Preliminary experiments quantifying the arcing process in a DC circuit breaker development project

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***Abstract*—AC circuit breakers are well-established technology today. However, DC circuit breakers (DCCB) are not easy to design and build since there are no zero crossings in a DC power supply. Mechanical and semiconductor switches are the key elements considered under various circuit topologies to design DCCBs. However, mass-produced commercial DCCBs are designed by modifying AC breakers by connecting multiple poles in series and/or using permanent magnets inside the breaker to lower the cost of DCCBs except for special applications such as in the military industry. Some of the major issues behind the DCCB design are fundamentally explained in this research with simple experimental results based on DC arc characteristics. We intend using these experimental observations in a new design approach for DC circuit breakers using supercapacitor energy absorption.**

***Index Terms*—Direct current, Circuit breaking, Supercapacitors, Arc characteristic.**

I. INTRODUCTION

DC microgrids and DC homes are very recent research topics in renewable energy applications. Protection systems are very essential in these systems [1–4] and in this context, one of the main barriers to implementation of DC systems is the difficulty of DC circuit breaking [5–9]. There are three types of DCCBs, the first type of circuit breakers involves only mechanical switches, the second type involves only solid-state switches, and the third type involves both mechanical and solid-state switches, known as hybrid DCCBs [4–14]. Research literature as well as the application notes from circuit breaker manufacturers, clearly indicate the comparative difficulties in designing a reliable low-cost DC circuit breaker [5]. Most of research ongoing on DCCBs are either in the direction of (i) fully solid-state implementations or (ii) hybrid (mechanical plus solid state) implementation [5, 7, 8, 11, 12, 15–22]. However, commercially available consumer-end DCCBs are simple adaptions of three phase AC circuit breakers, with the multiple mechanical contacts are placed in series to share the inductive energy associated with a DC circuit loop [5, 23]. By placing multiple poles (contact pairs) in series the arc can be quickly extinguished [5, 23]. Another commercially used approach for lower DC currents is to use permanent magnet(s) to extinguish the arc rapidly [5, 24–26]. Both types typically use mechanical contact pairs.

Solid state circuit breakers has been a hot research topic in protection systems, even though there were limited commercial implementations. Thyristor or silicon transistor based implementations were common in the last seventy five years [4] while wide band gap semiconductor technology is still passing its preliminary development stage. High reliability commercial DCCBs from leading manufacturers such as Sécheron for applications such as DC railways uses very high currents, such as 1000 A to 8000 A. Solid-state switches are even hard to include in DCCBs for the rated currents above 1000 A because the conduction losses in the solid-state devices are quite high. In a rare case of high voltage DC circuit breaker implementation by ABB-Siemens, developing a cooling system for the solid sate system was a significant challenge [27]. However if the current was only few amperes to ten amps, implementation is less of a challenge.

Hybrid circuit breakers on the other hand is a good way of avoiding the continuous conduction losses available on pure solid-state DCCBs, which is the moderated version in between the pure mechanical and pure solid-state DCCBs. However, complex control systems with additional power supplies need to be designed in order to drive the semiconductor switches in these systems [28, 29]. The authors' intention is not to do a detailed analysis of the existing DCCB typologies, but to follow a complete different approach for the arc energy absorption.

Well-informed about the uniquely useful properties of supercapacitors (SC), creatively and successfully applied in our supercapacitor assisted (SCA) techniques, we currently investigate how a DC circuit breaker can be designed based on a SC in the commutation path [30].

The paper is structured into seven sections. Section II analyses the DC arc characteristic during a fault condition. In section III, simplest arc extinguishing technique is analysed for a DCCB. Section IV provides a justification for the new approach based on supercapacitors. Section V summarises our current directions of research on the new topology. Challenges for the current approach are mentioned in the section VI and the conclusion and future works are presented in section VII.

II. ANALYSIS OF DC ARC CHARACTERISTIC

Fig. 1 shows a simple DC circuit where the DC source voltage - V_{source}, the parasitic inductance of the circuit loop - L_{stray}, mechanical switch - S, load resistance - R_{load}, parasitic resistance in the circuit loop - $R_{\text{parasitic}}$, and the fault current - I. During a fault condition, S needs to be opened quickly, and the stored energy of L_{stray}, $\frac{1}{2}L_{\text{stray}}I^2$ will be dissipated as an electric arc across the mechanical contacts (the commutation path is open-circuited). Repeated on off operations could deteriorate the contacts in a mechanical circuit breaker due to arcing. For typical case of a DCCB, experimentally observed arc voltage and current characteristics are shown in Fig. 2, where the commutation path does not carry any component (hence open-circuited), as shown in Fig. 1. The source voltage maintained at 25 V and the DC loop current prior to the circuit opening is 36 A where the load resistance excluding the parasitic resistance was 0.5 Ω.

