Postprint

Enhanced Active Resonant DC Circuit Breakers Based on Discharge Closing Switches

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Abstract—Direct current circuit breakers (DCCBs) have become a large research topic and are considered one of the critical components for future DC grids. Proposed DCCB concepts may be grouped into hybrid DCCBs and active resonant DCCBs. In this work, the enhanced active resonant (EAR) DCCB family is introduced. EAR DCCBs combine elements of hybrid and active resonant DCCBs. The EAR DCCB family consists of one unidirectional and six bidirectional concepts. All concepts feature proactive commutation. The main characteristic of the EAR DCCBs is that discharge closing switches are used instead of semiconductors with turn-off capability. Relevant discharge closing switch technology is reviewed, a laboratory prototype is explained, and experimental results are presented to demonstrate the feasibility of the proposed DCCB concepts.

Index Terms—DC circuit breakers, HVDC circuit breakers, DC power systems, Spark gaps, Gas discharge devices.

I. INTRODUCTION

HIGH-voltage direct current (HVDC) transmission is an established technology for bulk electrical power transmission. HVDC and medium voltage DC will play a significant role in the future power system [1], [2]. A remaining challenge is the handling of DC faults. If line commutated converters (LCCs) or modular multilevel converters (MMCs) with fault blocking submodules are used, the fault current may be controlled to zero. With half-bridge (HB)-MMCs, this is not possible and the converter has to be blocked if the arm currents become excessively high, leading to uncontrolled rectifier operation and a steeply rising fault current. HB submodules are cheaper and more efficient compared to other submodule types. In contrast to LCCs, HB-MMCs allow for flexible control of reactive power and connection to weak AC systems. Hence, the HB-MMC is the most prospective HVDC converter. In HB-MMC point-to-point links, the AC-side AC circuit breakers (ACCBs) are opened in a DC fault case. This solution is not appropriate for meshed HVDC grids and point-to-point links with overhead lines where temporary faults may occur frequently [3]. Thus, the availability of DC circuit breakers (DCCBs) is critical for future DC systems.

Electric circuits are interrupted by a medium whose properties can quickly change from conductive to insulating. Only two practical options are used nowadays: A plasma such as an electric arc or semiconductors. Arcs have been used in ACCBs for over a century. In DC systems, the main challenge is that currents do not cross zero naturally and arcs would keep

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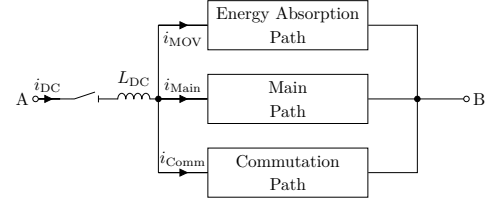M. Becerra is also with ABB Corporate Research, Västerås, Sweden, Forskargränd 7, 722 26 Västerås.

Fig. 1: General structure of DCCBs

burning in ACCBs. The general DCCB structure shown in Fig. 1 solves this problem. In normal operation, only the main path conducts. The inductor L_{DC} limits the rate of rise of the fault current. If the DCCB is tripped, the DCCB current i_{DC} is commutated from the main path to the commutation path. After a delay, i_{DC} commutates to the energy absorption path, which usually consists of metal-oxide varistors (MOVs). When the MOVs start to conduct, a voltage higher than the system voltage is inserted which drives i_{DC} to zero. A disconnector interrupts the residual MOV current.

An overview of DCCB development is given in [4]. One of the earliest solutions is the active resonant DCCB, where an LC circuit with a pre-charged capacitor is placed in the commutation path in parallel to the mechanical switch in the main path [5]. If the injection switch is closed, the LC circuit injects a counter current which causes a current zero crossing in the arcing mechanical switch. At the time of invention of active resonant DCCBs, developments aimed at multi-terminal LCC grids. Interest in such grids was lost. After the advent of voltage source converters for HVDC transmission in the new millennium, interest in HVDC grids and also DCCBs sparkled again. Research on active resonant DCCBs was picked up again [6], [7]. A problem of active resonant DCCBs is the pre-charging of the LC circuit. Several alternative concepts have been proposed to solve the pre-charging issue [8]–[10]. Moreover, the LC circuit can be bulky and its circuit parameters are dictated by the $\mathrm{d}i/\mathrm{d}t$ and $\mathrm{d}u/\mathrm{d}t$ limitations of the mechanical switches at current zero. The $\mathrm{d}i/\mathrm{d}t$ capability at current zero is higher in vacuum interrupters (VIs) than in SF6 interrupters [11] and hence VIs are preferable. VIs are rated for medium voltage and thus, depending on the DC grid voltage, several VIs have to be connected in series. In an emerging DCCB research direction, a change from plasma to semiconductor as interruption medium was made. A pure semiconductor breaker would be unmatched fast and could interrupt DC without the need for a current zero crossing, but it would exhibit comparably high losses. A solution are hybrid DCCBs which combine mechanical switches and power

electronics to interrupt DC. For instance, a hybrid DCCB was described with an ultra-fast disconnector (UFD) and a low-voltage semiconductor valve, called load commutation switch (LCS), in the main path and IGBT stacks in the commutation path [12]. Turning off the LCS commutates i_{DC} to the commutation path. Hybrid DCCBs have low on-state losses compared to solid-state DCCBs, although the number of semiconductors is similarly high and thus drives the cost up. Several hybrid DCCB concepts with comparable performance have been published [13]–[17], which nonetheless suffer from the same problems. In [18]–[20], the IGBTs in the commutation path were replaced with thyristors which are turned off with current injection. The LCS causes losses in normal operation. If an arcing mechanical switch with sufficiently high arc voltage is used in the main path, an LCS is not needed [21]–[23]. In [24], the LCS is connected between the main path and the commutation path to reduce the losses.

