<http://www.diva-portal.org>

Postprint

This is the accepted version of a paper published in . This paper has been peer-reviewed but does not include the final publisher proof-corrections or journal pagination.

Citation for the original published paper (version of record):

Augustin, T., Parekh, M., Magnusson, J., Becerra Garcia, M., Nee, H-P. (2022)
Thomson-Coil Actuator System for Enhanced Active Resonant DC Circuit Breakers
IEEE Journal of Emerging and Selected Topics in Power Electronics

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-292581>

Thomson-Coil Actuator System for Enhanced Active Resonant DC Circuit Breakers

Tim Augustin, Mrunal Parekh, *Student Member, IEEE*, Jesper Magnusson, Marley Becerra, *Member, IEEE*, and Hans-Peter Nee, *Fellow, IEEE*

Abstract—Enhanced active resonant (EAR) DC circuit breakers (DCCBs) are a promising set of recently proposed DCCB concepts. As other DCCBs, EAR DCCBs still require a fast mechanical switch. The requirements on the actuator of the mechanical switch depend on the DCCB concept and the DC grid and are derived here for an EAR DCCB. Thomson-coil actuators can open and close mechanical switches sufficiently fast to satisfy the requirements. This work studies experimentally a Thomson-coil actuator system with active damping for an off-the-shelf industrial vacuum interrupter used as mechanical switch in an EAR DCCB. The prototype is explained in detail and extensive measurement results are presented showing that active damping must be perfectly timed to be effective. A novel Thomson-coil driver is proposed and studied experimentally, which operates the Thomson-coil actuator more efficiently by recycling energy during the actuation. Moreover, the novel Thomson-coil driver reduces the capacitive storage by 50 % and allows for faster recharging with lower charging current. Finally, the auto-reclosing and proactive commutation operation of the Thomson-coil actuator system and the interruption capability of the prototype EAR DCCB are demonstrated experimentally.

Index Terms—Active damping, Actuator, DC circuit breaker, DC grid, Thomson-coil actuator, Vacuum interrupter.

I. INTRODUCTION

DC circuit breakers (DCCBs) are key components of DC grids [1]. DCCBs have to operate within a few milliseconds and, thus, must be considerably faster than their AC counterparts. A multitude of DCCBs has been proposed [2]. Most DCCBs can be categorized as current-injection DCCBs and hybrid DCCBs. In current-injection DCCBs, the arc in a mechanical switch is interrupted by injecting a counter current to force a local current zero [3]. In hybrid DCCBs, mechanical switches conduct the DCCB current in normal operation. The DCCB current is commutated from the mechanical switch to power semiconductors that turn OFF to interrupt the current flow [4]. Hybrid DCCBs offer more features than current-injection DCCBs, but power semiconductors are expensive. Enhanced active resonant (EAR) DCCBs are an intermediate solution based on discharge closing switches (DCSs) that extend the capabilities of current-injection DCCBs [5] by allowing for *proactive commutation* like hybrid DCCBs.

Tim Augustin's and Mrunal Parekh's research projects are funded through SweGRIDS, by the Swedish Energy Agency and ABB. Marley Becerra would like to acknowledge the financial support of the Swedish strategic research program StandUp for Energy.

T. Augustin, M. Parekh, M. Becerra, and H.-P. Nee are with KTH Royal Institute of Technology, Stockholm 100 44, Sweden (e-mail: timau@kth.se; mrunal@kth.se; marley@kth.se; hans@kth.se).

J. Magnusson and M. Becerra are with ABB Corporate Research, Västerås, Sweden, Forskargränd 7, 722 26 Västerås.

EAR DCCBs need a fast mechanical switch as most DCCBs. Vacuum interrupters (VIs) are suitable mechanical switches because the moving parts are light and the di/dt interruption capability at current zero is superior compared to gas circuit breakers [6]. Thomson-coil (TC) actuators (TCAs) allow for rapid opening and closing [7] and have also been used with a VI in a DCCB [8]. Decelerating the moving armature of the TCA is crucial to avoid that the armature hits the opposing TC with high speed. The short contact gap of VIs, however, complicates the deceleration. Active damping uses the opposing TC to electromagnetically decelerate the armature [9]. Active damping was successfully applied in [10] for a VI and the authors also demonstrated what happens if active damping is not timed well: Armature bouncing and even unintentional reclosing. Active damping was also used in [11] for a VI with a TCA with a light moving mass, thus reducing the required energy. The vibration characteristics of TCAs, which can adversely affect actuation, were studied in [12].

TCAs require a system including TC drivers, a DC power supply, a charging circuit, and a control unit. Various TC driver topologies were studied in [13] showing that the choice of the TC driver depends on the TCA requirements and design. Exciting the acceleration TC twice subsequently was studied in [14]. The authors showed that the second excitation is inefficient because the increasing contact gap reduces the electromagnetic coupling of the excited TC and the armature. Active damping of the TCA used in this work was already studied with finite element simulations for DCCB application [15]. The authors concluded that the requirements on the TCA system, specifically the DC power supply, are stringent and that active damping works only for a narrow parameter range.