Fig. 3 illustrates the similar waveforms as in Fig. 2, where the switch - S in Fig. 1 is replaced by three series connected mechanical switches (commercially available 3-pole AC circuit breaker is used with poles connected in series). Once the mechanical switch/switches open, the initial arc voltage is always around 10 V per pole because the arc will be initiated across the contacts (each contact) once the voltage across the contact breaker points reaches 10 V. Here, the approximation of 10 V is the minimum arc voltage, and it depends on the contact material of the circuit breaker. For copper, the minimum arc voltage is 13 V and the corresponding value is almost around 10 V for most of the metals where circuit breaker contacts are manufactured [31]. Fig. 2 illustrates that the arc voltage builds slowly after the initial jump of 10 V. Arc voltage has taken 450 μs to reach the source voltage (25 V). Note that the arc voltage always develops opposite to the source voltage, which will help to extinguish the arc. The electric arc is a jet of electrons where the conduction path resistance is initially low, so the arc voltage remains lower. With time, arc path resistance increases as the distance between the contact points increases. So the arc current decreases, and the arc voltage increases. Arc extinguishes completely around 950 μs for a case of loop inductance of 660 μH and with a single pole pair. Fig. 3 illustrates that the arc can be extinguished completely within 230 μs, much faster than using a single pole. The highlighted circle area in Fig. 3 shows three separate voltage jumps corresponding to each pole connected in series.

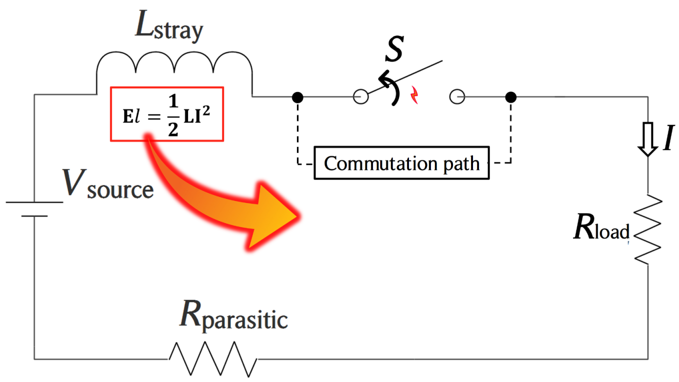


Fig. 1: Simple DC circuit breaker operation with a mechanical switch

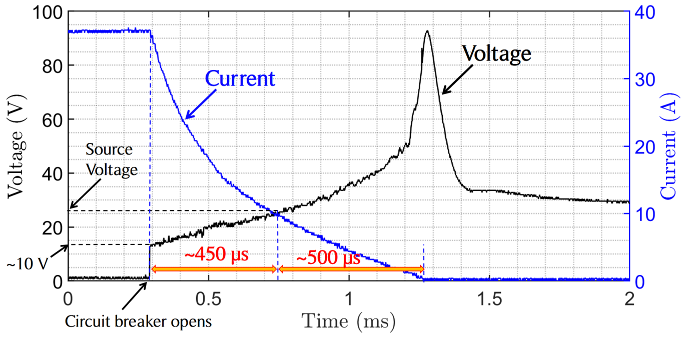


Fig. 2: DCCB arc voltage and current characteristic

Because of the accumulated initial voltage, arc voltage reaches the source voltage (25 V) within 50 μs. Fig. 4 clearly illustrates that the arc resistance increasing rate is much higher with higher number of poles circuit breaking compared to a less number of poles circuit breaking. As per this experience, commercial DC applications use standard AC circuit breaker poles in series. Manufacturers such as Schneider Electric advise using multiple poles to increase the breaking capacity [23].

III. INTRODUCING A COMMUTATION PATH FOR THE DCCB

A. Simplest arc absorption technique for a DCCB

The most straightforward technique to absorb the arc energy is shown in Fig. 1 based on a metal oxide varistor (MOV) in the commutation path. However, direct implementation is worthless due to the slow increasing rate of arc voltage as it

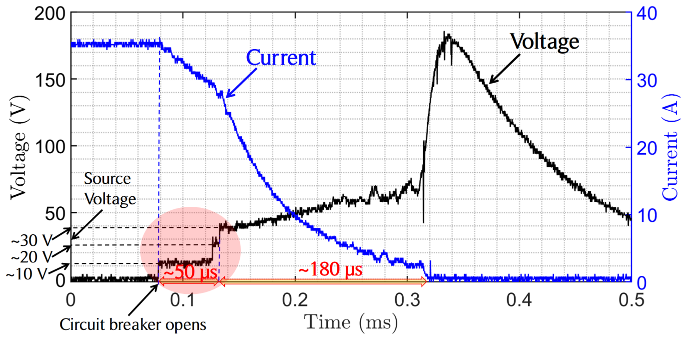


Fig. 3: DCCB arc voltage and current characteristic where DCCB includes three series-connected poles