However, the paradigm change from arc to semiconductor as interruption medium in DCCBs is questionable, because power semiconductor devices are made to switch with a switching frequency. DCCBs operate seldom and during the interruption its semiconductors would only switch twice. After the invention of solid-state switches, these replaced discharge tubes almost entirely. For instance, the thyristor replaced mercury-arc valves in early LCCs. Interestingly, a tube-based DCCB concept for HVDC was proposed in the 70s [25] that is very similar to a hybrid DCCB without LCS. The main difference is that a crossed-field tube is used in the commutation path instead of semiconductors. The physics of the crossed-field tube are described in [26]. As most of the tube technology, the crossed-field tube DCCB was forgotten as well. In recent years, the application of tubes in DCCBs has received increased attention again. A DCCB similar to a hybrid DCCB with a tube that can switch on and off is proposed in [27].

In this work, DCCBs are proposed in which discharge closing switches (DCSs) replace semiconductors with turn-off capability in the commutation path. DCSs are used in pulsed power applications and are available for higher voltage and current ratings compared to semiconductors. The proposed concepts feature characteristics of both hybrid DCCBs and active resonant DCCBs to provide advanced functionality and high reliability at low cost. Furthermore, DCCB concepts with asymmetric interruption capability in both interruption directions are introduced. The structure of this work is as follows. In Section II, selected DC grid protection aspects are discussed. In Section III, DCSs and their capabilities are reviewed. In Section IV, the proposed DCCB concepts are described. In Section V, experimental results are presented to demonstrate the feasibility of the proposed DCCB concepts. Lastly, all findings are summarized in Section VII.

II. MULTITERMINAL DC GRID PROTECTION CONSIDERATIONS

DC grid protection affects the requirements on the DCCBs and in turn, DCCBs may offer special features that affect DC grid protection. In this section, several aspects are discussed that are interesting for novel DCCB concepts.

A. Proactive Commutation

One of the main operational differences on the system level between the general DCCB and a typical hybrid DCCB is a mode named *proactive tripping* in [12]. This means that i_{DC} is already commutated from the main path to the commutation path without external trip signal, if the internal DCCB protection detects a potential fault. After that, the UFD is opened such that the DCCB can immediately insert the MOV if the DCCB is tripped. Proactive tripping has two very important implications. Firstly, it is very effective to compensate for protection delay [28]. This is only important for non-negligible protection delay. For protection delay $\geq 2\,\text{ms}$, which corresponds to the opening time of the UFD, a DCCB with proactive tripping interrupts as fast as a solid-state DCCB. Secondly, it also provides a measure to handle DCCB failure in HVDC grids. DCCBs on lines connected to the same bus are also ready to interrupt and may interrupt quickly, if it is detected that a DCCB on an adjacent line has failed. However, these DCCB units may not trip proactively depending on the grid structure. Therefore, it is suggested to provide external proactive trip signals between DCCBs on the same bus to allow for fast spread of information and to rename the mode to *proactive commutation*. If a DCCB is in proactive commutation mode and does not receive the trip signal from the DC system protection in a specified time, the event that caused the internal DCCB protection to react is assumed to be a temporary fault that is over and does not pose a threat to the DC system any longer. The DCCB has to be able to abort proactive commutation by commutating i_{DC} back from the commutation path to the main path to resume normal operation.

B. Directional Current Breaking Requirements

DCCBs can be unidirectional or bidirectional, i.e. interrupt current only in one direction or in both directions. For many hybrid DCCBs, bidirectionality requires that additional semiconductors are placed anti-parallel in the commutation path. Thus, the semiconductor expenditure doubles. Active resonant DCCBs can interrupt in both directions independent of the polarity of the voltage of the pre-charged capacitor. In one direction, the current injection causes a current zero in the first half cycle of the oscillation. In the other direction, the oscillating current will add to the fault current in the main path in the first half cycle and then lead to a zero crossing in the second half cycle. With regards to Fig. 1, interruption with $i_{DC} > 0$ and $i_{DC} < 0$ are called normal interruption and reverse interruption, respectively. If a DC line fault occurs in a DC grid, DCCBs on a faulty link see a positive i_{DC} while DCCBs on the healthy lines see positive or negative i_{DC}, see Fig. 2. Hence, DCCBs only have to reverse interrupt in case of DCCB failure on the faulty link as backup measure or if DCCBs are not placed at the end of each line. If a DC bus fault occurs, DCCBs in a grid and one DCCB in a point-to-point link would see a negative i_{DC}. The line inductors would only limit the infeed from other lines. The converter would supply the majority of the fault current. In most publications, the arm inductors of an MMC in a DC grid are smaller compared to
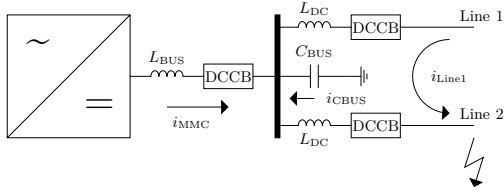
Fig. 2: HVDC converter bus with fault on line 1

the line inductors and thus the fault current would increase more steeply compared to a DC line fault. One option would be to use a DC bus DCCB as indicated in Fig. 2, but the requirements would be extreme. The more reasonable option could be reverse interruption of the line DCCBs and opening of the ACCB of the converter adjacent to the DC bus fault.