This work studies experimentally a TCA system with active damping for a VI used in an EAR DCCB. A novel TC driver for combined acceleration and active damping is described that partly recycles the capacitor bank voltage and, thus, boosts the efficiency of the TCA system. The novel TC driver substantially reduces the requirements on energy storage and power supply. In contrast to previous studies, an off-the-shelf industrial VI in an embedded pole is used and the operating scenarios *auto-reclosing* and *proactive commutation*, as required in practice, are demonstrated. Section II describes EAR DCCBs and their requirements on the actuator. Section III explains the TCA system, its subcomponents, and their operation. Section IV presents the experimental results. Section V discusses TCA systems for future industrial application. Lastly, Section VI summarizes all findings.

Fig. 1. Enhanced active resonant DC circuit breaker with asymmetric interruption capability.

II. ENHANCED ACTIVE RESONANT DC CIRCUIT BREAKERS

A. Concept

The EAR DCCBs and their operation were introduced and explained in [5]. One of the EAR DCCBs with asymmetric interruption capability is depicted in Fig. 1. The idea of EAR DCCBs is to replace the expensive power semiconductors with turn-OFF capability used in hybrid DCCBs with DCSs. DCSs are gas-filled or vacuum discharge tubes that can be turned ON, but not OFF, similar to a thyristor. To guarantee turn-OFF, an injection circuit or pulse generator as in current-injection DCCBs is used. As hybrid DCCBs, EAR DCCBs use a mechanical switch S in the normal conduction path that must be able to open and reclose fast, hence requiring a fast actuator. Even though this actuator could be used with any mechanical switch in any DCCB concept, its requirements are dictated by the particular mechanical switch and by the particular DCCB concept. Furthermore, the requirements on the DC grid also indirectly influence the requirements on the actuator. Here, the requirements on the actuator are derived from the operation modes of EAR DCCBs.

B. Operation Modes

1) *Interruption*: The interruption process is illustrated in Fig. 2. A real-life DCCB fault current would have a complex shape because of the converter behavior and the travelling waves [16]. The depicted DCCB current i_{DC} resembles the maximum boundary of the worst-case DCCB fault current for dimensioning purposes. The DCS is triggered when i_{DC} exceeds the proactive commutation threshold I_p and i_{DC} is commutated proactively to the DCS by turning OFF the LCS. After that, S is opened without arcing such that the EAR DCCB can immediately interrupt i_{DC} when it is tripped. The charge Q absorbed by the DCS is marked in Fig. 2 and it must be limited below the maximum charge Q_{max}

$$Q = \int_0^t i_{DC} dt' \leq Q_{max}. \quad (1)$$

If Q_{max} is exceeded or if i_{DC} exceeds the maximum current I_{max} , the EAR DCCB self-trips after the maximum permissible interruption time $T_{int,max}$

$$T_{int,max} = \min \left(\frac{2Q_{max}}{I_{max} + I_p}, (I_{max} - I_p) di/dt^{-1} \right) \quad (2)$$

Fig. 2. EAR DCCB during interruption process.

with the worst-case di/dt . Otherwise, the DCS conducts until the EAR DCCB is tripped by the DC grid protection. The switch S_C is turned ON to inject a counter current into the DCS extinguishing the discharge. Then, i_{DC} commutates to the metal-oxide varistor (MOV) after the interruption time T_{int} . The voltage of the MOV exceeds the DC-side voltage temporarily and, thus, decreases i_{DC} to zero.

The advantage of proactive commutation is that the actuator opens S before the EAR DCCB is tripped as indicated by the contact travel distance d in Fig. 2 at $t = 0$. Since S is already partially opened, proactive commutation speeds up interruption when the EAR DCCB is tripped. In Fig. 2, for example, the EAR DCCB can immediately interrupt when it is tripped. Note that the peak voltage stress of S is determined by the MOV. S can withstand temporarily substantially higher voltage than its rated voltage. Therefore, i_{DC} can be interrupted before S is fully open when d exceeds the critical distance D_{crit} by a safe margin with the critical time $T_{crit} < T_{int,max}$. S is fully open after the opening time T_{open} .

2) *Proactive Commutation*: The EAR DCCB may proactively commutate, even if it does not need to interrupt, for instance because of overcurrent or a temporary fault. A temporary fault can, for instance, be a fault that clears by itself, a lightning strike, or a fault on an adjacent line cleared by another DCCB or AC circuit breaker. The worst-case scenario must be determined for each DC grid individually. Considering that (1) must always be obeyed, a temporary overcurrent exceeding I_p by the factor λ is assumed to derive an expression. The internal DCCB protection must abort proactive commutation by the abortion time T_{abort}

$$T_{abort} = \frac{Q_{max}}{\lambda I_p} - T_{close} - T_{comm}, \quad (3)$$

if it does not receive the external trip signal, if i_{DC} decreases below I_p , and if other potential protection algorithms do not detect a fault. These additional protection algorithms could, for instance, monitor undervoltage or di/dt . Otherwise, the

Fig. 3. EAR DCCB aborting proactive commutation.

