A Fast Mechanical Switch for Medium-Voltage Hybrid DC and AC Circuit Breakers

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***Abstract*—This paper presents the design and experimental results of a Thomson coil-based fast mechanical switch for hybrid ac and dc circuit breakers rated at 30-kV voltage and 630-A current. The compact design with optimized circuit parameters and geometric dimensions of components targets 2-mm travel within 1 ms when driven by a 2-mF capacitor bank precharged to 500 V. The use and design of a disc spring as the damping and holding mechanism is presented. Structural design of a complete switch assembly rather than just the actuator is given. Experimental results show that the switch can travel 1.3 mm in the first 1 ms and 3.1 mm in the first 2 ms when driven by a 360-V 2-mF capacitor bank. Such fast mechanical switches facilitate hybrid circuit breaker interruptions within 2 or 3 ms for ultra-fast and highly efficient protections in 5–35 kV medium-voltage dc as well as ac systems.**

***Index Terms*—DC circuit breaker, fast mechanical switch, finite-element method, hybrid circuit breaker, operating mechanism, repulsion coil actuator, Thomson coil actuator.**

I. Introduction

THE RESURGENCE of interest in dc power for various applications presents an opportunity as well as a challenge for dc circuit breaker design. At power transmission and distribution level, the lack of fast and powerful high-voltage dc circuit breakers impede the extension of modern dc grids [1], [2]. Conventional mechanical high-voltage direct current (HVDC) circuit breakers are too slow to provide fault interruption in a meshed dc system [3], [4]. While solid-state devices can be more than fast enough to switch off current without arcing, their conduction losses are prohibitively high [5]. A promising approach is a hybrid configuration, which combines mechanical and electronic switches [6]–[9]. The mechanical branch conducts the current during normal operation and hence loss is minimized. During faults, the current is commutated to the electronic switch path for interruption such that the interrupter opens the contactor with zero current. While being developed for dc, this concept is likely to be of advantage for ac circuits as well. For best electrical protection, very fast contact opening is desirable since this mechanical opening dominates the total interruption time of the circuit breaker. For medium-voltage circuit breakers, the currently used solenoid actuators usually take tens of milliseconds up to more than one hundred milliseconds. The desirable features of such mechanical switches for hybrid circuit breakers are as follows:

1) low conduction loss when carrying current;
2) very fast opening operation;
3) high arc voltage and durability (optional, depending on the specific hybrid scheme used).

Fast mechanical switches suitable for this application are far from being readily available and are only discussed in a limited number of publications. According to some researchers [10], a mechanism based on repulsion coil, which is also called Thomson coil, can achieve much faster mechanical operation compared to a magnetic mechanism based on attraction forces. With regard to Thomson coils, prior studies reported analytical calculation methods for repulsive force and movement estimation, and also presented limited experimental evaluations [11]–[13]. Testing of a few prototypes was presented in the literature in the late 1990s and 2000s, but these were without any design guidelines [14]–[16]. Recent studies report finite-element-analysis (FEA)-based modeling and testing results, as well as alternative operating concepts, but none of these have implemented switch prototypes with current ratings for targeted applications [17], [18]. This paper complements an earlier publication [19] and presents the design and experimental results for a Thomson coil-based fast mechanical switch for 30-kV voltage level and 630-A current level. The electromagnetic, structural, and thermal responses of the switch have been analyzed through simulation using a multiphysics finite-element software COMSOL. The design guidelines are derived in terms of circuit and geometric parameters based on finite-element simulations. The prototype has been designed to achieve a minimum of 2-mm open distance (equivalent to 30-kV dielectric strength in vacuum) within 1 ms. Both electric and mechanical considerations aspects are discussed in order to obtain an efficient, compact, and robust design. The four main parts [namely, the vacuum interrupter (VI), the operating mechanism, the holding and damping system, and the energy storage and control unit] were tested, and the results are

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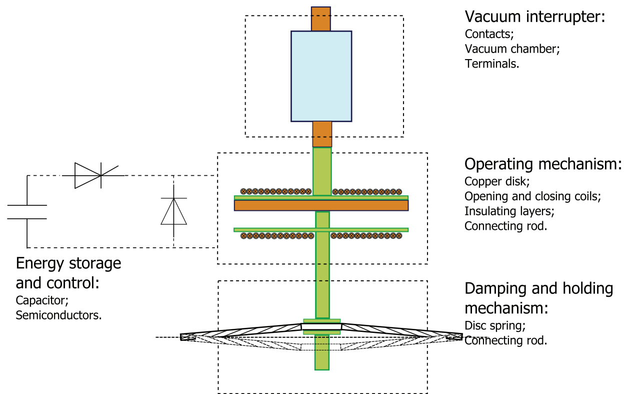

Fig. 1. Structure of the fast switch.

included in this paper. Experimental results of the integrated prototype on the switching and conducting operations are also presented.