The needed current breaking capability of DCCBs is less for reverse interruption compared to normal interruption [29]. This can be explained as follows. If the DCCB on a faulty line fails, the current infeed from the adjacent lines is relatively small compared to the infeed from the converter as the healthy lines have line inductors as well. Thus, proactive commutation may not be needed for reverse interruption. If the protection delay is small, proactive commutation may not be needed for normal interruption either. However, proactive commutation for reverse interruption may improve system stability in both cases, since DC faults cause severe voltage oscillations and faster backup protection may be needed. Overall, cases arise where proactive commutation is only needed for one interruption direction. These facts can be exploited to design DCCBs with asymmetric current interruption capability.

III. Review of Discharge Closing Switch Technology

Switches can be either opening or closing switches. Opening switches can be opened with current flowing. A closing switch can be closed, but not opened when it conducts as it cannot interrupt current. Closing switches may be mechanical switches, DCSs or solid-state devices. Solid-state devices like thyristors have replaced most DCSs. Thyristors can conduct large currents, but their hold-off voltage is currently limited to $10.5\,\mathrm{kV}$. DCSs are either gas-filled or of vacuum type. Gas-filled DCSs operate either based on a glow or arc discharge at low or high pressure on the left or right side of the minimum of the Paschen curve, respectively, which largely influences their operating characteristics. In vacuum DCSs, an arc discharge is required as thermoionization must provide a sufficient amount of charge carriers. In contrast to solid-state switches, the impulse voltage ratings of DCSs are significantly higher than their hold-off voltage. Hybrid DCCBs have to be overrated due to the MOV voltage during interruption and this may not be necessary for DCSs. DCSs are briefly reviewed as a DCS is the core element of the DCCB concepts that are introduced in Section IV. Countless DCSs have been proposed and only basic types that are available commercially for $40\,\mathrm{kV}$ and higher are covered in this review. Considering VI ratings, medium voltage DCCBs without series connection of active

switches are viable. For a more detailed review of DCSs, the reader is referred to [30], [31].

A. Triggered Spark Gap

Triggered spark gaps (TSGs) often have an auxiliary electrode to cause dielectric breakdown in the main gap. In a trigatron, the trigger electrode is contained within one or both of the main electrodes. The trigger electrode can also be placed between the main electrodes. An alternative is laser triggering. To avoid series connections, high-voltage high-pressure TSGs have to be used. The increased arc voltage would, however, make commutation to the commutation path difficult. Vacuum TSGs instead are interesting due to the low arc voltage and high $\mathrm{d}i/\mathrm{d}t$ capability at current zero. Since their hold-off voltage is limited they require series connections at high-voltage. The needed high triggering voltage is disadvantageous. Vacuum TSGs rated for currents $10\,\mathrm{kA}$ to $300\,\mathrm{kA}$, charges $5\,\mathrm{C}$ to $500\,\mathrm{C}$, and $40\,\mathrm{kV}$ hold-off voltage are described in [32].

B. Thyratron & Pseudospark Gap

Thyratrons are a type of DCS derived from early vacuum tubes but operating under high power. They are nevertheless filled with different gases at low-pressure and use a heated cathode. Thyratrons can switch with a frequency in the kilohertz-range, but their average current is limited allowing currents pulses with a duration of a few microseconds. It has been projected that they could handle a peak voltage $200\,\mathrm{kV}$ to $350\,\mathrm{kV}$, a peak current $100\,\mathrm{kA}$ to $200\,\mathrm{kA}$, and an average current $0.5\,\mathrm{kA}$ in the future [31]. Pseudospark gaps, or cold-cathode thyratrons, are low-pressure gas-filled DCSs with a hollow anode and cathode which extend the capabilities of thyratrons. They feature high $\mathrm{d}i/\mathrm{d}t$, high charge capability, reverse current conduction without electrode damage, and are rated up to $150\,\mathrm{kV}$. The plasma in a pseudospark gap is a superdense glow discharge and erosion is not a limitation due to the diffuse nature of this discharge. Multi-channel devices with several hollows increase current ratings. In [33], a multi-gap pseudospark gap with a modular structure for higher hold-off voltage is described. Back-lighted thyratron (BLT) are optically triggered pseudospark gaps. A flashlamp or laser triggers the BLT by UV light on the cathode and electrons from photoionization start a superdense glow discharge. BLTs can carry currents up to of $80\,\mathrm{kA}$. In [34], a multi-gap BLT for higher hold-off voltage $100\,\mathrm{kV}$ and $70\,\mathrm{kA}$ is described.

C. Ignitron

The ignitron is a DCS with a liquid metal cathode. Mercury is used as it is already liquid at room temperature. An ignitor electrode is in contact with the mercury pool. Triggering the ignitron vaporizes and ionizes the liquid mercury. The plasma spreads into the main gap and causes an arc between anode and cathode. Ignitrons have a low voltage drop and a low minimum operating voltage. Two types of ignitrons exist: grid-frequency units and units that can conduct high peak, high coulomb currents. Grid-frequency ignitrons have been

replaced by thyristors. High-current ignitrons require water cooling and can only be switched a few times per minute as the mercury vapor has to condense back into the mercury pool. The ignitron's performance is limited in high current, high coulomb discharges due to plasma instability, high voltage drop, and possible ignitor resistance collapse [35]. This can be solved by using a hollow anode. The toxicity of mercury is problematic and replacing it with gallium is an option [36].