EAR DCCB must self-trip. To abort proactive commutation as shown in Fig. 3, i_{DC} is commutated back to S by reclosing S within the closing time T_{close} and then turning ON the LCS to commutate within T_{comm} . The energy storage of the actuator may not be replenished within $T_{abort} + T_{close}$ for reopening with a reasonable DC power supply. Consequently, proactive commutation should only be aborted if it is highly probable that the hazardous condition is over or if back-up energy storage for the actuator is provided.

3) *Auto-Reclosing*: In DC systems with overhead lines, faults may clear themselves after interruption and auto-reclosing is attempted for a specified number of times after a system-dependent deionization time of arc faults $T_{reclose}$. EAR DCCBs can reclose by directly reclosing S or by triggering the DCS, reclosing S, and then commutating i_{DC} to S by turning ON the LCS. The latter approach requires a DCS that can operate at the frequency $1/T_{reclose}$. Since S is not operated in this case, current injection could immediately interrupt i_{DC} and, hence, auto-reclosing does not influence (1). Even with this auto-reclosing strategy, a fault could occur when or right after S recloses. Therefore, the actuator must still be able to execute an open-close-open sequence. Figure 4 illustrates auto-reclosing with S after an interruption. The fault persists and i_{DC} increases again. Before I_P is surpassed and before the DCCB is tripped, the DCCB detects the high di/dt and initiates interruption. S is reopened, now with arc, and current injection extinguishes the arc when d is sufficient. To execute the open-close-open sequence, the power supply of the actuator must be able to re-energize the energy storage of the actuator within $T_{reclose}$, while S is in the OPEN position.

C. Requirements on Actuator

T_{open} and T_{abort} of the actuator are calculated from (2) and (3) assuming $\lambda = 3/2$, $T_{open} = T_{close}$, and $T_{open} = 2T_{int}$ and are shown in Fig. 5. Since the requirements on the actuator become more stringent with increasing di/dt , the limits of

Fig. 4. EAR DCCB during auto-reclosing operation.

Fig. 5. Requirements on the actuator for an EAR DCCB ($I_P = 2.4$ kA, $T_{comm} = 50$ μ s, $T_{open} = T_{close}$).

actuators should also be considered when planning a DC grid. The upper graph in Fig. 5 shows that T_{open} is independent of Q_{max} . In contrast to that, T_{abort} increases with Q_{max} , giving more time to make a decision. Nevertheless, even the smallest Q_{max} gives reasonable T_{abort} . The lower graph shows that an optimal I_{max} minimizing the requirements on the actuator exists. EAR DCCBs can be designed for tremendous I_{max} as DCSs exist up to 700 kA, although the converters in the DC grid set the upper limit on I_{max} .

Fig. 6. Thomson-coil actuator system for vacuum interrupter.

TABLE I

Parameters of prototype Thomson-coil actuator system

U_{DC}/V	C/mF	D_{gap}/mm	N	m/kg	$R_{\sigma}/m\Omega$	$L_{\sigma}/\mu H$
1000	4	10-11	10	1.12	8.7	3.58

III. THOMSON-COIL ACTUATOR SYSTEM

A. Overview

The TCA system used in the experiments is shown in Fig. 6 and its key parameters are summarized in Tab. I. The TCA system includes the TCA, a VI in an embedded pole (as implementation of S), a TC driver, a control panel, and a DC power supply. The subcomponents are described hereafter.

B. Thomson-Coil Actuator

The TCA illustrated in Fig. 7 consists of two TCs with N turns each and an armature. The prototype with mounted embedded pole is included in Fig. 6. The upper TC is used for opening and the lower TC is used for closing. The TCs have to be excited with a current pulse, which induces eddy currents in the armature. The eddy currents cause a repelling magnetic field that accelerates the armature towards the opposing TC. The created force must be sufficient to accelerate the mass m of the armature and its connected components plus the mass of the moving parts of the embedded pole. Active damping is used to decelerate the armature before it hits the opposing TC. Active damping means that the opposing TC is also excited with a current pulse when the armature gets close to it. The eddy currents induced in the armature cause a repelling magnetic field that, in this case, decelerates the armature. Active damping has to be perfectly timed for proper deceleration as studied in [15]. Otherwise, the armature may hit the opposing TC with high impact and damage it. If active damping is initiated too early, the armature is still too far away from the opposing TC and the damping effect is not strong

Fig. 7. Illustration of the Thomson-coil actuator.

enough. If active damping is initiated too late, the remaining distance to the opposing TC may be insufficient to decelerate the armature or active damping is too effective, accelerating the armature back to its initial position.

