A Survey on Mechanical Switches for Hybrid Circuit Breakers

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***Abstract*—Hybrid circuit breakers are a class of protection devices to facilitate fault current limitation and fast interruption in AC and DC power systems. They are one of the key enabling technologies of multi-terminal DC transmission and distribution systems. As the power rating of DC power systems increases, mechanical switches in the normal conduction path are chosen to provide low on-state loss in a hybrid circuit breaker topology. These mechanical switches require fast actuation to achieve sub-millisecond switching capability, for which only a few actuation mechanisms have been reported to be suitable. Besides electromagnetic repulsion methods like the Thomson coil, piezoelectric actuators also appear to be a good candidate. This paper provides a survey on potential mechanical switches for hybrid circuit breakers considering different actuation mechanisms. Performances of mechanical switches reported in the literature have been summarized and compared, such as response time, displacement, and required actuation energy.**

Keywords*—hybrid circuit breaker, mechanical switch, ultrafast disconnect switch, Thomson coil, piezoelectric actuator.

I. INTRODUCTION

The increasing interest in DC power systems in medium and high voltage applications demands for a new class of protection devices including DC circuit breakers (DC CBs). The well-understood challenge with DC switching – the lack of natural zero-crossings – can be overcome by artificial counter currents of opposite polarity, generated by one of the following three methods: counter voltage, divergent oscillation, and current injection [1]. All three methods need additional branches parallel to the normal conduction path to facilitate fault commutation and energy absorption as shown in Fig. 1. Putting mechanical switches inside the normal conduction path is a common approach to minimize on-state loss and maximize overall efficiency of non-hybrid solid-state DC CBs. This combination of mechanical switch and semiconductor device for DC switching is typically called a hybrid circuit breaker

Unfortunately, the switching speed of mechanical switches is several orders of magnitude slower compared to solid-state breakers. For the sake of reducing the peak current and the amount of energy to be absorbed by semiconductor devices and surge arresters, mechanical switches needs to be driven by ultrafast actuators. The Thomson coil actuator is the most popular mechanism in the literature for ultrafast switching. It utilizes electromagnetic repulsion force to separate contacts. The opening time can be reduced to hundreds of microseconds. There are several other actuators based on electromagnetic repulsion, like moving coil actuators[2], doubled-sided coil actuators[3, 4], induction switch, series coil switch[5] and railgun actuator[6].

Besides electromagnetic actuation, emerging technologies like piezoelectric actuators provide ultrafast operation with new opportunities. Piezoelectric actuators have advantages with respect to travel control, nanometer-range resolution, and maximized actuation efficiency. Nevertheless, there has not been a study comparing different actuation mechanisms for ultrafast switching. The possibility of conventional switchgear like vacuum interrupters in DC switching could also be considered in hybrid circuit breaker configurations.

This paper presents a literature survey on mechanical switches applicable for DC CBs in medium-voltage and high-voltage applications. Both ultrafast disconnect switches and conventional mechanical circuit breakers will be discussed. The latest research on ultrafast mechanisms like Thomson coils and piezoelectric actuators are summarized and compared in terms of opening characteristics, energy conversion processes, and overall structural design.

II. ACTUATION MECHANISM OF MECHANICAL SWITCHES

A. Overview

Mechanical switches used for hybrid circuit breakers can be classified into two categories: disconnect switches and circuit breakers. The major difference is their fault current interruption capability. In hybrid DC CBs, ultrafast disconnect switches are used only if an artificial current zero-crossing could be achieved in the normal conduction path (Fig. 1). In the counter voltage type of DC CBs, where the arc voltage facilitates current commutation, circuit breakers are typically needed.

