc characteristic.
When opening the contacts simultaneously, the commutation between the individual paths may occur as a statistical phenomenon due to the following reasons:

- The exact number of parallel paths (contact points) and their initial current distribution in the closed position scatters statistically. For example: One lamella of an elementary switch (compare to Fig. 63 p. 108) typically shows one contact point but may accidentally have bad or no contact due to arc erosion from a previous interruption.
- There is a jitter within several $\mu$s of the instant of contact separation time (see also Fig. 44).
- The rise of contact resistance in each path prior to contact separation may be significant and is statistical.
- Finally, the exact voltage-current characteristic of the individual, very fast-elongated arcs is not known over the considered current range.

**Simulation of current commutation in 10 parallel paths**

To see the influence of the above-mentioned effects on the commutation process, a simulation model using 10 parallel paths was set up. The essential values in the model are: arc characteristic, path inductivity, path resistance, instant of contact separation and its instant current value. These parameters were varied to see their influence on commutation time in each single path. As already mentioned (Eq. 32), the arc characteristic of rapidly extended arcs is not known for the complete current range. Therefore, as a first approach, the characteristic of a free-burning arc taken from [3] p. 465 was used for these simulations. The second important factor is the instant of contact separation in each path. The instant of contact separation was randomly generated in a normal distribution around $t = 9.5$ ms using a standard deviation $\sigma_j = 10$ $\mu$s.

A result is shown in Fig. 65. Path resistance $R_{\text{path}} = 1.1$ m$\Omega$ and path inductivity $L_{\text{path}} = 500$ nH were equal for each path. Therefore, the overall current equally distributes in the 10 paths prior opening. When opening at $t = 9.5$ ms, the individual contacts separate randomly within 9.48 ms to 9.51 ms in the 10 path's. After 9.62 ms, the current in the various paths is commutated to others until finally at 9.75 ms only one final arcing path remains which carries the overall current. The corresponding arc voltage across all parallel paths is also shown in Fig. 65, reaching a maximum arc voltage of 60 V. The switch was opened at 17 m/s.
Fig. 65: Example: Arc currents in 10 parallel path’s and arc voltage during simulation when triggering to open at 9 ms (1ms ahead of overall current zero).

As the instant of contact separation is randomly generated, the commutation process differs statistically for every simulation, see Fig. 66.

**Commutation time as a function of path inductivity**

Several simulations using the above model for the commutation process were carried out, varying only the path inductivity. The results from these simulations are collected in Fig. 66 where the simulation parameters are also given. The results from these simulations using equal path inductivity and resistance and only varying the instant of contact separation statistically can be summarized as follows:

- Inserting a path inductivity of 2 μH already forces arcing in all parallel paths for around 50% of the overall arcing time.
- The commutation time (i.e. the arcing time in each path) increases to around 70% of the overall arcing time when inserting a inductivity of 10 μH in each path.
- Inserting a path inductivity of 2 μH therefore reduces the arc energy dissipated at synchronous interruption in the last remaining path by 50% (compare values in Fig. 53 p. 91). In all other path’s the dissipated arc energy is less than 1/5th of this value.
Fig. 66: Results from Simulations: instant of current zero in single path’s as a function of path inductivity, compare to the waveforms shown in Fig. 65. Parameters for the simulation are given on the chart.

It is therefore concluded from these simulations, that the commutation time between parallel path’s operated with one common drive is of the same order of magnitude as the overall arcing time for elementary switches if applying a path inductivity in the μH-range. The main impact on the interruption process is a significant decrease of arc energy dissipated in the finally remaining arcing path.

Impact on the performance of implemented elementary switches

From the study of synchronous interruption using elementary switches it was found, that the reignition voltage is depending on the switching medium and the opening velocity for arcing time < 150 μs (Fig. 48 p. 86). As the dielectric breakdown mechanism is not affected by a further reduction of arc energy, it is stated that the use of distinct parallel path’s does not result in a noticeable gain of dielectric strength after current zero higher than calculated by Eq. 28 or Eq. 29. However, the problem of arc erosion will be eased when using parallel path’s and thus reducing the arc current and dissipated arc energy. It is stated in [3] p. 496ff that the mass loss of an arcing contact is a function of power input and increasing with the arc current to the power of 1.6. If now the interruption capability is not affected by parallel arcing, then it is necessary to do measurements on arc erosion to determine the exact impact on the performance of elementary switches with distinct parallel path’s. This is not within the scope of the present work and thus is not further investigated. In addition, some experimental results given by [83] indicate, that distinct parallel paths and a high path inductivity lead to a breakdown strength described by Eq. 28 but has less dependence on the trigger time than shown in Fig. 48. This is of particular interest; especially if
one doesn't exactly know when current zero will occur, see application in a hybrid system in chapter 6.4.3 p. 117f.

Conclusion for the design of elementary switches with parallel paths
A standard design of an elementary switch (see i.e. Fig. 63) will typically show path inductivity less than one µH. Due to the advantages discussed above, it will be a good advise to design elementary switches with distinguished current paths and try to increase the length of any single current path to get higher path inductivity. Additionally inserted coils need to work only around current zero if parallel arcing is intended for synchronous interruption. Hence, saturation of an inserted coil may occur during the high current period. However, additionally inserting coils will be worth the effort only in applications where arc erosion is crucial.