The off-the-shelf embedded pole houses the VI rated for 12 kV RMS and includes all required mechanical components apart from the TCA. The embedded pole is rated for a maximum opening speed of 2 m s^{-1} and a maximum closing speed of 1.6 m s^{-1} . The rod of the embedded pole is directly attached to the armature. A bistable mechanism attached to the armature in four locations provides a symmetric holding force of approximately 500 N in the OPEN and CLOSED position to prevent spurious reopening and associated arcing. In addition, the force of the bellows of the VI tends to close the contact. In contrast to other studies, armature bouncing leading to unintentional reopening or reclosing has not been observed because the bistable mechanism used is sufficiently strong. The manufacturer did not disclose the mass of the moving parts within the embedded pole, but the moving contact of the VI alone weighs 1.1 kg.

The prototype TCA, which is not optimized for the particular embedded pole used, was provided by an external party. Hence, the TCA is treated as black box and the rest of the TCA system is designed around it to yield the desired performance.

C. Thomson-Coil Driver

A TC driver, such as the conventional TC driver *a* shown in Fig. 8a, delivers the current pulse to excite the corresponding TC. A capacitor bank made up by two sets of capacitors (C_1, C_2) and (C_3, C_4) stores the energy for opening and closing the TCA and the corresponding active damping. All capacitors are charged to the same voltage level U . To open or close, one of the capacitors in a capacitor set is discharged into a TC and the other capacitor of the capacitor set is discharged into the opposing TC for active damping as shown in Fig. 8a. The other capacitor set is still charged and, thus, the TCA can immediately operate again. The total parasitic resistance R_{σ} and parasitic inductance L_{σ} in the discharge path of the TC driver are given in Tab. I.

In a well-laid-out system, R_{σ} is small and the LC circuit formed by the TC driver and TC is weakly damped. The duration of the current pulse is determined by the LC circuit and the electromagnetic force has approximately the same shape as the current pulse. The electromagnetic coupling between the TC and the armature becomes weaker with increasing separation and the current in the TC will only

Fig. 8. Thomson-coil drivers, exemplified for opening.

weakly affect the acceleration of the armature after its peak. Thus, any freewheeling current through diode arrangements would not benefit noticeably the force production. Since only a fraction of the capacitor bank energy is dissipated in the armature, many authors claim that TCAs are inherently inefficient. However, an important amount of the capacitor bank energy is typically dissipated in the freewheeling path used to protect the capacitor bank from reverse voltage polarity. Hence, freewheeling in the TC driver is a common source of inefficient operation of a TCA system. Consequently, non-polarized capacitors not requiring reverse voltage protection are used and freewheeling diodes are not included in the TC drivers used in this work as shown in Fig. 8.

The capacitor voltage turns negative, because of the LC circuit resonance, and its absolute value was higher than 50 % of the initial capacitor voltage in the first experiments. For this reason, it is beneficial to recycle the remaining charge by reversing the negative voltage or by discharging the negatively charged capacitor into a TC again. The latter option is preferable because a voltage reversal would cause additional losses. Moreover, both options could be combined with recharging. Reconfiguring TC driver *a* yields the alternative TC driver *b* depicted in Fig. 8b. TC driver *b* only needs two capacitors; one for closing and one for opening. The thyristors are connected to the TCs such that, after exciting a TC for acceleration, the now negatively charged capacitor is discharged into the opposing TC for active damping. As the negative voltage is lower than the initial voltage, active damping is weaker compared to TC driver *a*. Having two capacitors less than TC driver *a*, TC driver *b* reduces the charging time of the capacitor bank and the charging current drawn from the DC power supply. After active damping, the capacitor voltage reverses to its initial polarity and, considering this remaining voltage, the charging time is reduced even more.

Fig. 9. Inside of Thomson-coil actuator control panel.

D. Control Panel

The control panel shown in Fig. 9 houses the charging circuit, the control electronics, thyristor gate drivers, and auxiliary equipment like DC power supplies for the thyristor gate drivers. The control electronics printed circuit board (PCB) features an 8-bit microcontroller that handles all I/O via optical fibers. The control electronics reacts to commands from the internal DCCB protection, i.e. whether the capacitors should be charged or whether the TCA should operate, and sends back status signals. The control electronics controls the charging of the capacitors, the TC driver, and, hence, active damping by activating the corresponding thyristor gate driver after a hard-coded damping delay t_d after actuation was started.

The charging circuit shown in Fig. 10 charges the capacitor bank from the DC power supply with the maximum voltage U_{DC} . The charging circuit is realized on a PCB using a simple design with thyristors that naturally turn OFF when the capacitors are charged and the charging current decreases below the holding current of the thyristors. By firing the thyristors subsequently, each capacitor set is charged to the voltage U above U_{DC} , because of the inductance of the DC power supply and the rectifying effect of the thyristors. High inrush currents destroyed the first charging circuit PCB prototype in the initial experiments since the conventional DC power supply used failed to limit the charging current. Therefore, a DC generator had to be used as DC power supply in the experiments. The normally-open contactor NO and discharge resistor R_D safely discharge the capacitors when the TCA system is not in operation. The charging circuit was used with TC driver *a* and *b*. However, C_2 and C_4 are not connected for TC driver *b* and actually the charging circuit could be simplified because D_1 - D_4 , D_6 , and D_8 are not needed.