The operation principles and the modeling are presented in Sections II and III, respectively, along with parameters and key simulation results for a baseline case. Section IV gives a design description of the switch with the target ratings. Section V reports the structural design and includes some mechanical operations. Section VI shows some experimental results, while Section VII concludes the paper.

II. Operation Principle

The principles of the fast opening and closing operations of the Thomson coil-based switch are explained, and the main components are discussed as follows.

A. Opening and Closing Operations

Referring to Fig. 1, the four main parts of the fast mechanical switch are: 1) interrupter; 2) operating mechanism; 3) energy storage and control; and 4) damping and holding mechanism. When the switch is must open, the trip signal is sent to the control switch for the opening coil; this switch turns on and allows the precharged capacitor bank to discharge through the opening coil. In Fig. 1, the upper coil is for the opening and the lower one is for the closing operation. The fast-rising discharge current in the coil induces current in the copper disk, located between the opening and closing coils, which results in a strong repulsive force between the coil and copper disk. As the coil is held firmly by its container on a stationary frame, the copper disk will be repulsed to move downward and open the switch. This movement is stopped by a disc spring with a hold and latch mechanism. This spring absorbs some of the mechanism kinetic energy, thus damping the movement before the stop is reached.

The closing operation is accomplished in a similar way by turning on a second switch that controls the discharge through the closing coil. Then, the copper disk moves upward to close the contacts. It should be noted that, in the hybrid circuit breakers that consist of semiconductor switches as a parallel branch, the requirements for the closing operation, in terms of fast actuation, are much less stringent than for opening.

B. Main Parts

1) Interrupter: The interrupter has to conduct current with very low losses and disconnect the circuit quickly by providing a galvanic isolation distance between contacts. The interrupter is used as a disconnector or as a set of contacts and does not have to extinguish a burning arc if the current is commutated to a bypass conducting path before it opens. The implemented prototype uses a VI for the purpose of withstanding the medium voltage with a small gap and minimizing the overall size of the unit. In this experimental setup, a VI is used.

2) Operating Mechanism: Four types of operating mechanisms are commonly used in commercial products: 1) spring; 2) pneumatic; 3) hydraulic; and 4) magnetic mechanisms. In vacuum circuit breakers, the spring and magnetic mechanisms are most common.

Spring-operated mechanisms have been widely used for vacuum as well as SF6 circuit breakers, but they exhibit mechanical delays because of too many moving parts and large moving masses. Magnetic mechanisms often come with VIs because they are suitable for short stroke movement with fewer moving parts [20]. Examples are commercial products such as ABB AMVAC series medium-voltage circuit breakers [21].

Compared to magnetic mechanisms based on attractive forces, which usually consist of coils of many turns because of holding requirement, Thomson coil mechanisms have a limited number of turns for the coil but significantly higher current. Because of the small number of turns, the inductance is small and the energization is quick which is preferred for very fast operation. Considering the challenges with the pneumatic and hydraulic actuators, and the faster actuation characteristics of electromagnetic actuation, the Thomson coil-based operating mechanism has been chosen for this research.

3) Energy Storage and Control: As both high current magnitude and high di/dt are required, capacitor banks are used to store electric energy beforehand such that the energy can be delivered quickly into the coil when actuation is desired. The voltage ratings of capacitors range from several hundreds to thousands of Volts and the discharge current could reach to more than 10 kA; a dedicated charging circuit is used for the energy storage. Power semiconductor switches are used to control the discharge of the capacitors. Thyristors and integrated gate-commutated thyristors (IGCTs) are often used because of their high-surge current capability [22].

4) Damping and Holding Mechanism: A holding mechanism or a latch for the closed position provides a holding force that helps achieve low contact resistance and keeps the contacts reliably closed even during short-circuit current. When opened, it holds the contacts in open position as required to avoid undesirable reclosing. A customized disc spring (also called Belleville spring) was designed and manufactured for this purpose because of the simple and compact structure of such springs, and the mechanism characteristics are explained in Section IV.