6.4 A hybrid system as current limiting circuit breaker
In chapter 5.3 p. 71ff it was shown that an arrangement of switching elements can be used for synchronous short circuit interruption in the medium voltage range. These approaches do not have neither dc-switching capability nor fault current limiting characteristics. How to approach the latter functions by hybrid solutions is discussed in the following section.

6.4.1 Principle of the hybrid system
A hybrid fault current limiting system, which utilizes three fast switches in three parallel paths', was extensively discussed in Fig. 9 p. 27 of [42]. Its functionality was provided by the switches together with power semiconductors as a commutation aid and by a pure wire resistor that features a positive temperature coefficient. The current limitation was experimentally verified at $U_n = 10$ kV, $I_n = 2$ kA, $I_w = 11$ kA$_{pos}$ [42]. Simulated waveforms of the interruption process are given in Fig. 9.

Using the features of combined elementary switches presented in chapter 6.2 p. 103ff, it is now possible to adapt this hybrid system such as no power semiconductors are necessary. Such a hybrid system with current limiting circuit breaker functionality is proposed in Fig. 67. This system follows the general principle for medium voltage limiters already given in Fig. 8 p. 26 that is shown for comparison.
Fig. 67: Principle (a) and implementation (b) of a hybrid current limiting circuit breaker for medium voltage made of elementary switches and a PTC-resistor.

A current limitation and interruption process is identical to the one explained in Fig. 9 p. 27. The only difference is, that not a GTO but switch B generates the voltage drop sufficiently high to commutate \( i_b \) onto path C. This process is now briefly recapitulated using the zoom in the commutation process given in Fig. 68:

Fig. 68: Simulated waveforms of a commutation process from path A to path C in the hybrid system shown in Fig. 67. The simulation is based on the arc characteristic given in Eq. 32 p. 91.

The elementary switch in path A is designed to carry the continuous current and, on triggering, commutates the current onto path B within several 100 \( \mu \)s. The two fast switches in path B and C are elementary switches with multiple breaks in series (see chapter 6.2 p. 103). The switch in path B is closed when switch A opens, and carries the current for around 100 \( \mu \)s to provide switch A time to recover. At opening, the sum of the arc voltages of the
many series connected breaks commutates the current on path C that contains the PTC and another elementary switch with many breaks in series. The process of commutating high currents on a parallel resistance was discussed in chapter 5.4.1 p. 92ff. The current is now limited by the PTC, which increases its resistance due to ohmic heating. At the following current zero crossing, the current is synchronously interrupted by switch C. The arc voltage of switch B has the same instant values than \( i_c(t) \) in Fig. 68 as the cold resistance of the PTC was chosen to \( R_{PTC} = 1 \Omega \).

6.4.2 Test and requirements of the hybrid system
The reason to design this hybrid system was to implement current limiting in the medium voltage range. The feasibility of the hybrid system for fault current limiting was studied in a medium voltage resonant circuit according to Fig. 36 p. 72. The values for the resonant circuit for these tests were: \( C_p = 5.4 \, \text{mF} \), \( L_s = 5.1 \, \text{mH} \), \( f_{\text{res}} = 95 \, \text{Hz} \).

Measured current limiting and interruption using the hybrid system
Measured waveforms during a current limiting and interruption using the hybrid system in Fig. 67 are shown in Fig. 69. A photo of the hybrid system is given in the appendix 10.2 p. 142. For this experiment, switch A was not connected. The current flows through switch B, which is triggered to open at \( t = 0.8 \, \text{ms} \) at an instant current of \( i_s = 900 \, \text{A} \). Switch B is opened with \( v_{k,8} = 12 \, \text{m/s} \). Until \( t = 1.2 \, \text{ms} \), the current commutates onto the nickel resistor, which has a cold resistance of \( R_{PTC,cold} = 0.7 \, \Omega \). From \( t = 1.2 \, \text{ms} \) until \( t = 5 \, \text{ms} \), the current is flowing through the PTC and switch C. The PTC is heated during this time with peak power of 3.5 MW and therefore it increases its resistance up to 5.5 times its cold value. (Power and resistance are shown as negative values to get a less crowded plot).
The overall energy input in the PTC results to $E_{PTC} = 6.5 \text{ kJ}$. Switch C is triggered to open at $t = 4.7 \text{ ms}$, which is 200 $\mu$s ahead of current zero of the limited current. While opening with $v_{kC} = 17 \text{ m/s}$, arcing occurs in the 24 series breaks for $t_{ar} = 150 \mu$s, resulting in a maximum arc voltage of $U_{arc} = 600 \text{ V}$ until current zero of the limited current. The transient recovery voltage reaches 3600 $\text{ V}$ within 85 $\mu$s, which corresponds to $\text{RRRV} = 43 \text{ V}/\mu\text{s}$. The interruption is successful.

The current is limited to $i_{lim,peak} = 1300 \text{ A}$, which is 40% of the 50 Hz prospective peak current with the same initial $dl/dt$.