Custom thyristor gate drivers are used with the charging circuit and TC drivers. Each thyristor gate driver has an 8-bit microcontroller to precisely control the gate current duration and to suppress EMI, caused by nearby switching and arcing, with software routines.

Fig. 10. Charging circuit for Thomson-coil actuator.

IV. EXPERIMENTAL RESULTS

According to the VI manufacturer, the force pulse of a TCA could destroy the plastic pull rod of the embedded pole. To avoid this, the TCA system is first studied with a solid steel load mass with approximately the same weight as all moving parts of the embedded pole at speeds exceeding the embedded pole ratings. Then, the TCA system is studied with the actual embedded pole. An oscilloscope records relevant electrical quantities during the operation of the TCA system. The motion of the armature is tracked with a high-speed camera with the frame frequency 7000 Hz and d is extracted from the pictures. The triggered oscilloscope sends a trigger signal to the high-speed camera to start taking pictures.

A. Solid Load Mass

Figure 11 shows the measured armature travel distance d and the estimated speed v (by numerically differentiating d) of the armature during the opening and closing operation with TC driver a . The electrical quantities are also shown in Fig. 11 for closing. Since opening and closing work in the same way, the depicted quantities look similar, but inverted, for both operations. Therefore, only closing operation is explained for Fig. 11. Initially, the armature is at rest in the OPEN position with $d \approx 11$ mm and the capacitors (C_3, C_4) are charged to $U = 636$ V. Then, C_3 is discharged to create the current pulse i_{TC2} at $t = 0$ accelerating the armature above -3 m s^{-1} . The current pulse in i_{TC2} finishes indicating that the electromagnetic force subsided. During this intermediate phase, the bistable mechanism slows the armature slightly down. Because of its dynamical characteristic, the bistable mechanism decelerates the armature even when it travelled more than $D_{\text{gap}}/2 = 5.5$ mm. Active damping is started after the active damping delay $t_d = 3.1$ ms by discharging C_4 to create the current pulse i_{TC1} decelerating the armature to $v = 0$ at $t \approx 4$ ms. The armature is still at $d \approx 2$ mm and the bistable mechanism pulls the armature towards the CLOSED position. During this process, the bistable mechanism reaccelerates the armature up to almost $v = -1 \text{ m s}^{-1}$ until the armature hits the opposing TC bringing the armature to an abrupt stop at $t \approx 8$ ms. The period between $t \approx 4$ ms and $t \approx 8$ ms can be reduced by proper timing of active damping. The current pulses i_{TC1} and i_{TC2} are equal because (C_3, C_4) are charged to the same voltage. After the

Fig. 11. Armature travel distance, speed, and electrical quantities for opening and closing operation using solid load mass and 3.1 ms active damping delay at $U = 636$ V with Thomson-coil driver a .

respective current pulse, u_{C3} and u_{C4} turn negative with a residual negative voltage U_{neg} .

The influence of U on d is studied in Fig. 12 for TC driver a with t_d set to initiate active damping at approximately constant d . The armature is accelerated to higher velocities for increasing U and, hence, t_d must be reduced. The active damping effect does not change greatly with U showing that the active damping force has the same dependency on U as the acceleration force at constant d when the acceleration current pulse equals damping current pulse.

In Fig. 13, opening operation with TCA driver a is studied with various t_d and U kept constant at the value used to yield the highest v in these experiments. Since the armature being closer to the opposing TC improves electromagnetic coupling, active damping becomes more effective for increasing t_d . Already at $t_d = 3.2$ ms, active damping is strong enough to reaccelerate the armature backwards again. This effect is more pronounced for increased t_d and slightly compensates the higher d already reached. If t_d is increased even further, the armature actually recloses. It is not known whether the reduced contact gap due to backwards reacceleration affects T_{crit} of the VI. Thus, an optimal t_d cannot be identified. A modified TC driver with a different U for each capacitor could reduce the active damping effect potentially allowing for a performance similar to curve 7) without backwards reacceleration.

The cabling to the closing TC is longer than to the opening

Fig. 12. Armature travel distance for opening operation using solid load mass and various active damping delay and voltage combinations with Thomson-coil driver *a*.

Fig. 14. Negative capacitor voltage after closing acceleration with Thomson-coil driver *a*.

Fig. 13. Armature travel distance for opening operation using solid load mass and various active damping delays at $U = 636$ V with Thomson-coil driver *a*.

Fig. 15. Armature travel distance for closing operation using solid load mass and various active damping delays at $U = 527$ V with Thomson-coil drivers *a* and *b* and electrical quantities for Thomson-coil driver *b*.

TC in the prototype used and, thus, U_{neg} is higher for closing operation. U_{neg} is shown in Fig. 14 as function of U for closing operation as worst case with TC driver *a*. U_{neg} decreases linearly with increasing U , because of the resistive losses in R_{σ} and in the TC. To boost U_{neg} , the TC driver must be optimized to minimize R_{σ} .