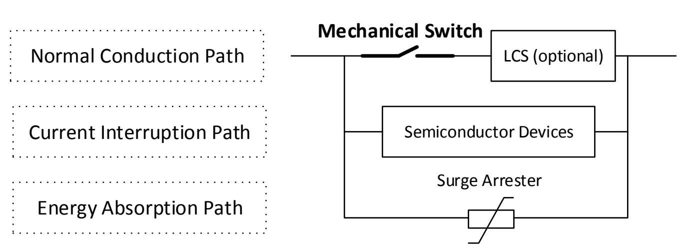

Figure. 1. Schematic of hybrid DC CB
(LCS refers to Load Commutation Switch)

TABLE I. APPLICABLE ACTUATION MECHANISMS

Switchgear Type	Actuation Mechanism	Compatible Zero-crossing Method in DC CB
Ultrafast Disconnect Switch	Electromagnetic Magnetostrictive Piezoelectric	Counter voltage Current injection
Mechanical Circuit Breaker	Electromagnetic Hydraulic Pneumatic Mechanical spring	Current injection Divergent Oscillation

The current interruption capability also influences the actuation mechanism. Traditional mechanisms like pneumatic, hydraulic, and electromagnetic actuation could support both fault current interruption and disconnecting function. However, they generally take tens of milliseconds for the interruption process because of arc quenching, which is too slow for DC current interruption. In a DC power system with a source voltage V_s and source inductance L_s, the most severe case can be expected when a bolted fault happens next to DC CB. The short-circuit current through DC CB follows this equation (assume a linear rise of fault current):

$$\frac{di}{dt} = \frac{I_{peak} - I_0}{\Delta t_{open}} = \frac{V_s}{L_s} \tag{1}$$

$$E_a = \frac{1}{2} L_s I_{peak}{}^2 \tag{2}$$

Where I_{peak} is the peak current at the time of interruption, I_0 is the normal current, Δt_{open} is the opening time in hybrid DC CB, E_a is the fault energy to be absorbed. In the same DC system, using an ultrafast switch ($T_{open} < 1$ ms) instead of a traditional circuit breaker ($T_{open} > 16$ ms, typically) could significantly reduce the maximum short-circuit current to be interrupted by solid-state main switch and the energy to be absorbed by surge arrester, and it endows more versatility of design and applications to the overall DC CB.

Actuation mechanism with superior speed and force output, like a Thomson coil, could play a role in ultrafast switching. Piezoelectric and magnetostrictive actuators could have even shorter response times than a Thomson coil and better controllability of contact travel; but the stroke distance and force output might be sacrificed. A correlation between applicable actuation mechanism and mechanical switch type in different topology of DC CBs is listed in generalized form in Table I.

B. Electromagnetic Actuation

In an electromagnetic actuation system, there is always a driving coil generating a magnetic field. Since the magnetic field is rising quickly, an electromagnetic voltage is induced in a moveable metal part, typically shaped as a disc or coil. The repulsion force between driving current and induced current will accelerate the moveable metal disc (since the driving coil is usually fixed), thus actuate attached contacts to separate.

The most common implementation of electromagnetic actuation is the Thomson coil. Using a Thomson coil to actuate an ultrafast mechanical switch requires an opening coil, a closing coil, and a moveable disc carrying contacts between two coils for axial displacement. Since merely half of the electromagnetic fields generated by the opening and closing coils are utilized in Thomson coil, a doubled-sided Thomson coil with two moving discs on both sides of opening coil could achieve higher efficiency [7]. The efficiency could be further increased in a doubled-sided coil configuration, where the driving current flows into a movable second coil [3, 4].

Due to the large actuation force and long stroke distance, the Thomson coil actuator could be implemented in both ultrafast disconnect switches or mechanical circuit breakers. A detailed discussion about Thomson coils will be presented in Section III.

TABLE II. COMPARISON OF ACTUATOR CHARACTERISTICS FOR ULTRAFAST DISCONNET SWITCH

Actuation Characteristics	Electromagnetic (Thomson Coil)		Piezoelectric	
Drive system	Indirect drive by electromagnetic force		Solid deformation by inverse piezoelectric effect	
Displacement	+	< 28 mm (Table III)	−	< 2 mm [8]
Displacement accuracy	−	> 0.1 mm [9]	+	0.01 mm to 0.1 mm [9]
Response speed	−	Varying (Table III)	+	100 µs to 1 ms [9]
Energy efficiency	−	Capacitor loss Coil winding loss	+	Power Amplifier loss
Proportional control	−	ON/OFF control [9]	+	Voltage proportional control [9]
Drive voltage	−	Several kilovolts	+	Hundreds of volts per millimeter [9]

+: Advantage −: Disadvantage

C. Piezoelectric Actuation

Piezoelectric actuators exploit the so-called inverse piezoelectric effect: an applied electric field could create mechanical strain over the piezoelectric stack of crystalline material, which leads to an actuation force and a displacement output. The piezoelectric actuation is fast, accurate and efficient in nature. A comparison between electromagnetic actuation and piezoelectric actuation is presented in Table II. The disadvantages of piezoelectric actuator are limited stroke and actuation force is currently being tackled by researchers and manufacturers [8, 9].