Requirements for the switches and the PTC in the hybrid system

The requirements and dimensioning of the PTC-resistor are identical to the one in the hybrid system given in Fig. 9 p. 27 [42]. Therefore, this is not repeated in this work but it should be noted, that values for the cold resistance of a PTC for medium voltage applications typically result to be around 1 $\Omega$.

In order to fulfill a certain specification for a current limiting hybrid system, for the switches A, B, C individual specifications (requirements) can be determined by simulation. An example for the individual requirements is given in Fig. 70 for the following ratings:

- $U_p = 24 \text{ kV} \Rightarrow \text{RRRV} = 470 \text{ V}/\mu\text{s} ([100] p.49)$
- $I_n = 2 \text{ kA}$
• \( I_{\text{pros}} = 30 \text{ kA} \)
• \( I_{\text{lim}} = 6 \text{ kA} \)

Fig. 70 compares the requirements for these ratings to measured values (from Fig. 46 p. 83). This clearly shows, how this arrangement in a hybrid system splits up and eases the requirements for any single switch. The given requirements are gained from simulations as no tests with the above ratings were performed.

![Image](image.png)

**Fig. 70: Required interruption capability of the three switches in the hybrid system compared to measured values and standard circuit breaker.**

There are ranges given for the requirements of each switch, because the actual values are depending on the system and switch parameters. For instance: the values for switch C are depending on phase angle between limited current and voltage, which itself depends on the energy input to the PTC. As mentioned, switch A and B mainly do have a commutation duty; therefore, its current interruption qualities are not decisive but the values are given for comparison in Fig. 70.

The results from this comparison can be summarized as follows:

- The requirements on the rate of rise of recovery voltage for fast continuous current switch (switch A) and the commutation switch (switch B) are low. Therefore, the design of both switches can be focused on the current carrying- and the commutation capability.
- The requirement for the synchronous interruption switch (switch C) is mainly to withstand a high transient recovery voltage.

If now the requirements for the switches in this hybrid system are known, they can be compared to the features provided by elementary switches or combinations of elementary switches. This is done in the following chapter so to find best match.
6.4.3 Guideline to select switches for this hybrid system

Up to now, the requirements for elementary switches have been discussed for its interrupting or commutation capability without restricting on a specific design. For the switches in the hybrid system, it is now tried to match the features of elementary switches or its combinations from Fig. 61 p. 106 also with ancillary conditions.

Fast continuous current switch: Rotational operation and 2 series breaks

The fast continuous current switch can be designed according to the guidelines given in chapter 4.2 p. 42ff. It was concluded from Fig. 24, that rotational operation only requires $1/3^{rd}$ of the drive energy of linear operation. Therefore, it is proposed to use a rotational operated, double break elementary switch as fast continuous current switch to get high opening velocity at low drive energy.

Commutation switch: Linear operation, many series breaks, some parallel

The commutation switch has to provide a low contact resistance and a low stray inductance in the closed position so to allow a fast commutation onto it. This suggests having several parallel contact points for each of the serial breaks.

The required number of series breaks in path B can be estimated as a function of system parameters $U_n$, $I_n$, $I_{prox}$, $\omega_n$, and the maximum let-through current $I_{lim}$ during limitation. Using $k_{lim} = I_{lim}/I_n$ and characteristic of the PTC-resistor $k_{PTC} = R_{hot}/R_{cold}$ and the arc voltage from Eq. 32 p.91, the required number of series breaks in path B $n_{kB}$ is estimated using Eq. 41.

$$n_k > \frac{U_n (I_{prox} \cdot \omega_n \cdot t_{comm} + \sqrt{2} \cdot I_n)}{\sqrt{2} \cdot U_{arc} \cdot I_n \cdot k_{PTC} \cdot k_{lim}}$$

Eq. 41

Some values resulting from Eq. 41 are given in Fig. 71 as a function of rated voltage (a) and prospective current (b). Parameters are given on the chart. The number of series breaks in path B strongly depends on the system voltage and on the limitation factor $k_{lim}$ and is less depending on the prospective short circuit current. For instance: Utilizing a pure nickel-PTC ($R_{cold}/R_{hot} = 1/5$) for limitation in a 24 kV-system. This leads to $n_{kB} = 25$ for $k_{lim} = 5$ and $n_{kB} = 43$ for $k_{lim} = 3$, which are reasonable values (see e.g. Fig. 42 p. 80 with $n_k = 24$ and 3 parallel contacts each). Generally, current limitation will be more effective, if increasing the number of series breaks $n_{kB}$ in path B.
Fig. 71: Required number of series breaks in path B as a function of (a) rated voltage and (b) prospective short circuit current.

As the commutation time depends on the actual current value, it will vary for each operation and can result to several 100 µs, see i.e. Fig. 68. Therefore, a linear operated switch is best suited, because this allows the arc to be drawn to a greater length and for a longer time then if using rotational operation. Additionally, it has not to be designed to carry continuous current, which eases the need for drive energy.

Therefore, it is proposed to use a linearly operated elementary switch with many breaks in series and some breaks in parallel as commutation switch B.