TC driver *a* and *b* are compared in Fig. 15 for closing operation. Since U_{neg} is lower in magnitude than U , the damping current pulse is lower than the acceleration current pulse for TC driver *b*. Thus, active damping is weaker for TC driver *b* compared to TC driver *a*. Because of this weaker active damping, TC driver *b* decelerates the armature without backwards reacceleration in contrast to TC driver *a*. Compared to the case without any damping, active damping with TC driver *b* also reduces armature bouncing. The active damping effect for TC driver *b* appears weak, but this is due to the low U used in the experiment leading to a speed not much higher than the speed after the bistable mechanism reaccelerates the armature. Even though it was found that active damping is similar for varying U at constant d , U is not further

increased for TC driver *b* to not risk breaking the prototype. Active damping could be insufficient at higher speed and the prototype must be optimized to boost U_{neg} for such studies.

Charging the capacitor bank is studied in Fig. 16 for TC driver *a* and *b*. TC driver *b* uses two capacitors less than TC driver *a*. Since only one capacitor is charged at a time for TC driver *b* with the charging circuit used, the charging time and charging current i_{ch} are considerably reduced.

Fig. 16. Capacitor charging for Thomson-coil driver *a* and *b* at $U = 637$ V.

B. Embedded Pole

The armature travel distance during the opening operation of the embedded pole with TC driver *a* is shown in Fig. 17 at two voltage levels. When active damping is applied, the armature starts oscillating for both voltage levels. The mechanical structure, unlike the TCA with the solid steel load mass, is prone to oscillations since the plastic pull rod and possibly the bellows in the VI are elastic. As active damping immediately decelerates the armature, the inertia of the trailing contact compresses the pull rod against the armature, causing the oscillation. This happens independent of U because almost any U is sufficient to decelerate the armature. The oscillating armature is too far away from the opposing TC for reliable reclosing within T_{abort} . Moreover, the oscillation is not uniform across the wobbling armature surface. The bistable mechanism attached to the armature in four spots pulls one part of the armature to the top and another to the bottom. As a result, the armature is stuck and cannot be moved by exciting a TC. For this reason, the configuration with TC driver *a* is not viable given the requirements of EAR DCCBs and only TC driver *b*, whose weaker active damping avoids oscillations, is used hereafter. Alternatively, a charging circuit allowing to charge the capacitors to different values of U could have been used.

Opening with TC driver *b* and various t_d is studied in Fig. 18. Because of the weaker active damping obtained with TC driver *b*, the armature does not oscillate any longer. Compared to the case without damping, the reduced armature bounce with active damping is essential for reclosing within T_{abort} . The setting $t_d = 5.9$ ms is chosen for experiments described hereafter, because of the improved electromagnetic coupling compared to earlier active damping and the reduced armature bounce compared to later active damping. However, active damping was ineffective for closing operation. The bellows exerts a higher-than-specified force and closing takes less than 6 ms with an average speed exceeding its rating. The opening speed is not steady at all and, in spite of the maximum speed 2.8 ms^{-1} , full opening takes rather long 7 ms, which is, nonetheless, sufficient for the EAR DCCB prototype.

Fig. 17. Armature travel distance for opening operation of VI with 6.4 ms active damping delay with Thomson-coil driver *a*.

Fig. 18. Armature travel distance for opening operation of VI with various active damping delays at 575 V with Thomson-coil driver *b*.

Considering that the EAR prototype has $Q_{\text{max}} = 60 \text{ C}$ and if $I_{\text{max}} = 9 \text{ kA}$, the achieved T_{open} would currently require the limits $di/dt = 2 \text{ kA ms}^{-1}$ and $T_{\text{abort}} = 10 \text{ ms}$ according to Fig. 5.

The capability of the TCA system to abort proactive commutation in an open-close sequence is demonstrated in Fig. 19. The solid line part of the d trace corresponds to the tracked motion as detected by the high-speed camera and the position of the armature before and after the measurement is assumed to be stable. Because of its machine dynamics, the DC power supply used, the DC generator, charges the second capacitor slightly higher than the first capacitor. Although undesirable in practice, this actually benefits the experiments. Opening requires a higher U than closing to achieve similar speed as described before and, therefore, C_1 is charged after C_3 . Since armature bouncing is eliminated in the OPEN position, the TCA system can reclose the embedded pole after $T_{\text{abort}} = 10 \text{ ms}$ to abort proactive commutation as required.

As demonstrated in Fig. 20, the TCA system executes the open-close-open sequence for auto-reclosing within 100 ms.

Fig. 19. Armature travel distance and electrical parameters during proactive commutation and its abortion with VI and Thomson-coil driver *b*.

Fig. 20. Armature travel distance and electrical parameters during auto-reclosing operation of VI with Thomson-coil driver *b*.

After the first opening operation, C_1 is recharged below the previous U , because of the dynamics of the DC generator. Consequently, the reopening speed deviates from the regular opening speed and the unchanged t_d is mistimed. The resulting armature bouncing is partly due to actual bounce and partly due to the compression of the armature after hitting the closing TC. Both capacitors are recharged after reopening and the TCA system is ready for auto-reclosing, again.