III. FEA Modeling

This section describes the basic method used in FEA modeling. Equations that include electromagnetic, thermal, and

TABLE I
FE MODELING EQUATIONS

Expressions	Descriptions
$\sigma_e \frac{\partial \mathbf{A}}{\partial t} + \nabla \times \mathbf{H} - \sigma_e \mathbf{v} \times \mathbf{B} = \mathbf{J_e}$	Electromagnetic
$\mathbf{B} = \nabla \times \mathbf{A}$	Electromagnetic
$\rho c_p \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q$	Thermal
$\sigma_e = \sigma_{e0}[1 + \alpha(T - T_0)]^{-1}$	Conductivity
$\mathbf{f}_{em} = \mathbf{J} \times \mathbf{B}$	Lorentz force
$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} - \nabla \cdot \boldsymbol{\sigma}_m = \mathbf{f}_{em}$	Displacement

TABLE II
FE MODELING VARIABLES

Variables	Descriptions
$\boldsymbol{A}$	Magnetic vector potential
$\mathbf{H}$	Magnetic field
$\mathbf{v}$	Velocity
$\mathbf{B}$	Magnetic flux density
$\mathbf{J_e}$	Electromagnetic
ρ	Density of material
Q	Ohmic heat source
c_p	Specific heat at constant pressure
σ_e	Electric conductivity
σ_{e0}	Reference conductivity
α	Temperature coefficient of resistance
T	Temperature
T_0	Reference temperature
$\mathbf{f}_{\mathrm{em}}$	Lorentz force
$\boldsymbol{\sigma}_{\mathrm{em}}$	Mechanical stress tensor
$\mathbf{u}$	Displacement

structural characteristics are included in the FEA software to simulate the transients during operation. Those equations are applied to the copper coil, the copper disk, the air gap in between, the shaft, and external lumped circuit. The set of equations used in FEA are given in Table I with all variables explained in Table II. The FE modeling-based analysis is used for design optimization of the prototype.

For additional details of the FE modeling of the fast mechanical switch, the readers are referred to [19].

In the FEA software, the z-component force is calculated for each element and integrated over the volume of the moving copper disk to get the total driving force. Then after adding the payload of the VI, the acceleration as well as displacement are calculated with time steps of 2 µs. A moving mesh using arbitrary Lagrangian–Eulerian formulation method is defined on the moving copper disk so that the geometry especially the distance between coil and disk is updated at each time step. The same model can predict the force distribution on the copper disk, yielding useful information concerning local stresses, and the mechanical integrity of the conducting disk.

A. FEA Modeling and Base Design

A base design is first studied using parameters presented in Table III. Fig. 2 shows the 3-D view of the model, and Fig. 3 shows the results of the operation transients. Important results concerning performance are shown in Fig. 3, namely: speed of the moving part v, total displacement u, total force f exerted on the moving mass, and current in the coil i. i is the current in the lumped circuit and finite-element modeled coil, f is obtained by integration over the volume of the moving part, and v and u are calculated based on load. By discharging a 2-mF 500-V capacitor, the current surges to approximately 13 kA and the

TABLE III
BASE DESIGN PARAMETERS

Disc outer diameter	80	(mm)
Disc thickness	4	(mm)
Coil inner diameter	12	(mm)
Wire gauge	10	(AWG)
No. of turns	10	
Gap	3	(mm)
Moving mass	1	(kg)
Capacitance	2	(mF)
Voltage	500	(V)

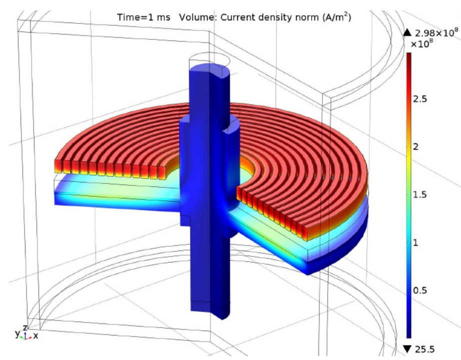

Fig. 2. FEA simulation model in 3-D view.