**Interruption switch: Linear operation, many series breaks, some parallel**

The interruption switch also has not to be designed for continuous current. As it has to synchronously interrupt the limited current, but the exact instant of current zero will vary for each operation, it is also suggested to use a linear operated switch to allow longer arcs and a longer arcing time.

The required number of series breaks can be estimated from the synchronous interruption capability, which was given by Eq. 29 p. 82. Rearranging Eq. 29 and adding the phase shift between system voltage and the limited current leads to Eq. 42 for estimating the required number of series breaks in path C.

\[
n_k > \frac{4 \cdot \sqrt{2} \cdot U_n \cdot \sin \varphi \cdot f_T}{\nu_k \cdot \eta_r \cdot p \cdot E_{\text{max}}}
\]

Eq. 42

Some values resulting from Eq. 42 are given in Fig. 72 as a function of system voltage with a phase angle of \( \varphi = 50^\circ \) and \( p \) as parameter (a) and \( p = 5 \) bar
and φ as parameter (b). Constants: \( f_T = 20 \text{ kHz}, \eta_f = 0.5, E_{\text{max}} = 25 \text{ kV/(cm-bar)}, v_k = 20 \text{ m/s}. \)

![Graph showing n_{kc} vs. U_a [kV] for different pressures and phase angles.]

**Fig. 72:** Required number of series breaks in path C as a function of (a) pressure of the switching medium air and (b) phase angle between system voltage and limited current.

For instance: In a 24 kV-system, assuming \( f_T = 20 \text{ kHz} \) and \( \phi = 50^\circ \), this leads to a minimum number of \( n_{kc} = 18 \) series breaks when opening with 20 m/s in air at 5 bar (\( \eta_f = 0.5 \)). The very difference to the number of series breaks in path B (see Fig. 71) is, that \( n_{kc} \) is strongly affected by the ambient pressure and \( n_{KB} \) is not.

The use of many serial breaks for the interruption switch has additional influence on the interruption process:

- Using many series breaks increases the overall arc voltage (see e.g. Fig. 52 p. 90). Therefore, the phase angle between system voltage and limited current is decreased by opening the interrupting switch, causing a smaller phase angle \( \phi \). This in turn eases the TRV after interruption (Eq. 42). Nevertheless, the arcing time in the interruption switch will vary for each operation. Therefore, it is suggested to use distinct parallel path’s to ease arc erosion in the final arcing path.

- When having a high arc voltage there is no need for a detailed prediction of current zero: When an ohmic-inductive circuit can be assumed, (this is true for most medium voltage applications; especially at the occurrence of a short-circuit) than current zero of the limited current always occurs (shortly) after system voltage zero, compare to Fig. 9 p. 27. Therefore, an optimal trigger time will be at the system voltage zero because this is sufficient for the elementary switches to open, compare e.g. to the arc-
ing time Fig. 47 p. 85. The task of finding the optimal instant for trigger-
ing switch C thus reduces to detect system voltage zero crossing.

6.4.4 Trigger strategy for load switching with the hybrid system

For effective limitation and interruption of a fault current, the switching
sequence described in chapter 6.4.1 has to be immediately started after fault
detection. The same sequence can be used for load switching with this hy-
brid system. However, when using the hybrid system for load switching, it is
to question what is an optimal trigger time to get lowest arc erosion and
thus a large number of make-and-break operations. This optimisation is
comparable to the so-called "intelligent switching" of standard circuit
breaker, see e.g. [109].

Trigger strategies for low contact wear in all three switches

To get low contact wear in the three switches A, B, C, it is best to open them
very close to current zero. Therefore, an optimal strategy for load switching
in an ohmic-inductive circuit is as follows:

Store the instant $t_{i=0}$ for every current zero. If an external open command is
given, wait until shortly ahead of the following current zero to trigger switch
A at $t_s$, see Eq. 43 and Fig. 73. $t_{com}$ is the commutation time from path A to
path B and is very small for small currents, see e.g. Fig. 68 p. 113.

![Diagram](image)

**Fig. 73: Trigger strategy to get low contact wear in all three switches.**

$$t_A(t_{i=0}) + \frac{1}{2 \cdot f} = t_{com}$$  \hspace{1cm} \text{Eq. 43}

Triggering of switch B is accomplished after commutation of the very small
instant current onto path B is completed, which now is also very close to
current zero. This commutates the small instant current onto path C. The
PTC will be moderately heated, resulting in a slight limitation of current.
Switch C is triggered at system voltage zero as already done for fault current
limitation to finally interrupt the current.
Using this strategy, there's a small instant current at the instant of contact separation in all three switches, which does result in a high arc voltage, fast commutation processes and thus low contact wear. The algorithm given in Eq. 43 is simple and requires only current and voltage zero measurement.

6.4.5 Dimensioning values and limits compared to standards

The requirements on the single switches in this hybrid system and which combinations are to be chosen have been discussed in the sections 6.4.2 and 6.4.3. As the hybrid system is designed for fault-current limitation at medium voltage levels, its dimensioning values are to be compared to the values given by standards and the limits for the system with respect to current and voltage are to be discussed.