C. Testing of Enhanced Active Resonant DCCB

In the preliminary tests, the EAR DCCB prototype did not include a mechanical switch [5]. Figure 21 shows the results from an interruption test, in which the embedded pole with TCA studied in this work is installed in the EAR DCCB prototype. The armature contact travel distance d from the previous opening experiments is also included in Fig. 21. The EAR DCCB interrupts before the armature is in the OPEN position and, comparing to the results from [5], the embedded pole does not affect the currents. Therefore, continued testing of EAR DCCBs without mechanical switch is reasonable whenever it is not the subject of study. Nonetheless, the

interruption test with the embedded pole proves that EAR DCCBs are viable for industrial application.

V. DISCUSSION

The auto-reclosing and proactive commutation abortion tests of the TCA system and the interruption test of the EAR DCCB demonstrate that TCAs are suitable for industrial applications. Note, though, that the studied TCA system, including TC driver *b*, could be used with any fast mechanical switch in any circuit breaker. During the experiments, the TCA system operated approximately 1000 times to exclude stochastic phenomena and all results were consistently reproduced. Although TC driver *b* is a breakthrough for the efficient operation of TCAs with active damping, the active damping obtained is too weak to increase the armature speed. Hence, the laboratory prototype must be improved if faster interruption is required.

The active damping provided with TC driver *b* is highly dependent on R_σ , which has to be minimized. Carefully selecting and connecting the capacitors in parallel could reduce the total ESR considerably. A tightly integrated TCA system with smartly routed busbars could be advantageous and the TC driver should be as close to the TCs as possible. As

Fig. 21. Interruption test of an EAR DCCB.

shown above, an actuation time of 3.5 ms could already be achieved with a voltage in the range of 600 V and, hence, more compact capacitors than those used (rated for 2 kV) are available. Thyristors with very low ON-state resistance in the TC driver and optimized thyristor gate drivers could further reduce R_{σ} . To improve damping, the energy could be cycled multiple times in TC driver *b*. In contrast to actuation, the armature moves closer to the damping TC during active damping, thus improving electromagnetic coupling, such that subsequent weaker current pulses could affect damping. If the active damping obtained and above measures are insufficient at elevated speeds, active damping could also be combined with another damping system. Finally, the voltage is not only recycled after the acceleration current pulse, but also after the damping current pulse. The capacitors were charged to 30 % of the initial voltage with the initial polarity and this figure will be higher in an optimized TCA system, hence reducing the requirements on the DC power supply and charging circuit.

To improve the TCA system, a more sophisticated charging circuit capable of limiting inrush currents and controlling the charging process should be used. The weight of all moving parts should be minimized to decrease the required capacitive energy. Moreover, the strong holding mechanism needed reaccelerates the armature after active damping. The armature hits and damages the TCs, especially the insulation, and extra protection must be added. Because of mechanical oscillations, the TCA system could not be operated with stronger active damping limiting the armature speed. For this reason, the manufacturers should reinforce embedded poles.

Alternatively, actuators with a more steady force profile should be considered. The interruption tests of the EAR DCCB show that DCCBs can interrupt before the mechanical switch is fully open. Future research should quantify this overvoltage capability of mechanical switches, which can reduce the interruption time or the requirements on the actuator.

Many studies focus on the electromagnetic design of the TCA. The TCA used, on the contrary, was provided by a third-party and despite not being optimized for the embedded pole used performed acceptably. In a real TCA system, it is not unlikely that the inductance of the TCA is smaller than L_{σ} . Particular design aspects such as the armature and the number of turns in the TC are less important than previously assumed and other design aspects of a more practical nature as described above are equally important and must be considered from the beginning of the design process. For example, too long or too thin connections determining R_{σ} , L_{σ} , and, thus, the shape of the current pulses in the TCs could completely deteriorate the performance of the TCA.

VI. CONCLUSION

Even though all relevant DC circuit breakers (DCCBs) use a mechanical switch, the requirements on the actuator of the mechanical switch highly depend on the particular DCCB concept. The requirements on the actuator were derived, exemplary for an enhanced active resonant (EAR) DCCB, showing that the di/dt of the fault current has a drastic impact. In the EAR DCCB prototype, an industrial vacuum interrupter in an embedded pole is used as mechanical switch with a Thomson-coil (TC) actuator (TCA) with active damping. Extensive experimental studies show that the timing of active damping is crucial. Nonetheless, active damping worked for all tested actuation speeds by adjusting its timing. The experiments revealed that the elasticity of parts of the embedded pole limits the feasible actuation speed. The armature of the TCA oscillated and got stuck between the OPEN and CLOSED position if active damping was too strong. The operation of a novel TC driver recycling the energy needed to excite the TCA for active damping was demonstrated experimentally. The novel TC driver boosts the efficiency of the TCA system and it reduces the capacitive storage requirements by 50 %, the charging time, and the charging current. Moreover, the experiments demonstrated the proactive commutation and auto-reclosing operation of the TCA system as required in DC grids. The test of the EAR DCCB prototype proves that DCCBs can interrupt before the mechanical switch is fully open.