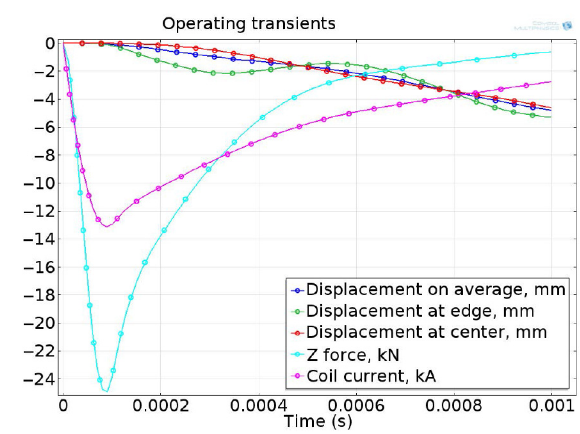

Fig. 3. Opening operation curves.

corresponding peak force is 25 kN that accelerates the load to move at least 4 mm within 1 ms. Including safety margin and possible artifacts due to practical implementation, the target of 2 mm in 1 ms is within reach.

IV. DESIGN DESCRIPTION

A. Design Guidelines

The design guidelines for the Thomson coil actuator as the operating mechanism are derived from comprehensive multiphysics transient simulations [19] and are summarized as follows.

1) The unidirectional circuit shown in Fig. 1 is better than a bidirectional circuit in terms of the operating speed of the mechanism. The components in both circuits used for evaluation have the same current and voltage ratings.
2) A device with higher voltage and lower capacitance but with the same stored energy generates higher and earlier peak current and peak force. This is preferred

TABLE IV
VI PARAMETERS

Contact stroke	6	(mm)
Basic Impulse Level (BIL)	75	(kV)
Rated current	630	(A)
Contact resistance	55	(μΩ)
Contact force from atmosphere pressure	70	(N)
Holding force required when open	110	(N)
Holding force required when closed	110	(N)
Moving mass	0.5	(kg)

TABLE V
OPERATING MECHANISM PARAMETERS

Disc material	copper	
Disc OD	80	(mm)
Disc thickness	4	(mm)
Coil ID	12	(mm)
Wire gauge	2.31*4.62	(mm)
No. of turns	13	
Gap	3	(mm)
Payload	0.5	(kg)

for high-speed operation, but this also requires higher semiconductor device ratings.

3) To design a switch that is required to open within 1 ms, it is useful to design a Thomson coil and capacitor with a resonant frequency somewhat above 1 kHz (resonant frequency as defined by the capacitor bank and the coil inductance), such that the force peaks in the first quarter cycle, and then optimize the geometry accordingly.
4) Higher voltage or larger capacitance will drive the mechanism to a faster speed, but will add both mechanical and electrical stresses on the components.
5) Copper disks with thickness in the range of 2–5 mm result in almost the same operation speed (see [19], these thicknesses are somewhat larger than the skin depth at the design frequency); coils made with AWG 8–12 wires give almost the same operation speed. Therefore, they are considered not sensitive in these ranges.
6) To achieve fast opening, the gap between disk and coil should be kept to a minimum. The disk and the coil outer diameters should be kept the same, which will give better coupling between disk and coil.

B. Vacuum Interrupter

The VI selected is originally designed for 12-kV ac contactors rated at 630 A with a maximum allowable stroke of 6 mm. 1 mm in vacuum is equivalent to 15–20 kV voltage withstand capability. The most important VI parameters are given in Table IV.

C. Operating Mechanism

The operating mechanism includes a Thomson coil actuator that is designed to deliver enough power to drive a payload of approximately 0.5 kg over the entire 6-mm stroke of the VI, and especially to move the first 2 mm of that 6-mm travel in less than 1 ms. The main parameters of the Thomson coil actuator-based operating mechanism are given in Table V. The wires used are rectangular for two purposes: 1) the rectangular wires have larger thermal capacity and 2) the structure is more robust when wound into a spiral coil.

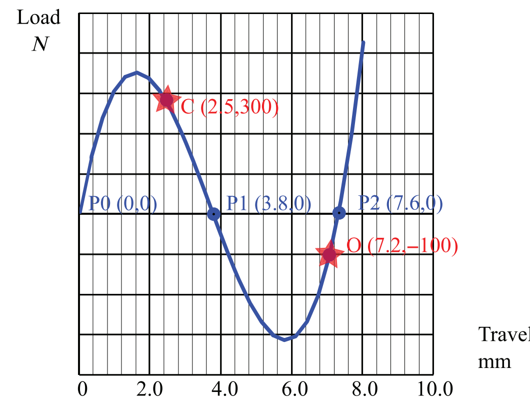

Fig. 4. Characteristics of the disc spring.