III. ULTRAFAST DISCONNECT SWITCH

As introduced before, ultrafast disconnect switches refer to mechanical switches with ultrafast opening time and no arc quenching capability. Common ultrafast disconnect switches for hybrid circuit breakers presented in the literature are driven by Thomson coil actuators or piezoelectric actuators. The performance characteristics of respective actuation mechanisms are discussed in detail below.

A. Thomson Coil Actuator

Studies of Thomson coil actuators cover both simulation analysis and experimental demonstration. Simulation models are built with a combination of analytical expressions (Maxwell equations and Lorentz force) and finite element methods. The main purpose of simulation models are: 1) determine structural parameters of driving circuit [10, 11], actuator structure [11-14] and damping system [15-17]; 2) evaluate and optimize design variables of Thomson coil [18, 19]; 3) improve actuator performances such as efficiency [4]. Major structural variables discussed in design and simulation of Thomson coil are summarized in Table IV.

Numerous studies have presented experimental results of Thomson coil actuators designed for hybrid circuit breakers, with or without arcing capability. As shown in Table III, the power ratings of DC CBs vary significantly. The highest voltage rating, 320 kV [20], was achieved using a unique sliding contact system with solid insulation that can withstand high voltage levels of up to 500 kV. The reported highest voltage rating achieved by vacuum insulation is 40.5 kV [21]. Actuating vacuum interrupters with Thomson coil is a common approach in which both the stationary and moving contacts are encapsulated in a vacuum chamber [22-24]. Design of the insulation strength needs to take the transient interruption voltage into consideration, which is caused by the current commutation process. This requires careful coordination of semiconductors and surge arresters.

The opening response time of Thomson coils is impressively fast for a mechanical system. The contact separation time (from actuation signal triggers to contact surfaces detach) was reported to be as low as 100 µs [25], and 7 mm of contact travel was completed within 600 µs [26]. Full contact opening travel required 27 mm and 2 ms in total [27]. The closing process will take much longer time, such as 5.5 ms [26], 10 ms [28, 29] or even 195 ms [27]. The long closing time is caused by a latch release mechanism, contact bouncing, and lower energy to drive the closing coil.