Limit for the rated voltage of the hybrid system around 24 kV

The opening velocity of elementary switches was found to be crucial for its current interruption capability (Eq. 28 p. 78), arc voltage (Eq. 32 p. 91) and current commutation capability on a parallel resistance (Eq. 36 p. 94) and a parallel capacitance (Eq. 39 p. 96). Opening velocity is also crucial for the interruption capability using many series breaks (Eq. 29 p. 82) and finally for the number of series breaks of the interruption switch in a hybrid system (Eq. 42 p. 118). The following parameters are limiting the rated voltage of a hybrid system:

- To obtain adequate opening velocity at higher voltage levels, one has to exponentially increase the drive energy of every single switch at higher voltage levels (Fig. 23 p. 56) what limits dimensioning voltage to ≈ 150 kV.
- Every switch in the hybrid system is to be designed for the rated insulation level according to the definitions given for the dimensioning voltage (chapter 4.2.1 p. 42f). A circuit breaker with a rated voltage of 25.8 kV already requires an insulation level of 150 kV ([100] p. 39).
- The required RRRV (e.g. 470 V/μs for a 24 kV breaker [100] p. 49), applies to the interruption switch C (compare to Fig. 70 p. 116).
- For effective limitation, the number of series breaks in the commutation switch has to be linearly increased with system voltage (Eq. 41 p. 117). This increases size and mass of the moving part and therefore further increases drive energy. Looking at the given example, this is a severe restriction on the system voltage and can be eased only by using another limiting element (PTC).
- For the overall design of a hybrid switch, the three independent drive systems are to be insulated from the three main current paths up to the same dimensioning voltage level.
From these influences, it is concluded that a rated voltage above 24 kV (36 kV) is hardly feasible for the hybrid fault current limiting breaker shown in Fig. 67, p. 113.

**Limit for the rated current of the hybrid system around 2 kA**

The dimensioning current defines the cross section of the moving part in an elementary design (Eq. 9 p. 45.). According to the definitions given for the dimensioning current (chapter 4.2.1 p. 42f), this current corresponds to the rated normal current given by standards ([24] p. 45).

- In the hybrid system, the continuous current switch only has to be dimensioned for the rated normal current. The commutation switch and the interruption switch both are carrying current for at most one half cycle during interruption. Therefore, the dimensioning current for both switches is referred to in the standards as rated peak withstand current ([24] p. 45), which has to be applied for each of the series breaks. The peak withstand current is several 10 times higher than the rated current for the multi-contact lamellas discussed in Eq. 10 p. 46 (values given in [84] are: rated current 40 A, peak current 3 kA).

- The rated current mainly affects the commutation process between the parallel paths, which has to be considered for the worst case i.e. for fault current limitation. The instant current value to be commutated depends on the fault detection time, the phase angle at fault occurrence and the prospective current. Using the fault detection algorithm given by Stege [92], the instant current is lower than 2 p.u. at the instant of detection. This gives the maximum current to be commutated by the continuous current switch. Adding some 100 μs for this first commutation process (compare Fig. 68 p. 113), the fault current may rise to 3...4 times the rated current when the commutation switch is opened and initiates the second commutation process. This commutation process depends on the number of series breaks (Eq. 41) but causes contact wear on each break and thus gives the limit for the rated current of the hybrid system.

From these impacts, it is concluded that a rated current above 2 kA (3 kA) is hardly feasible for the hybrid fault current limiting system shown in Fig. 67, p. 113.

**Limits for applications at an interrupting power around 1 GW**

Taking the limits for rated voltage and rated current derived in the above section, applications of this hybrid system as fault current limiting circuit breaker up to a rated power of several 10...100 MW are feasible.
As the limitations for the rated current are mainly given by the commutation switch B and furthermore the design of switch B shows a small dependence on the prospective short circuit current (Fig. 71 p. 118), a prospective short circuit current of 50 kA (60 kA) seems feasible. With a rated voltage of 24 kV, this results to an interrupting power of 1.2 GW for one phase, which should be compared to the values given for standard switchgear in Fig. 7 p. 24. The proposed hybrid system for fault current limiting can also be used as fault current limiting dc-switch for the current and voltage ratings. The main difference on the application as a dc-switch is concerned to the dimensioning of the PTC-resistor and the trigger strategy.

6.5 Summary: Applications of elementary switches

Based on the switching capabilities of fast-acting elementary switches and with the very advantage of simplicity at implementation, several possible applications have been proposed:

- Elementary switches can be applied as closing switches to protect sensitive devices from overcurrent in medium voltage applications. An overall closing time of 500 µs was measured for a rotationally operated switch. Prestrike time is lowered to 10 µs if closing with 50 m/s in air at 5 bar. Compared to single thyristors, elementary switches shows higher withstand voltage.

- The design of elementary switches can be altered to get switches with many serial and parallel breaks but one common repulsion drive. Increasing the number of parallel breaks results less contact wear at synchronous interruption. Increasing the number of serial breaks lowers the ability for carrying continuous current but increases arc voltage, instantaneous dielectric recovery immediately after current zero and rate of rise of reignition voltage.