IV. ENHANCED ACTIVE RESONANT DCCB CONCEPTS

The basic idea of the proposed concepts is to replace semiconductors with turn-off capability in the commutation path of hybrid DCCBs by a DCS. An injection circuit or pulse generator as in active resonant DCCBs is used to guarantee turn-off and all proposed concepts offer proactive commutation. For these reasons, the proposed DCCB concepts are here referred to as *enhanced active resonant* (EAR) DCCBs.

A. Unidirectional Concept

The proposed unidirectional EAR concept in its different operation states during interruption is illustrated in Fig. 3, where gray path indicate conducting branches. The corresponding internal DCCB currents are depicted in Fig. 3i. Diode D and a DCS are used in the commutation path. D and DCS have to be rated to withstand the MOV voltage. The point between D and DCS is connected to a grounded RC circuit consisting of the resistor R_{DCS} and the capacitor C_{DCS} to provide a high-voltage potential at the terminal of DCS. An injection circuit is needed to extinguish the arc in DCS by forcing a current zero crossing. For instance, the injection circuit can be realized with a pre-charged capacitor C_C, an inductor L_C, and a closing switch S_C as in conventional active resonant DCCBs.

D acts as a rectifier and C_{DCS} is charged up to the line voltage (Fig. 3a). R_{DCS} is required to limit the charging current. In normal operation, only UFD and LCS are closed (Fig. 3b). If i_{DC} surpasses the proactive commutation threshold, DCS is triggered and the RC circuit injects a current into DCS with an appropriate time constant. LCS is turned off to commutate i_{DC} from the main path to the commutation path (Fig. 3c). The charge from C_{DCS} is needed to sustain the plasma state in DCS, because the discharge could otherwise extinguish due to its formative delay and the commutation delay. For this purpose, the RC circuit can be dimensioned like a small snubber circuit with a very high R_{DCS} and very low C_{DCS} as the required current is extremely small compared to i_{DC} and the total delay is in the microseconds range. When i_{DC} has completely commutated from the main path to the commutation path, UFD is opened as well (Fig. 3d). When UFD is fully opened or its dielectric withstand capability is sufficient, the DCCB enters the tripping mode, if an external trip signal is received or if the maximum DCCB current is reached. If the tripping mode has not been entered after a set time and i_{DC} decreased below the proactive commutation threshold, first UFD and then LCS are closed to return to normal operation. In tripping mode, S_C is closed to inject a current into DCS to force the DCS current to zero (Fig. 3f).
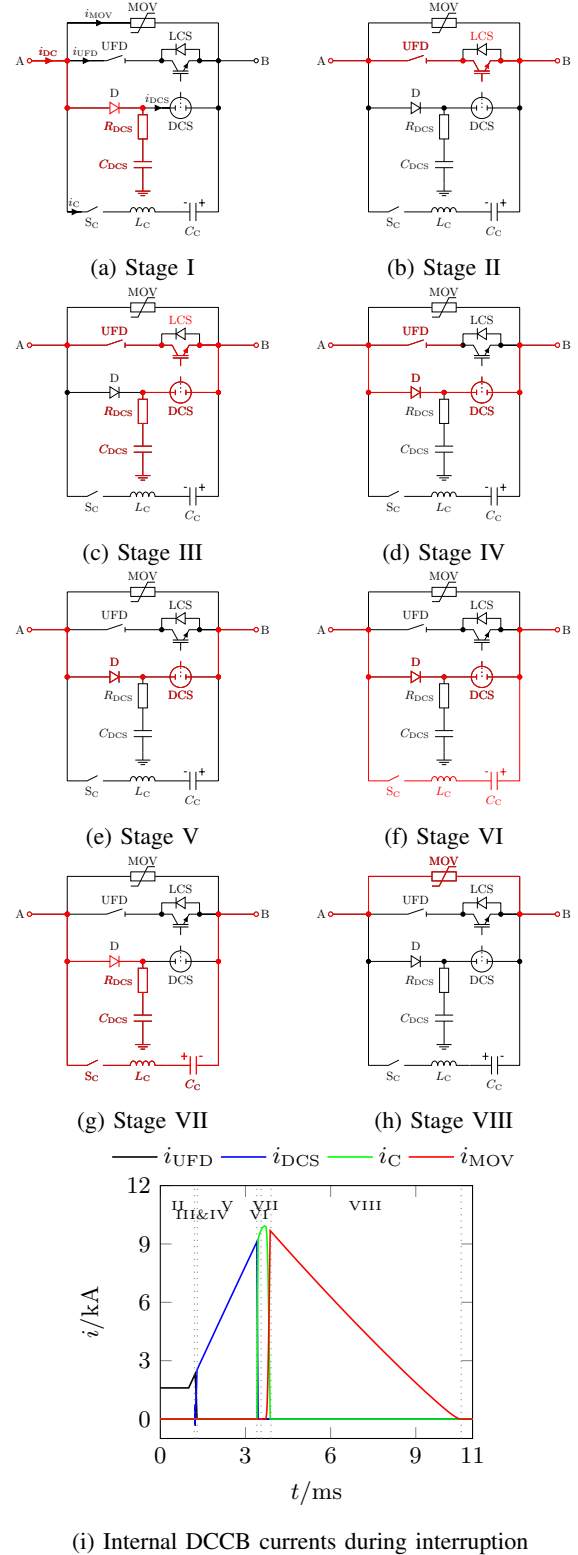

(a) Stage I   (b) Stage II

(c) Stage III   (d) Stage IV

(e) Stage V   (f) Stage VI

(g) Stage VII   (h) Stage VIII

(i) Internal DCCB currents during interruption

Fig. 3: States of unidirectional EAR DCCB during interruption

C_{DCS} and C_C recharge from the line (Fig. 3g) until MOV clips the voltages of the capacitors and inserts a counter voltage, which forces i_{DC} to zero (Fig. 3h).