TABLE III. EXPERIMENTAL PERFORMANCES OF THOMSON COIL ACTUATORS IN LITERATURE

Investigator	DC Breaker Rating	Opening Characteristics				
		Opening Time *t*	**Speed** *v* / **Acceleration** *a*	**Contact Weight** *w* / **Repulsion Force** *F*	**Driving Energy** *E*	**Stroke Distance** *d*
Kishida et al. [26][*]	7.2/6.6 kV, 12.5 kA	$t_{\text{full travel}}$ = 0.6 ms	N/A	N/A	N/A	d_{max} = 7 mm [+]
Holaus et al. [30][*]	24 kV	$t_{\text{full travel}}$ <1 ms	v_{peak} = 30 m/s	N/A	$E_{\text{precharge}}$ = 200 J	N/A
Steurer et al. [25][*]	12 kV, 2/20 kA	$t_{\text{contact separation}}$ = 100 µs t_{arcing} = 30 – 250 µs	$v_{t=40\mu s}$ = 20 m/s	w_{contact} = 0.05 kg	N/A	Around 10 mm
Roodenburg et al. [27]	3 kV, 7 kA	$t_{\text{4mm separation}}$ = 422 µs $t_{\text{full travel}}$ = 2 ms	$a_{average}$ = 19000 m/s^2 [+] $v_{peak,calculated}$ = 31.8 m/s	w_{contact} = 2 kg $F_{\text{contact, closed}}$ = 2.4 – 3 kN $F_{\text{EM repulsion, average}}$ = 100 kN	$E_{\text{precharge}}$ = 3.87 kJ C_{source} = 0.86 mF $V_{\text{precharge}}$ = 3 kV	d_{max} = 27 mm [+]
Meyer et al. [31][*]	1.5 kV, 4 kA	t_{opening} = 300 µs $t_{\text{mechanical delay}}$ = 180 µs	$v_{average}$ = 10 m/s	$F_{\text{contact, closed}}$ = 500 N $F_{\text{EM repulsion}}$ = 35 kN [+]	N/A	N/A
Roodenburg et al. [15]	8 kA	$t_{\text{4mm separation}}$ = 450 µs $t_{\text{25mm travel}}$ = 2 ms	$a_{average}$ = 38000 m/s^2	w_{contact} = 2.7 kg $F_{\text{EM repulsion, peak}}$ = 200 kN	$E_{\text{precharge}}$ = 1.4 kJ – 2.75 kJ	d_{max} = 28 mm [+]
Skarby et al. [20]	320 kV, 2.6 kA	$t_{\text{50\% travel}}$ = 1.2 ms	N/A	$F_{\text{EM repulsion}}$ = 20 – 30 kN	N/A	N/A
Bissal et al. [4]	N/A	N/A	v_{peak} = 12 m/s (11 mF, 700 V)	N/A	$E_{\text{precharge}}$ = 2.64 kJ C_{source} = 10 mF $V_{\text{precharge}}$ = 726 V	N/A
Wen et al. [21]	40.5 kV	$t_{\text{13mm travel}}$ = 2.3 ms	v_{peak} = 10 m/s [+]	N/A	C_{source} = 2.5 mF $V_{\text{precharge}}$ = 1.4 kV	d_{max} = 28 mm [+]
Peng et al. [28, 29][*]	30 kV, 630 A	$t_{\text{contact separation}}$ = 300 µs $t_{\text{1mm travel}}$ = 1 ms	$v_{average}$ = 1.3 m/s	w_{contact} = 0.5 kg	C_{source} = 2 mF $V_{\text{precharge}}$ = 300 V	d_{max} = 5 mm [+]
Vilchis-Rodriguez et al. [32]	N/A	N/A	v_{peak} = 10 – 15 m/s [+]	$w_{\text{Cu, amature}}$ = 0.369 / 1.7 kg $w_{\text{Al, amature}}$ = 0.051 kg	C_{source} = 10.03 + 9.95 + 10.37 mF $V_{\text{precharge}}$ = 100 – 250 V	N/A

[+] : Curve of measurement results is included in literature

[*] : DC CB with semiconductor and energy absorption components built and tested

The high repulsion force exerted by Thomson coils is another significant feature. This electromagnetically-generated force that separates contacts can easily reach tens of kilonewtons [15, 20, 27, 31], driving 2 kg of contacts accelerated up to 19,000 m/s^2 with a 31.8 m/s peak speed [27]. Because of the tremendous repulsion force, Thomson coils can output, contacts could have closed contact forces of 500 N [31] or even 3 kN [27] at closed state, which allows for a low contact resistance and low on-state losses of the mechanical switch.

The fast opening speed, high interruption force, and long stroke distance are all supported by the impulse energy input from pre-charged capacitors. Most Thomson coils need several kilojoules of energy from capacitors stored in millifarads of capacitance with kilovolts of pre-charged voltage. Such high-voltage, high-capacitance capacitors need extra attention to select, implement and maintain, because high-capacitance capacitors tend to slowly degrade over time and consequently fail after service life.

The efficiency of Thomson coil actuators is quite limited. 5% of input electric energy converted into kinetic energy is already considered as a fair performance, and 54% is the highest theoretically calculated efficiency that could be achieved in a Thomson coil [4]. There are two ways proposed to increase efficiency: minimized stroke distance using series-connected contacts as in [20], or shorter current pulse driving the opening coil [4].