REFERENCES

- [1] D. Jovicic, D. v. Hertem, K. Linden, J. Taisne, and W. Grieshaber, "Feasibility of DC transmission networks," in *2011 2nd IEEE PES Int. Conf. and Exhib. on Innovative Smart Grid Technologies*, Dec. 2011, pp. 1–8.
- [2] C. M. Franck, "HVDC Circuit Breakers: A Review Identifying Future Research Needs," *IEEE Trans. Power Del.*, vol. 26, no. 2, pp. 998–1007, Apr. 2011.
- [3] K. Tahata, S. El Oukaili, K. Kamei, D. Yoshida, Y. Kono, R. Yamamoto, and H. Ito, "HVDC circuit breakers for HVDC grid applications," in *11th IET Int. Conf. on AC and DC Power Transmiss.*, Birmingham, Feb. 2015, pp. 1–9.

- [4] J. Häfner and B. Jacobson, "Proactive Hybrid HVDC Breakers - A key innovation for reliable HVDC grids," in *CIGRÉ Symp.*, vol. 264, Bologna, Sep. 2011.
- [5] T. Augustin, M. Becerra, and H.-P. Nee, "Enhanced Active Resonant DC Circuit Breakers Based on Discharge Closing Switches," *IEEE Trans. Power Del.*, pp. 1–9, Aug. 2020, doi: 10.1109/TPWRD.2020.3014084.
- [6] S. Tokoyoda, T. Inagaki, F. Page, M. Sato, K. Kamei, M. Miyashita, and H. Ito, "Interruption characteristics of vacuum circuit breaker and the application to DCCB," in *13th IET Int. Conf. on AC and DC Power Transmiss.*, Manchester, Feb. 2017, pp. 1–5.
- [7] A. Bissal, J. Magnusson, and G. Engdahl, "Comparison of Two Ultra-Fast Actuator Concepts," *IEEE Trans. Magn.*, vol. 48, no. 11, pp. 3315–3318, Oct. 2012.
- [8] C. Peng, X. Song, A. Q. Huang, and I. Husain, "A medium-voltage hybrid dc circuit breakerpart II: Ultrafast mechanical switch," *IEEE Trans. Emerg. Sel. Topics Power Electron.*, vol. 5, no. 1, pp. 289–296, 2017.
- [9] G. Engdahl, J. Magnusson, A. Bissal, and M. Sparr, "An Exploratory Study of the Retardation Ability of a Thomson Coil Actuator," in *15th Int. Conf. on New Actuators*, Bremen, Jun. 2016, pp. 1–4.
- [10] C. Peng, L. Mackey, I. Husain, A. Huang, W. Yu, B. Lequesne, and R. Briggs, "Active Damping of Ultrafast Mechanical Switches for Hybrid AC and DC Circuit Breakers," *IEEE Trans. Ind Appl.*, vol. 53, no. 6, pp. 5354 – 5364, Aug. 2017.
- [11] D. S. Vilchis-Rodriguez, R. Shuttleworth, A. C. Smith, and M. Barnes, "Design, Construction, and Test of a Lightweight Thomson Coil Actuator for Medium-Voltage Vacuum Switch Operation," *IEEE Trans. Energy Convers.*, vol. 34, no. 3, pp. 1542–1552, Mar. 2019.
- [12] Z. Zhu, Z. Yuan, L. Chen, J. He, and Z. Zhu, "Vibration Characteristics of Thomson Coil Actuator Based on Simulation and Experiments," *IEEE Trans. Energy Convers.*, vol. 35, no. 3, pp. 1228–1237, Mar. 2020.
- [13] C. Peng, A. Huang, I. Husain, B. Lequesne, and R. Briggs, "Drive circuits for ultra-fast and reliable actuation of Thomson coil actuators used in hybrid AC and DC circuit breakers," in *2016 IEEE Appl. Power Electron. Conf. and Expo. (APEC)*, Long Beach, Mar. 2016, pp. 2927–2934.
- [14] D. S. Vilchis-Rodriguez, R. Shuttleworth, A. C. Smith, and M. Barnes, "Performance of high-power thomson coil actuator excited by a current pulse train," *J. Eng.*, vol. 2019, no. 17, pp. 3937–3941, Jun. 2019.
- [15] T. Augustin, M. Parekh, J. Magnusson, M. Becerra, and H.-P. Nee, "System Design of Fast Actuator for Vacuum Interrupter in DC Applications," in *2018 28th Int. Symp. on Discharges and Elect. Insul. in Vacuum (ISDEIV)*, vol. 2, Sep. 2018, pp. 527–530.
- [16] T. Augustin, I. Jahn, S. Norrga, and H.-P. Nee, "Transient Behaviour of VSC-HVDC Links with DC Breakers Under Faults," in *19th Eur. Conf. on Power Electron. and Appl. (EPE'17 ECCE Europe)*, Warsaw, Sep. 2017, pp. 1–10.