- A hybrid system using three fast switches and a PTC-resistor for fault current limitation and interruption at medium voltage level is proposed. The requirements on the three switches in this hybrid system can be fulfilled by single elementary switches or switches with many series breaks and some in parallel. The application limits for this system have been given to a rated voltage of 24 kV (36 kV) and a rated current of 2 kA (3 kA).
7 Conclusions and outlook

7.1 Conclusions

- The theoretically investigated and tested elementary switches show a great potential for synchronous current interruption in medium voltage systems and for applications in hybrid systems for fault current limiting and dc switching. With the new invented rotationally operated elementary switches with repulsion drive, opening velocities up to 50 m/s have been measured.
- The theoretical and experimental investigations in the present work show the feasibility of a hybrid fault current limiting circuit breaker for the medium voltage range, which is composed of three very fast switches and a metal wire resistor.
- Due to the elementariness of the applied switches and because no power semiconductors are required, the costs of this hybrid system are assumed to be competitive to other fault current limiting systems and for the use in distribution systems.
- Fault current limiting circuit breakers and dc breakers based on the elementary switches show feasibility at the following ratings: \( U_n = (5 \ldots 36) \) kV, \( I_n = (0.1 \ldots 3) \) kA, \( I_{\text{pros}} = (1\ldots60) \) kA.
- Higher ratings are feasible if applying facilities for increasing the arc voltage of elementary switches in the hybrid system (e.g. deion-plates) to get faster commutation between the parallel paths. Another possibility is to apply a PTC-resistor, which shows a higher increase in resistance during limitation as the pure-metal resistor does.

7.2 Outlook for future work

- The geometry and drive efficiency of implemented switches for linear and rotational operation is to be further optimised by means of electromagnetic field calculation.
- The arc characteristic of rapidly extended arcs is to be studied from a physical point of view for various contact materials and switching media as a function of arc current and opening velocity and parallel impedance.
• Experimental investigation of the switching capability of very fast switches is to be carried out in other gases than air, using single elementary switches and hybrid systems.

• The influence of such fault current limiting hybrid systems on the operability of power systems is to be studied in field tests.
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# Abbreviations and symbols