TABLE IV. DESIGN VARIABLES FOR THOMSON COIL ACTUATOR

Structure	Design Variable	
Circuit	Circuit topology	Capacitance
	Precharge voltage	Connection impedance
	Thyristor/diode resistance	Thyristor/diode voltage drop
Exciting Coil	Wire diameter	Layers
	Turns/layer	Outer radius
	Inner radius	
Moving Disc	Thickness	Weight
	Outer radius	Initial air gap
	Strength & Deformation	Outer shape
Damper	Gas type: pressure	Mechanical type: spring constant
Latch	Structural design	Action sequence & mechanism

TABLE V. EXPERIMENTAL PERFORMANCES OF PIEZOELECTRIC ULTRAFAST DISCONNECT SWTICH IN LITERATURE

Investigator	DC Breaker Rating	Opening Characteristics		
		Opening Time	Contact Force	Stroke Distance
Graber et al. [33, 34] *	15 kV, 200 A	~0.5 ms	110 N	0.5 mm
Zen et al. [35]	1 kV, 100-500 A	~0.5 ms	40-50 N	0.3 mm

[*] : DC CB with semiconductor and energy absorption components built and tested

B. Piezoelectric Actuator

There are fewer design variants of the piezoelectric disconnect switches compared to those with Thomson coils, mainly due to the small stroke of piezoelectric actuators limiting the voltage and insulation level when the switch is open. Typical piezoelectric actuators have a strain of 0.1%, which would require a 1 m long actuator to produce a 1 mm stroke. Amplified piezoelectric actuators (APAs), which have an elliptic shell around the actuator stack to amplify the strain, are used in all existing prototypes of piezoelectric ultrafast disconnect switches. In APAs, the piezo stack is aligned along the major axis of the elliptic shell. A small deformation in the major axis transforms into an amplified deformation in the minor axis. Typical values range from 5 to 20 times of amplification [36]. At the same time, the stiffness is reduced by the same factor and the response time is increased.

Other methods to amplify the stroke are variants of the APA concept, such as flextensional [37] and lever arm [38] mechanism. Flextensional mechanism can result in either contraction or expansion of the shell even if the dominant motion of piezo stack is expansion. The lever arm mechanism is a two-step amplification mechanism, which results in up to 40 times greater stroke for the same length of the stack. Both amplified actuator mechanisms produce larger stroke at the cost of opening speed and contact force. Lower contact force can increase the resistance between the contacts when closed because of thin film and constriction effects [39], which leads to increased power loss in the normal conduction path.

The piezoelectric ultrafast disconnect switches in open literature include a 15 kV, 200 A vacuum switch based on APA [33, 34]. The switch has 4 contact pairs, which are separated by the APA by 0.5 mm within 0.5 ms. A force of 110 N is distributed equally among the contact pairs when closed which results in power loss of 50 W at 200 A. Another variant of the piezoelectric switch is a 300 V, 350 A version with a single contact pair. It can achieve an open contact separation distance of around 300 µm, contact force around 40 N, and an opening speed around 0.5 ms [40]. The latter switch operates in air, which results in a lower voltage withstand capability compared to the former vacuum-insulated switch [35] [40]. These prototypes demonstrate that despite lower stroke distance and contact force, ultrafast disconnect switches with a piezoelectric actuator can have comparable ratings to the Thomson coil. The piezoelectric disconnect switches are, in general, faster than the Thomson coil with more control over contact travel.

IV. CONCLUSION

This paper started by introducing the role of mechanical switchgear in DC switching, then summarized and compared applicable actuation mechanisms. With a focus on ultrafast disconnect switch, experimental results of Thomson coils and piezoelectric actuators had been presented, compared, and their suitability for hybrid circuit breakers analyzed. Even though the Thomson coil has been the most frequent choice shown in the literature, there are alternative methods to realize ultrafast switching, such as piezoelectric actuators. Conventional switchgear like vacuum interrupters could also be utilized in DC circuit breaker with suitable circuit topology and control strategy. As DC switching draws widespread attention from different subfields of power engineering, we hope this paper could serve as a survey and selection guide to design, implement and optimize mechanical switches in DC circuit breakers.

ACKNOWLEDGMENT

This work has been supported in part by the NSF grant #1700887.

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