TABLE VI
CAPACITOR RATINGS (EACH)

Capacitance	0.5	(mF)
Capacitor voltage	1100	(V)
Peak current	6000	(A)
dV/dt	12	(V/us)
ESR	1.1	(mΩ)
ESL	80	(nH)

D. Damping and Holding Mechanism

A special disc spring whose load characteristics are optimized for this specific application is utilized to dampen the fast-opening movement and hold the movable parts in closed and opened positions. The designed load curve of a first prototype is shown in Fig. 4.

In Fig. 4, "P0," "P1," and "P2" are positions of the disc spring of zero load, while "C" and "O" represent the load points of the disc spring when the switch is in the closed or open positions, respectively. In the closed position, a 300-N closing force is applied to the closed contact which will greatly reduce the contact resistance; in the open position, the disc spring provides −100 N counteracting force that cancels the force from the atmospheric pressure, and reliably maintains the contacts in that open position. The nonlinear characteristic of the spring, with a negative force that peaks before reaching the open position, is a critical design element and one reason behind selecting such springs. This is because the area below the spring curve corresponds to the energy the spring can absorb, and the negative peak makes significant damping possible, along with a sufficient holding force.

E. Energy Storage and Control Unit

A 2-mF 500-V capacitor bank is used in the experimental Thomson coil actuator. Several capacitors are paralleled and can be configured to different capacitance values. According to the FEA simulations, a peak current of 13 kA can be expected. Therefore, the capacitor bank as well as the control switch must be able to withstand such large surge current. The parameters of the capacitors and control switch are given in Table VI and VII, respectively. A picture of the control switch is shown in Fig. 5.

TABLE VII
THYRISTOR RATINGS

Thyristor $\mathbf{V_{DRM}}$	1600	(V)
Thyristor $\mathbf{I_{T(AV)M}}$	2600	(A)
Thyristor $\mathbf{I_{TSM}}$	30	(kA)
Diode $\mathbf{V_{RRM}}$	2000	(V)
Diode $\mathbf{I_{F(AV)M}}$	3270	(A)
Diode $\mathbf{I_{FSM}}$	28	(kA)

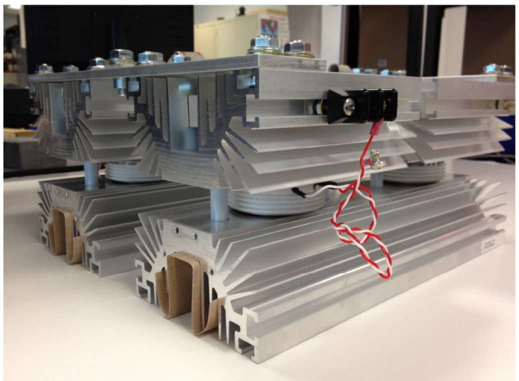

Fig. 5. Thyristor control switch.

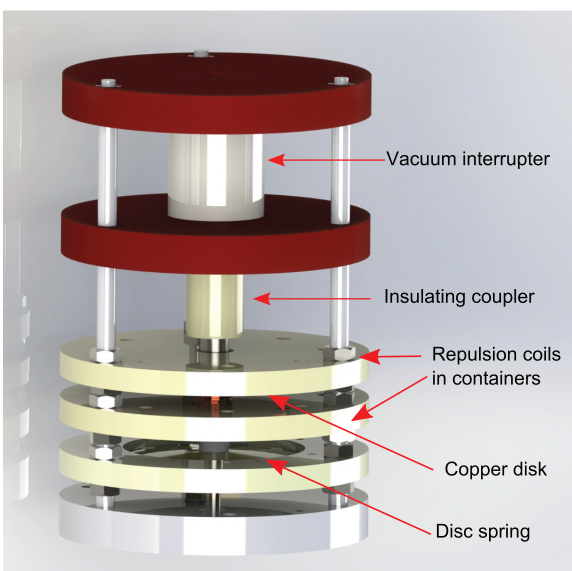

Fig. 6. Switch design.