In a cable system, the line disconnector interrupts the residual MOV current to prevent thermal overloading. In

overhead line systems, auto-reclosing is attempted after a system-dependent deionization time without opening the line disconnector. Auto-reclosing is only attempted with the DC-CBs adjacent to a rectifier. The operation sequences for auto-reclosing and system start-up are the same. C_{DCS} is recharged from the line through D. C_C is still reversely charged after interruption and the pre-charging circuit of the injection circuit has to reverse the voltage polarity as, for instance, in [9] or recharge C_C as in conventional active resonant DCCBs. Voltage polarity reversal is advantageous as it takes a few hundred microseconds up to a few milliseconds. If C_C's voltage should not be sufficient at that time, auto-reclosing has to be delayed until the pre-charging circuit topped up C_C's voltage sufficiently. DCS is triggered and the line is energized. If i_{DC} does not increase beyond a defined threshold, or triggering DCS is unsuccessful due to a high load impedance, the fault is assumed to be cleared. C_{DCS} recharges again. LCS and UFD are closed to resume normal operation. Otherwise, tripping mode is resumed.

B. Bidirectional Concepts with Injection Circuit

The unidirectional concept is mirrored with several adaptions to obtain a DCCB with symmetrical bidirectional current breaking capability as shown in Fig. 4a. Two UFDs and two unidirectional LCSs are needed. Thus, the semiconductor expenditure is the same as for the LCS in [12]. The half of the main path away from the fault side remains turned on when the other one turns off. The two LCSs share a low-voltage protection MOV to ensure that the LCSs are not destroyed by overvoltage and to guarantee commutation from the main path to the commutation path. The operation sequence is the same as for the unidirectional concept for both interruption directions. Connecting the injection circuit in parallel with DCS complicates interruption. Throughout the DCCB operation, DCS and the diode towards the fault-side terminal would essentially be in parallel, so that a part of the current from the injection circuit goes through this diode when the voltage of C_C becomes negative. As solution, the injection circuit can be connected to ground with two closing switches $S_{C,1}$ and $S_{C,2}$ to obtain EAR concept A shown in Fig. 4b. Depending on the fault side, either $S_{C,1}$ or $S_{C,2}$ is closed for current injection.

An alternative is the bidirectional EAR concept B with asymmetric current breaking capability shown in Fig. 4c. The concept works as the unidirectional concept in the normal interruption direction and as an active resonant DCCB in the reverse interruption direction. To achieve this, an arcing mechanical switch, for instance a VI, has to be used as S in the main path instead of an UFD. When operating as the unidirectional EAR concept, S opens without arcing nonetheless. Proactive commutation is only possible in one interruption direction. The LCS is unidirectional. The injection circuit is charged in the depicted direction to cause a current zero crossing in DCS in the first half of the current injection period similar to the unidirectional concept. No means are provided to reverse the voltage. Thus, S_C and the LCS have to be able to sustain the sum of the DCCB current and

(a) Unidirectional EAR DCCB mirrored
(b) Bidirectional A

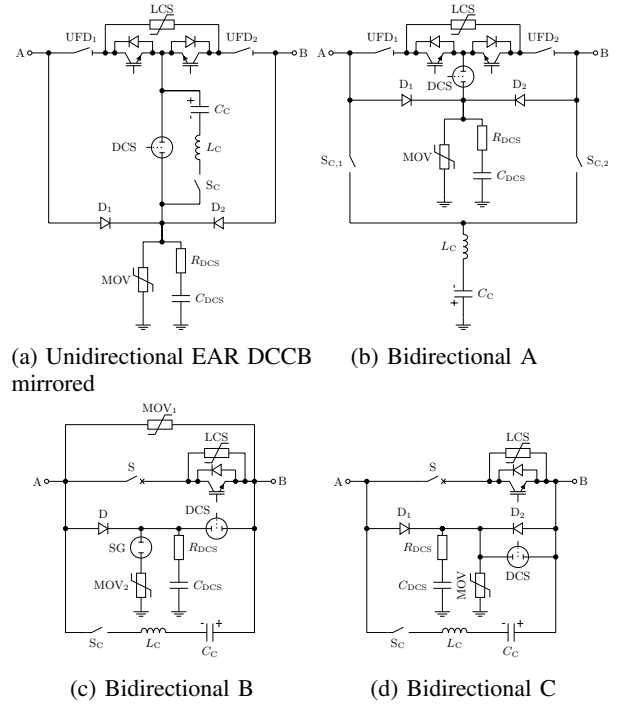(c) Bidirectional B
(d) Bidirectional C

Fig. 4: Bidirectional EAR DCCBs with injection circuit

the injected current for one half period when interrupting negative i_{DC}. If a temporary fault occurs towards terminal B, the DCCB can commutate proactively. When the fault disappears after a few milliseconds, the potential of terminal B changes from close to ground to the DC line voltage and the output impedance of the DCCB may be in the same order of magnitude as R_{DCS}. Significant current flow in the RC branch would lead to severe overvoltage, because MOV_1 is not in parallel to the RC circuit as in the other proposed bidirectional concepts. Therefore, the spark gap SG and MOV_2 in parallel to the RC branch are needed for overvoltage protection. MOV_1 is dimensioned to absorb the system energy and MOV_2 is dimensioned for overvoltage protection, but also absorbs parts of the system energy. It is not possible to move MOV_1 to replace MOV_2 as MOV_1 must also be available to absorb the system energy for reverse interruption.