## 9.1 Abbreviations and shortcuts

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ac</td>
<td>short for “alternating current”</td>
</tr>
<tr>
<td>CB</td>
<td>circuit breaker. Used synonyms are: breaker, switchgear, switch (for low interrupting power)</td>
</tr>
<tr>
<td>dc</td>
<td>short for “direct current”</td>
</tr>
<tr>
<td>FC</td>
<td>fixed contacts of linearly and rotationally operated switches</td>
</tr>
<tr>
<td>FCCS</td>
<td>fast continuous current switch</td>
</tr>
<tr>
<td>FCLB</td>
<td>fault current limiting breaker</td>
</tr>
<tr>
<td>FCLD</td>
<td>fault current limiting device</td>
</tr>
<tr>
<td>GTO</td>
<td>gate turn-off thyristor. Synonym: IGCT</td>
</tr>
<tr>
<td>hc</td>
<td>half cycle of system voltage or current</td>
</tr>
<tr>
<td>HV</td>
<td>High Voltage</td>
</tr>
<tr>
<td>IGCT</td>
<td>Integrated gate commutating thyristor. Synonym: GTO</td>
</tr>
<tr>
<td>MBP</td>
<td>moving bridging pieces for switches with many serial breaks</td>
</tr>
<tr>
<td>MP</td>
<td>moving contact part of linearly and rot. operated switches</td>
</tr>
<tr>
<td>N_d</td>
<td>number of turns of the drive coil</td>
</tr>
<tr>
<td>PTC</td>
<td>positive temperature coefficient resistor</td>
</tr>
<tr>
<td>rrrv</td>
<td>rate of rise of recovery voltage</td>
</tr>
<tr>
<td>SF₆</td>
<td>sulfur hexafluoride. Gas for insulation and arc quenching</td>
</tr>
<tr>
<td>TRV</td>
<td>transient recovery voltage after current interruption</td>
</tr>
</tbody>
</table>
## 9.2 Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega$</td>
<td>1/s</td>
<td>angular velocity of rotationally operated switches</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>rad</td>
<td>angle of the moving part</td>
</tr>
<tr>
<td>$\rho_{Al}$</td>
<td>$\Omega m$</td>
<td>resistivity of aluminium</td>
</tr>
<tr>
<td>$\rho_c$</td>
<td>$kg/m^3$</td>
<td>mass density of the moving part MP</td>
</tr>
<tr>
<td>$\rho_{Cu}$</td>
<td>$\Omega m$</td>
<td>resistivity of copper</td>
</tr>
<tr>
<td>$\tau_d$</td>
<td>s</td>
<td>time constant for the damping of the drive current</td>
</tr>
<tr>
<td>$\eta_f$</td>
<td>1</td>
<td>field inhomogenity factor</td>
</tr>
<tr>
<td>$\rho_{Mg}$</td>
<td>$\Omega m$</td>
<td>resistivity of magnesium</td>
</tr>
<tr>
<td>$\mu$</td>
<td>1</td>
<td>coefficient of friction between fixed and moving contact</td>
</tr>
<tr>
<td>$A_c$</td>
<td>$m^2$</td>
<td>cross section of the moving part (perpendicular to current flow)</td>
</tr>
<tr>
<td>$b$</td>
<td>m</td>
<td>thickness of the moving contact part</td>
</tr>
<tr>
<td>$C_p$</td>
<td>F</td>
<td>parallel capacitance to the switch</td>
</tr>
<tr>
<td>$d_i$</td>
<td>m</td>
<td>inner diameter of a ring-contact system</td>
</tr>
<tr>
<td>$E_o$</td>
<td>V/m</td>
<td>breakdown field strength in a homogenous gap</td>
</tr>
<tr>
<td>$E_d$</td>
<td>J</td>
<td>energy stored in the drive capacitor</td>
</tr>
<tr>
<td>$W_{Dlin}$</td>
<td>J</td>
<td>required drive energy for a linearly operated switch</td>
</tr>
<tr>
<td>$W_{Drot}$</td>
<td>J</td>
<td>required drive energy for a rotationally operated switch</td>
</tr>
<tr>
<td>$W_{lin}$</td>
<td>J</td>
<td>kinetic energy of the linearly moving part while moving</td>
</tr>
<tr>
<td>$W_{rot}$</td>
<td>J</td>
<td>kinetic energy of the rotationally moving part while in motion</td>
</tr>
<tr>
<td>$f_d$, $\omega_d$</td>
<td>Hz</td>
<td>resonant frequency and angular frequency of the drive</td>
</tr>
<tr>
<td>$F_{rep}$</td>
<td>N</td>
<td>repulsion force of the Thomson drive</td>
</tr>
<tr>
<td>$i_{swi}$</td>
<td>A</td>
<td>current through a fast switch</td>
</tr>
<tr>
<td>$i_d$</td>
<td>A</td>
<td>current in the drive coil of the Thomson drive</td>
</tr>
<tr>
<td>$i_{dim}$</td>
<td>A</td>
<td>dimensioning current for an elementary switch</td>
</tr>
<tr>
<td>$i_E$</td>
<td>A</td>
<td>eddy current in the moving part after triggering the drive</td>
</tr>
<tr>
<td>$i_p$</td>
<td>A</td>
<td>current in a parallel path to a fast switch</td>
</tr>
<tr>
<td>$J_c$</td>
<td>kgm$^4$</td>
<td>inertia of the moving part</td>
</tr>
<tr>
<td>$J_{dim}$</td>
<td>A/m$^2$</td>
<td>applicable current density in the moving part</td>
</tr>
<tr>
<td>$K_d$</td>
<td>N/A$^2$</td>
<td>factor: maximum repulsion force over squared drive current</td>
</tr>
<tr>
<td>Symbol</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>$k_{safe}$</td>
<td>1</td>
<td>safety factor for the dielectric breakdown</td>
</tr>
<tr>
<td>$l$</td>
<td>m</td>
<td>length of the moving part in a switch</td>
</tr>
<tr>
<td>$L_s$</td>
<td>H</td>
<td>series inductance to the switch</td>
</tr>
<tr>
<td>$m_c$</td>
<td>kg</td>
<td>mass of the moving part</td>
</tr>
<tr>
<td>$N$</td>
<td>1</td>
<td>number of turns of the drive coil</td>
</tr>
<tr>
<td>$p$</td>
<td>bar</td>
<td>pressure of the switching medium in the switching chamber</td>
</tr>
<tr>
<td>$R_{o}, L_o$</td>
<td>$\Omega, H$</td>
<td>supply-impedances of the repulsion drive</td>
</tr>
<tr>
<td>$R_d$</td>
<td>$\Omega$</td>
<td>series resistance of the drive (supply and coil)</td>
</tr>
<tr>
<td>$R_s$</td>
<td>$\Omega$</td>
<td>series resistance to the switch</td>
</tr>
<tr>
<td>$s_k$</td>
<td>m</td>
<td>distance between the fixed contacts</td>
</tr>
<tr>
<td>$T$</td>
<td>s</td>
<td>period of ac systems</td>
</tr>
<tr>
<td>$t_o$</td>
<td>s</td>
<td>time of natural current zero in ac circuit</td>
</tr>
<tr>
<td>$t_{arc}$</td>
<td>s</td>
<td>arcing time during interruption</td>
</tr>
<tr>
<td>$t_c$</td>
<td>s</td>
<td>time of contact parting</td>
</tr>
<tr>
<td>$t_T$</td>
<td>s</td>
<td>trigger-time of a switch</td>
</tr>
<tr>
<td>$U_a$</td>
<td>V</td>
<td>voltage across the open switch</td>
</tr>
<tr>
<td>$U_{arc}$</td>
<td>V</td>
<td>arc voltage</td>
</tr>
<tr>
<td>$U_b$</td>
<td>V</td>
<td>reignition voltage of the contact gap</td>
</tr>
<tr>
<td>$U_{dim}$</td>
<td>V</td>
<td>dimensioning voltage of an elementary switch</td>
</tr>
<tr>
<td>$U_{ir}$</td>
<td>V</td>
<td>value of the instantaneous dielectric recovery voltage per break.</td>
</tr>
<tr>
<td>$v_k$</td>
<td>m/s</td>
<td>opening velocity (circumferential velocity if rot. operating)</td>
</tr>
<tr>
<td>$V_{MP}$</td>
<td></td>
<td>volume of the moving part</td>
</tr>
<tr>
<td>$x$</td>
<td>m</td>
<td>instant gap during opening</td>
</tr>
<tr>
<td>$Z_d$</td>
<td>$\Omega$</td>
<td>characteristic impedance of the drive</td>
</tr>
</tbody>
</table>
10 Appendix