V. Structural Design

The structural design in this paper focuses on the VI, the operating mechanism, and the disc spring, and excludes the energy storage and control unit, which are all stationary parts that do not involve any mechanical movement. Future studies can take into account the size and weight of capacitor bank and control switch; therefore, the overall design is more compact.

As shown in the computer-aided design (CAD) rendering in Fig. 6, the structure of the fast mechanical switch is arranged in a way that the translation movement is vertical. In fact, each of the movable components allows movement that is in any direction as the gravity is insignificant compared to the driving force. On the other hand, although a single axis is employed here to reduce the moving mass and make the structure simpler and more robust, double axes with a lever shaft could also be used.

In the prototype, two coils sitting in coil holders are placed one above the other, with a copper disk in between. It is supported by a steel shaft that goes through the center holes on the coil holders, and connects with the disc spring at one end and the VI at the other end. All three parts are fixed to a rigid frame through several supporting rods. The VI is supported by two insulating plates, and the movable terminal is coupled to the steel shaft through an insulating rod.

The finished, generally cylindrical prototype is presented in Fig. 7. The diameter is 200 mm and the height is approximately 300 mm.

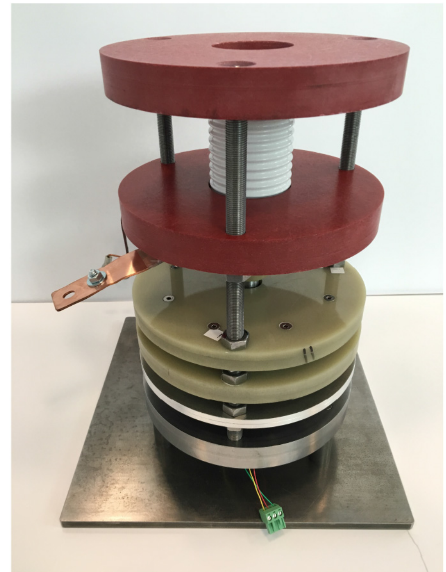

Fig. 7. UFMS prototype assembly.

VI. Experimental Evaluation

The prototype has undergone approximately 200 switching operations. These tests provide reliability data and initial indication of durability. Consistent with the hybrid circuit breaker concepts, the interrupter was not energized. Since in such designs, the mechanical switch is not exposed to high voltage or arcing during operation, such tests are valid to study the mechanical operation transients.

A. Opening Operation

One of the most important function of the switch is to achieve a very rapid opening operation; Fig. 8 shows such an operation. With a 2-mF capacitor bank precharged to 300 V, a 4.5-kA current pulse is injected into the driving coil which accelerates the moving parts in the first few hundreds of microseconds. The initial parting of the contacts happens at approximately 300 µs after the trip signal is commanded. The moving mass then travels at an approximately constant speed of 1.3 m/s. The gap is 1 mm at 1 ms and 2.2 mm at 2 ms.

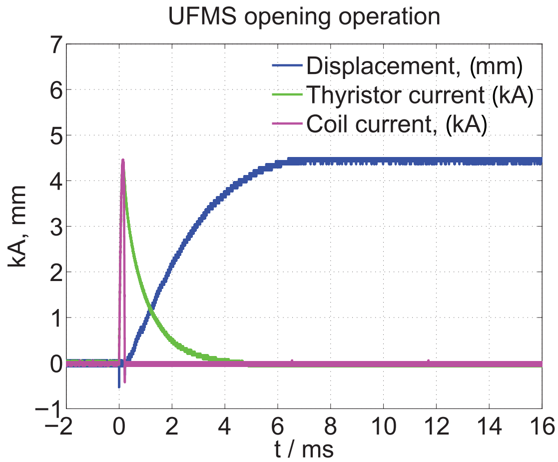

Fig. 8. Opening operation (test data).

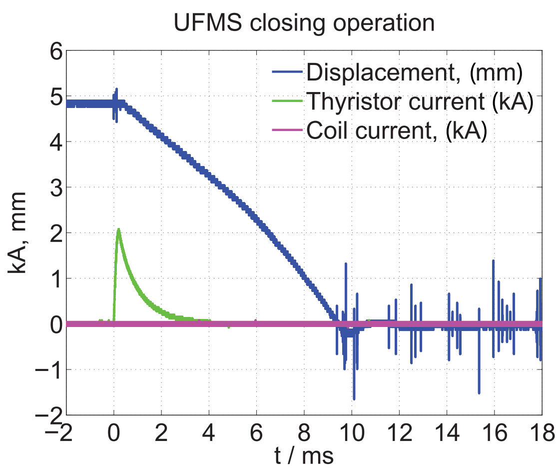

Fig. 9. Closing operation (test data).