EAR concept C shown in Fig. 4d is a modification of EAR concept B. Diode D_2 in parallel to DCS makes MOV available for reverse interruption and allows charging C_{DCS} from terminal B as well. If DCS is realized as series connection of DCSs, diode stacks in parallel to each DCS allow for zero-voltage switching as described for VIs in [8]. Only one MOV is required for overvoltage limitation and energy absorption. EAR concept B and C are operated in the same way.

C. Bidirectional Concepts with Pulse Generator

A power supply to pre-charge C_C at high voltage potential could be complicated and expensive. A solution is to use a pulse generator that is charged from the DC line [8]. This pulse generator is also beneficial for auto-reclosing operation because fast recharging of C_C is required and because voltage

reversal is not required. Such a pulse generator is used in EAR concept D, E, and F. As described in [8], the MOV can also limit overvoltage on the DC line in such a three-terminal configuration. EAR concept D is shown in Fig. 5a. The main path consists of one UFD and a bidirectional LCS as the hybrid DCCB in [12]. Due to the three-terminal structure, two DCSs are required. To commutate proactively, either DCS_1 or DCS_2 is triggered depending on the current direction. If the DCCB is tripped, S_C is closed which injects a counter current through C_C, L_C, and diodes D_4 and D_5 into the arcing DCS and the diode in parallel to the DCS which has not been triggered. The diodes D_1, D_2, and D_3 allow charging of the capacitors C_C and C_{DCS} as in the other EAR concepts. D_1 and D_2 are connected in parallel to the arcing elements DCS_1 and DCS_2, which allow for zero-voltage switching when the pulse generator injects current to force the current to zero.

EAR concept E is depicted in Fig. 5b. In contrast to concept D, UFD and bidirectional LCS have been replaced by the mechanical switches S_1 and S_2 which may sustain arcing and two unidirectional LCSs, LCS_1 and LCS_2. Diode D_1 is connected from the midpoint of the two LCSs to the top of the pulse generator to get a three-terminal structure in the main path and to provide a charging path for the pulse generator. To commutate proactively, DCS_1 or DCS_2 is triggered and the LCS in the corresponding parallel branch is turned off. The mechanical switch in series with the turned off LCS is opened, whereas the other mechanical switch and LCS stay closed/turned on. The current commutates from one segment of the main path through D_1 to the triggered DCS, but continues to flow in the other segment of the main path. Removing LCS_1 and DCS_1 from EAR concept E yields EAR concept F with asymmetrical current breaking capability. Mechanical switch S_1 has to sustain arcing and mechanical switch S_2 may sustain arcing.

D. Load Current Interruption & High Impedance Faults

Load current interruption and high impedance faults are uncritical scenarios that only require a relatively low current to be interrupted compared to low impedance faults. Proactive commutation is not needed in these scenarios. DCSs have a minimum operating voltage. This means that a DCS cannot be closed if the potential difference from anode to cathode is smaller than the minimum operating voltage. C_{DCS} is charged above the line voltage due to the rectifying effect of the connected diodes. The voltage decrease on the faulty line depends on the fault impedance. Possibly, the voltage across the DCS may not be sufficient for closing in case of load current interruption or high fault impedance and commutation to the commutation path fails. If this happens, EAR concepts B, C, E, and F with arcing mechanical switches in the main path are advantageous. They can still interrupt as an active resonant DCCB in both directions, which is sufficient to handle these uncritical scenarios.

V. EXPERIMENTAL RESULTS

In order to demonstrate the operation of EAR DCCBs, a simplified laboratory prototype of bidirectional concept C from