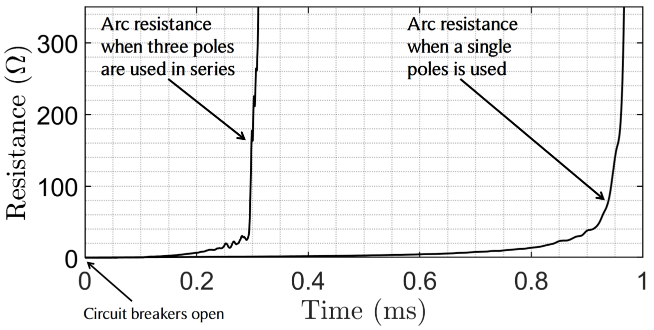


Fig. 4: Arc resistance increases rapidly with the series connected number of poles.

takes considerable time to trigger the MOV compared to the total arcing time. Experimental results in Fig. 5 prove that arc energy commutated to the MOV is low compared to the energy dissipated across the contact breaker points because arc voltage takes a higher time to reach the breakdown voltage of the MOV. For the experiment, B72214S0140K101 MOV is used, and its varistor voltage is 22 V, and it is triggered when the arc voltage reaches around 35 V, as shown in Fig. 5.

B. A capacitor uses in the commutation path to enhance the arc commutation

The MOV, B72214S0140K101 was used in the commutation path and it can be triggered quickly and commutate more fault current through the MOV if there is a way to increase the arc voltage. Using multiple poles is one option, as explained using Fig. 3. Another technique is to use an electrolytic capacitor (EC) with a small capacitance value and a high voltage rating connected parallel to the MOV. Then the current flows to the EC will increase the initial voltage seen by the MOV and help to activate the MOV quickly. Fig. 6 shows the experimental results related to a low current circuit with a source voltage of 5 V. 2.2-µF, 63-V EC was used. The peak value of the MOV current is increased by 326%. The same experiment is done for 20 V of source voltage and high current which is illustrated in the Fig. 7. Now the peak value of the MOV current is increased only by 82%.

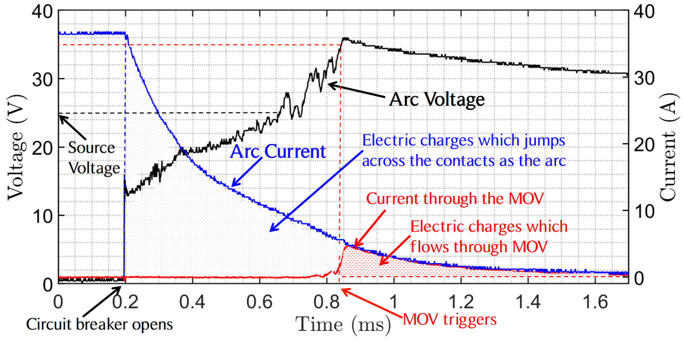


Fig. 5: Arc energy absorbed by the MOV is low compared to the energy dissipated across the contacts.

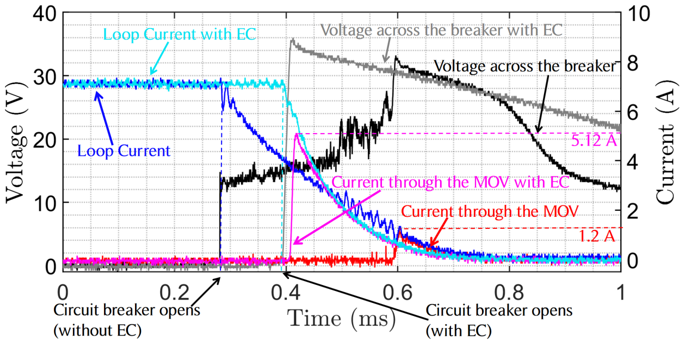


Fig. 6: The current through the MOV increases by 365% after connecting the parallel EC where the source voltage is 5 V.