If the VI is able to withstand 20 kV with a 1-mm gap, then the hybrid circuit breaker can potentially limit and switch off fault current in a 15-kV class distribution system within 2 ms.

The target was separation of 2 mm within 1 ms. The tests conducted so far indicate that this should be possible by precharging the capacitors to 500 V, instead of 300 V. This belief is based on comparing modeling results at 300 and 500 V, and the good correlation of tests and model at 300 V shown in Section VII.

B. Closing Operation

Even though closing speed is of less concern in terms of the overall protection speed, it does have some effect on the thermal transient in the high-voltage semiconductor switch, since the semiconductors need to conduct current first before the mechanical contacts are fully closed. The closing coil is different from the opening coil in the conductor size and the number of turns for this prototype, and the precharged voltage is different as well. In Fig. 9, it takes 10 ms for the movable contact to reach the closed position and some more ms for bouncing. The bouncing is because of inefficient damping of the closing movement in this initial prototype.

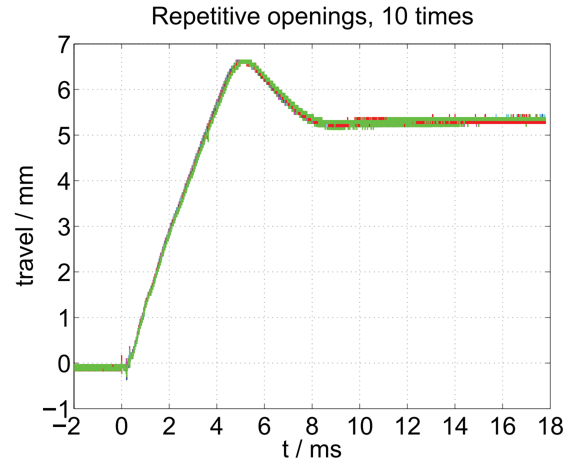

Fig. 10. Repeatability of opening operations.

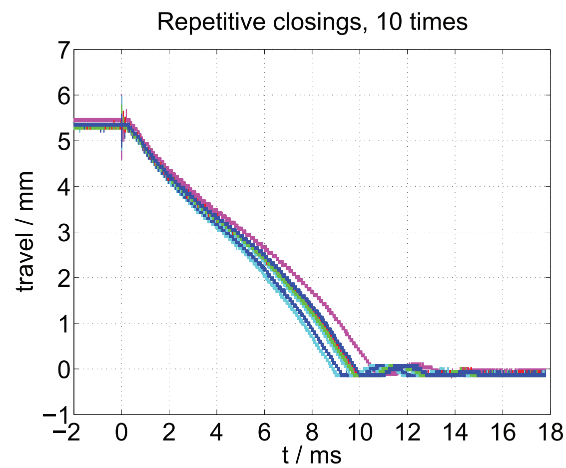

Fig. 11. Repeatability of closing operations.

C. Operation Reliability and Repeatability

The reliability of circuit breakers is of special importance since the circuit breakers secure the power systems against faults. The prototype has therefore been tested under repetitive operations as a means to validate its operation reliability. Ten repetitive opening operations as well as closing operations are shown in Figs. 10 and 11, respectively, with the displacement versus time curves. The switch openings and closings were scheduled for approximately every 10 min.

The test results show that the switch features almost identical opening travel curves when repeatedly driven by the capacitor bank precharged to the same voltage (360 V), and the switch can open to a gap of 1.3 mm in the first 1 ms and a gap of 3.1 mm in the first 2 ms. Slightly more variability is observed during closing strokes, attributed to varying initial conditions, such as exact disc spring preload.

VII. Validation and Modification of the FEA Model

In the experimental setup, certain deviation from measurements occurred since the multiphysics FEA simulation only considers the dimensions of the coil and the plate, and all other

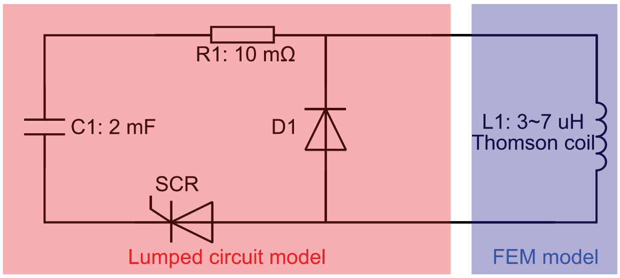

Fig. 12. Model before modification.