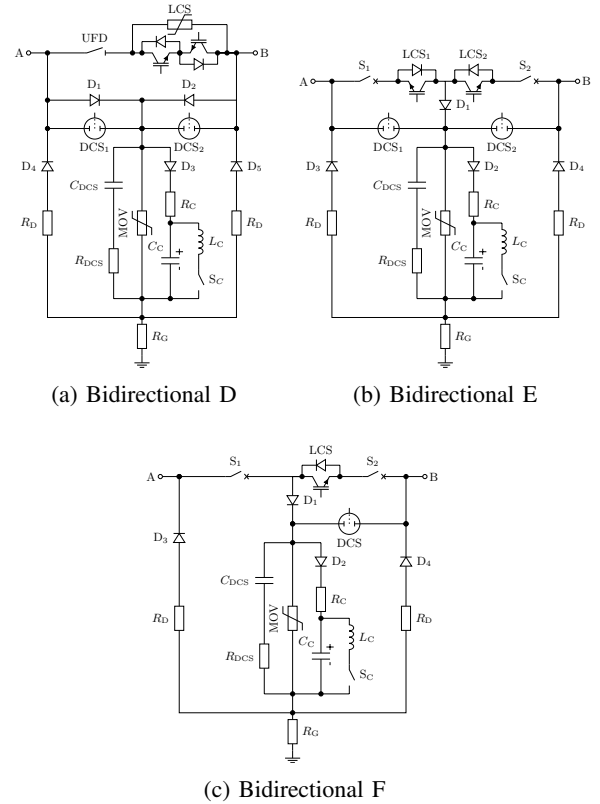(a) Bidirectional D (b) Bidirectional E

(c) Bidirectional F

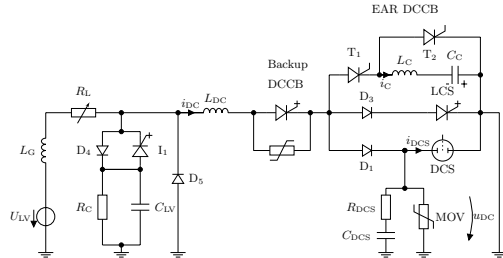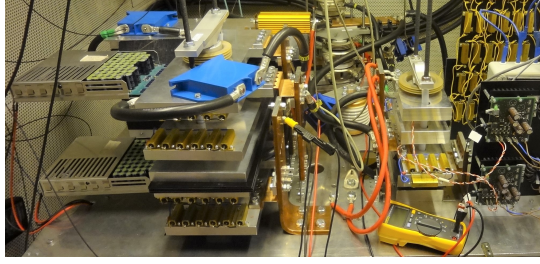Fig. 5: Bidirectional EAR DCCBs with a pulse generator

Fig. 6: Advanced test circuit for EAR DCCB

Fig. 4d has been constructed. The studies of commutation between the main path and DCS are, nevertheless, representative for all proposed EAR DCCBs. The prototype is rated to withstand $2.4\,kV$ and to interrupt $6.2\,kA$. The prototype has been tested using the DCCB test circuit from [37] shown in Fig. 6 which allows replicating scenarios consisting of combinations of load current, faults, and temporary faults. It also enables testing the proactive commutation mode and its abortion. The parameters of the test circuit are given in Tab. I. Currently, it allows interruption tests up to $I_F = 1.2\,kA$ and the peak voltage across the DCCB depends on the voltage-current characteristic of the chosen MOV.

The prototype is depicted in Fig. 7a. The back-up DCCB is integrated in the EAR DCCB prototype due to practical reasons. The solid-state backup DCCB and LCS are ABB 5SHY 35L4521 IGCTs. A $25\,kV$ and $60\,C$ per pulse vacuum TSG from VEI-AVIS was used as DCS, see Fig. 7b, with its corresponding triggering unit. The main reason for this choice

TABLE I: Parameters of DCCB test circuit and EAR DCCB

I_{DC}/A	I_F/A	U_{LV}/kV	U_{HV}/kV	L_{DC}/mH	C_{LV}/mF	R_C/kΩ	R_L/Ω	R_{DCS}/Ω	C_{DCS}/µF	L_C/µH	C_C/µF
150	1200	0.5	2.8	1.4	11.2	10	3.3	5	10	9	60

(a) Prototype EAR DCCB
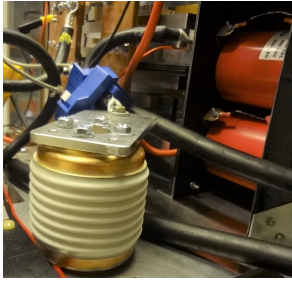
(b) Close-up of vacuum TSG, C_{DCS} in background

Fig. 7: Prototype EAR DCCB

Fig. 8: EAR DCCB currents and voltage during interruption

Fig. 9: EAR DCCB currents during temporary fault

was that it is commercially available for the required ratings without the need for a cooling system. Diode D_2 has not been included in the prototype as current interruption is tested only in one direction. The closing switch S_C is realized as thyristor T_1. The voltage swing approach from [9] was adapted with thyristor T_2 to avoid an extra power supply for C_C. Thus, C_C is charged by first firing thyristor T_1 while the backup DCCB is closed before the test scenario starts. Then T_2 is fired to reverse the polarity of C_C's voltage shortly before interruption. Mechanical switch S is not included in the prototype. The counter current would freewheel through the main path after the current zero in DCS due to the intrinsic anti-parallel diode in IGCT LCS and the absence of S. To prohibit this, an extra diode D_3 is added in series with LCS. D_1 and D_3 are realized with ABB D1961SH diodes.

Not having S in the test does not impact the measurements as S would operate without arcing and its contact resistance is negligible. S will be realized as VI in future tests. A mock VI has been included in the control platform that emulates the VI and its actuator. The mock VI has the same interface as the control system of the VI that will be used. This interface enables communicating with the control system of the DCCB. The relevant parameters have been extracted from simulations of a prototype VI actuator system [38]. The opening and closing time of the VI will be $3.5\,\mathrm{ms}$ and $4\,\mathrm{ms}$, respectively. The values deviate from the ones reported in [38] due to minor design changes. To interrupt, current injection is started after an interruption delay of $2\,\mathrm{ms}$ which can be shorter than the
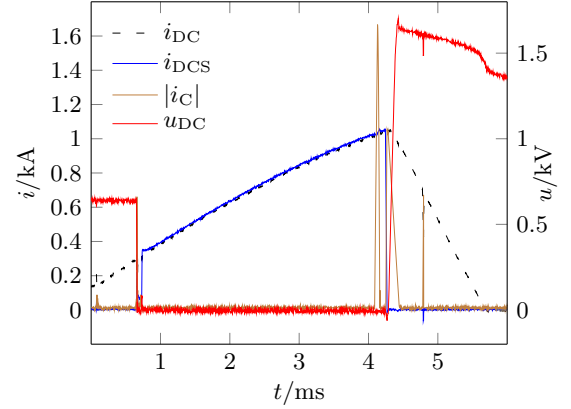
actuation time due to the high impulse voltage rating of VIs.