10.1 Examples of implemented elementary switches

For the experimental investigation of the switching capability of fast switches, several linearly and rotationally operated switches with minimal moved mass have been realized, following the design guidelines given in chapter 4.2 p. 42. The results from presented measurements have been given as a function of opening velocity and field inhomogeneity to abstract from a specific geometry. However, to show the true elementariness of the implemented switches, some examples are given in this section. Photos of the contact region of a linearly operated switch (Fig. 63 p. 108) and a switch with many breaks in series (Fig. 42 p. 80) have already been given.

Example on an implemented switch with linear operation up to 17 m/s

A cross section of a ring-shaped linear operated switch is given in Fig. 74 according to Popelka [83]. Opening and closing is done using the drive coils shown. No forced arc cooling facilities have been applied.

![Cross section of an implemented linearly operating switch SLIN with various parameters.](image)

\[17 \text{ mm}, d_i = 183 \text{ mm}, b = 2 \text{ mm}, N = 7, A_{\text{coil}} = 3.6 \text{ mm}^2, m_a = 55 \text{ g}, s_l = 2 \text{ mm}.\]

Moving part: Aluminium, partly coated with 50 µm silver.

The maximum opening and closing velocity achieved with this switch was \(v_{\text{max}} = 17 \text{ m/s}\) at a drive energy \(E_d = 200 \text{ J}\). The dependence of drive efficiency with distance from drive coil given in Fig. 22 p. 54 was also measured with this switch.
Example on an implemented switch with rotational operation up to 50 m/s

A cross section of rotationally operated switch is shown in Fig. 75 according to Magri [82]. The moving part is a flat cuboid. Opening and closing is done using the drive coils shown.

Fig. 75: Cross section of a realized rotationally operated switch SROT with $a_k = 26$ mm, $l = 90$ mm, $b = 2$ mm, $N = 10$, $A_{coil} = 0.8$ mm$^2$, $m_c = 10.5$ g, $J_c = 59 \cdot 10^{-6}$ kg-m$^2$.

Moving part: Aluminium, partly coated with 50 μm silver.

The maximum opening and closing velocity achieved with this switch was $v_{\text{max}} = 50$ m/s (circumferential velocity) at a drive energy $E_d = 200$ J. Due to less symmetry, the maximum efficiency of this switch turned out to be slightly smaller than for linear operation at $\eta_{\text{max}} = 5\%$.

Fig. 76: Photo of the rotationally operated switch shown in Fig. 75.
**Measured change of mutual inductance in the moving part**

To study the change of mutual inductance with turning angle of the moving part (see Eq. 4 p. 22), a particular moving part has been implemented for this switch to measure the induced voltage during energizing drive, see drawing on Fig. 77. The eddy current loop is not closed in this moving part, therefore the induced voltage can be measured. This was also done, varying the initial angle of rotation of the moving part to get the dependence of mutual inductance with distance from the drive coil. The change of mutual inductance turns out to be around 15 μH/m and becomes zero at an angle of 75 ° (compare to Fig. 75).

**Fig. 77:** Waveforms of drive current and induced voltage in a particularly prepared moving part for a rotationally operated switch (left) and the change of mutual inductance with the initial angle of rotation of the moving part (right).
10.2 Example of an implemented hybrid system

An implementation of the hybrid system discussed in chapter 6.4.1 p. 112 has been conducted and described by Muminovic [86].

Fig. 78: Cross section of a realized hybrid system.
Heating of the pure-wire resistor during current limitation

The pure-wire resistance in the hybrid system is made of nickel and is heated to red-glowing within 2 ms during current limitation, see Fig. 79 and Fig. 80.

**Fig. 79:** Waveforms of current, voltage and wire-resistance during limitation.

**Fig. 80:** Photo of the red-glowing nickel resistor during limiting a current of 1.8 kA.
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12 Curriculum Vitae

Walter Holaus

Born on 24 December 1972 in Schwaz, Austria. Citizen of Austria.

Education and Professional Experience

1992        Lumberman.
1997 – 2001  Doctoral studies at the High Voltage Laboratory of the Swiss Federal Institute of Technology, Zurich.
2000        Founding of the switchgear company TripleMC GmbH, Zurich.

Recognitions

1995        Awarded the third best student of electrical engineering in 1995 by the Vienna University of Technology.
2000        Awarded the “GEP-Sonderpreis” for the business idea of TripleMC GmbH by the Venture 2000 competition.