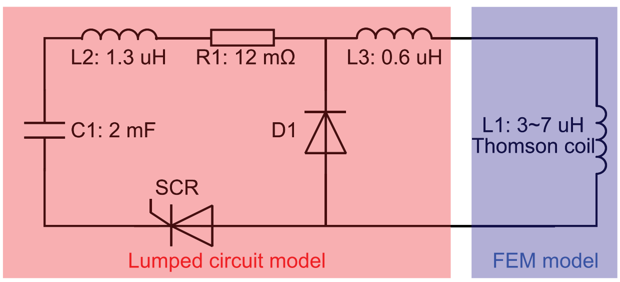

Fig. 13. Modified model.

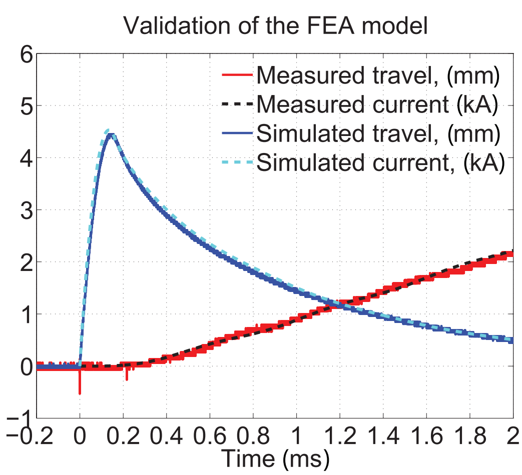

Fig. 14. Modified simulation and measured results.

parameters are lumped. With the measurements, the authors were able to identify missing details that affect the real performance, and then integrate them into the model for further analysis as well as for second generation design.

In the multiphysics model, there are two parts involved to calculate the electromagnetic transients. The first part is the lumped circuit domain consisting of the components such as capacitors and their equivalent series resistance, control switches, and stray parameters. The second part is the coil and moving mass in the finite-element domain. The original model shown in Fig. 12 included the stray resistance, but not the stray inductance. To match the test results, the lumped circuit is modified based on the information from the discharging current, while the FEA domain component remains the same. As shown in Fig. 13, additional inductances are inserted, with values derived from the frequency and damping ratio of the rising and falling of the discharging current. With such modifications, the simulated transients match very well with the measured transients (Fig. 14). This also points to the need for a careful layout design, in the case of Thomson coil, as the lead cable inductance cannot be neglected compared to the inductance of the coil.

VIII. Conclusion

This paper has proposed a fast mechanical switch based on the Thomson coil with 1–2 ms actuation response time suitable for up to 50-kV medium-voltage dc circuit breakers as well as ac circuit breakers, and could be scaled up to fit high-voltage applications. The design guidelines, prototype assembly details, and experimental results are included in this paper.

Experimental results have shown that the mechanical switch is able to travel 2.2 mm in 2 ms when driven by a 2-mF capacitor bank precharged to 300 V. It is anticipated that if the capacitor bank is precharged to 500 V, 2-mm travel in 1 ms is achievable, which corresponds to at least 30-kV withstand capability in vacuum. The closing takes around 20 ms, if the entire bouncing period (10 ms) is included. The opening and closing operations were repeated under 360 V driving voltage for ten times, and the travel curves match very well with small deviations observed.

This fast mechanical switch prototype, with the VI current rating of 630 A, could be used in hybrid dc and ac circuit breakers to interrupt a 30-kV circuit of 2-MW power in approximately 2 ms (1-ms estimated energy absorption time is included), while the loss of conduction is as low as 22 W.

Future experiments will test and characterize the switch from the electrical point of view so as to verify the low conducting loss and high voltage isolation after fast opening, and the long-term reliability of the VI and the disc spring under fast operation conditions.

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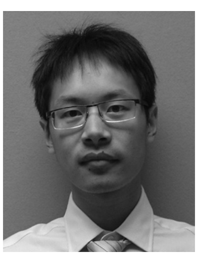

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