The results from an interruption capability test are shown in Fig. 8. The proactive commutation and interruption threshold were set to $0.25\,\mathrm{kA}$ and $1\,\mathrm{kA}$ for the tests, respectively. The test current i_{DC} increases such that the proactive commutation threshold is surpassed at $t = 0.7\,\mathrm{ms}$ and DCS is triggered. The RC circuit injects a small current into DCS and after a $50\,\mathrm{µs}$ delay LCS is turned off to completely commutate i_{DC} from LCS to DCS. At $t = 4\,\mathrm{ms}$, the interruption delay is over and the interruption threshold is surpassed and T_2 is fired to reverse the polarity of C_C's voltage. After a delay of $50\,\mathrm{µs}$ to allow T_2 to turn off, T_1 is fired to inject the counter current into DCS to extinguish its arc. Then i_{DC} recharges C_C and C_{DCS} until MOV starts to conduct which inserts the counter voltage u_{DC} to interrupt i_{DC}. EMI noise is recognizable at $t = 0.7\,\mathrm{ms}$ and $t = 4.8\,\mathrm{ms}$ due to the triggering of DCS and insertion of MOV, respectively.

In case of a temporary fault, i_{DC} increases and then decreases again before the interruption threshold is reached. The results for a temporary fault are shown in Fig. 9. When i_{DC}

surpasses the proactive commutation threshold at $t = 0.7\,\mathrm{ms}$, i_{DC} is commutated from LCS to DCS. If no external trip signal has been received for $5\,\mathrm{ms}$ and i_{DC} has dropped below the proactive commutation threshold again, proactive commutation is aborted. After a delay of $4\,\mathrm{ms}$ corresponding to the closing time of VI, LCS is turned on to commutate i_{DC} back from DCS to LCS. Observe that the abortion of proactive commutation works even though DCS cannot be turned off and no counter current is injected either. This is possible because of the arc voltage of DCS. When LCS is turned on, its voltage drop approximately equals the voltage drop of $\mathrm{D_1}$. However, the arc voltage of DCS is in the range of $10\,\mathrm{V}$ to $20\,\mathrm{V}$ due to the vacuum arc which is sufficient to commutate i_{DC} from DCS to LCS. Note that VI would be irrelevant for the commutation process as it would be closed without an arc while LCS is still turned off.

VI. Discussion & Future Work

The proposed EAR DCCBs extend the capabilities of conventional active resonant-type DCCBs and share similarities. In Section I, the $\mathrm{d}i/\mathrm{d}t$ and $\mathrm{d}u/\mathrm{d}t$ limitations of VIs were mentioned and how this leads to bulky LC circuits. Even DCS technology suffers from such limitations and further research is required to quantify these. Comparing VIs with vacuum TSGs as used in our prototype, our hypothesis is that the limitations are less stringent for vacuum TSGs for following reasons. The limitations are mainly influenced by residual charge carriers and metal particles after current zero that reduce the dielectric withstand capability of vacuum. This can lead to arc reignition when the transient recovery voltage appears. However, the vacuum arc evolves differently in a vacuum TSG and a VI. In a vacuum TSG, the triggering unit forces a dielectric breakdown in the main gap. In a VI, a molten metal bridge is formed when the contacts separate. This molten metal bridge eventually explodes and an arc starts burning. We assume that this process leads to more metal particles in the main gap compared to a vacuum TSG. Furthermore, the contact system of a VI has to be designed for motion and thus more degrees of freedom are available to boost the $\mathrm{d}i/\mathrm{d}t$ and $\mathrm{d}u/\mathrm{d}t$ capabilities of vacuum TSGs. For instance, the main electrodes can be bigger as weight does not matter and the arcing chamber can be enlarged to spread out the residual charge carriers and metal particles. That being said, concept B, C, E, and F use arcing switches, which would most likely be realized with VIs. The weakest link in the chain dictates the dimensioning of L_{C} and C_{C} in this case. VIs used in DCCBs today are actually ACCBs and further development can lead to improved VI performance in DCCBs or special VIs for DC applications. Such developments would benefit conventional active resonant-type DCCBs and EAR DCCBs.

Although a commercially available vacuum TSG was used in our prototype, this does not mean that this is the perfect choice. Even other DCS technology should be tested and compared. The development of DCS technology has been confined to niche applications in the past years and now research needs to apply recent progress in related fields. Further research is necessary to optimize DCS technology

specifically for DCCBs or other DC protection devices that will evolve as DC grids become ubiquitous.

VII. Conclusion

In this work, the enhanced active resonant (EAR) DCCB concepts are introduced. In contrast to hybrid DCCBs, discharge closing switches (DCSs) are used in the commutation path instead of semiconductors with turn-off capability. Suitable DCS technology is reviewed. DCSs allow increasing current ratings, require less series connections, and improve robustness. Furthermore, DCSs can endure impulse voltages above their hold-off voltage, so that DCCBs potentially do not need to be rated for the MOV voltage. An injection circuit or pulse generator as in active resonant type DCCBs is used to turn the DCSs off. In total, one unidirectional and six bidirectional concepts are introduced. All EAR DCCBs offer auto-reclosing, proactive commutation, and can handle arc reignitions in the DCSs. As novelty, bidirectional DCCBs with asymmetric current breaking capability are also introduced. These concepts have high potential for meshed DC grids with protection schemes that require proactive commutation only in one interruption direction. The proposed EAR DCCB concepts with arcing mechanical switches in the main path are superior, because they interrupt reliably in all foreseeable scenarios. Experimental results from tests of a prototype EAR DCCB are presented.

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