Further results in the oscillograms in Fig. 8 proved that the peak current percentage reduces with the fault current increase as the capacitor's equivalent series resistance (ESR) limits the surge current to the capacitor. Fig. 8 illustrates that the fault current was entirely absorbed by the EC (2.2 µF, 63 V). However, the arc absorption is discontinued when a 1-Ω resistor connected in series with the capacitor. When the capacitor ESR is high, it reduces the ability of the capacitor to absorb the arc energy. Most of the literature based on mechanical switches also discusses about the ways of increasing the arc voltage quickly by cooling the arc [31] and stretching the arc (using the multiple poles) to extinguishing the arc quickly, however, what we are referring is to increasing the arc voltage in order to commutate the current in to a different path quickly. The ability of an electrolytic capacitor or a film capacitor to absorb the arc is quite restricted by the capacitor's ESR. Hence based on these preliminary results, next section onwards, authors plan to investigate the suitability of a supercapacitor (SC) to the commutation path and report the initial observations on introducing a SC to the commutation path by claiming the superior (low) ESR performances of SCs.

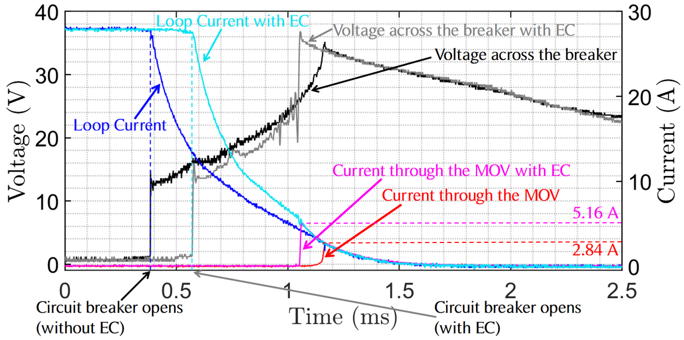


Fig. 7: The current through the MOV increases by 82% after connecting the parallel EC where the source voltage is 20 V.

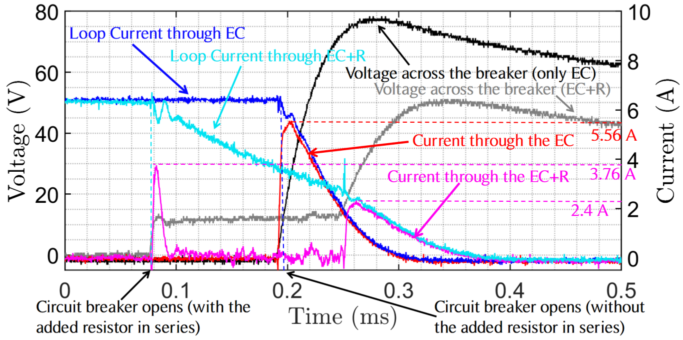


Fig. 8: The EC completely absorbs the surge current through only its ESR; however, perfect arc absorption cannot be achieved when an additional resistor is connected in series with the EC.

IV. JUSTIFICATION FOR SUPERCAPACITOR BASED DESIGN APPROACH FOR DCCBS

A. A summary on supercapacitor device technology development

A SC can be described as a one million times larger capacitor compared to a normal (electrolytic or a film type) capacitor for the same canister volume. Commercially available SCs come in several different types, (i) symmetrical double layer (ii) hybrid (iii) battery capacitors. Most common and well-established type is the symmetrical double layer devices. Based on the three electrical properties, capacitance, rated DC voltage and the ESR of selected commercial devices from a single manufacturer, we have created the contents of Table I.

One useful property is that the capacitance and the canister volume increase, their ESR keeps dropping. Maximum energy storable in a SC based on $\frac{1}{2}CV^2$ is in Column 4. Maximum power delivery capability - P_{max} of a SC [32] given by $\frac{V^2}{4*ESR}$ is shown in Column 5, which indicates that these devices are superior in (short term) power delivery (compared to rechargeable batteries). Other most useful property of a SC, high charge and discharge current capability is demonstrated by short-circuit current - I_s capability given by $\frac{V}{ESR}$ in Column 6. As per Table I, larger the SC, its short circuit current capability increases. Given that the stray inductive energy in the DC loop is given by $\frac{1}{2}LI^2$, if loop current – I is less than short circuit current capability of the SC - I_s, a SC can be used in the commutation path. However, it is important to note that a single cell SC's DC voltage rating is much lower than the DC voltage of the source. This makes it impossible to keep the SC across the switch after opening the DC loop. In developing a useful DC circuit breaker topology based on SC, this becomes a major research challenge.

B. Supercapacitor in the breaker loop to transfer arc energy

Circuit shown in Fig. 1 demonstrates that (now the commutation path is a supercapacitor) if we can find a SC with a higher DC voltage rating than the V_{source} and if the $\frac{1}{2}CV^2$ of the capacitor is larger than the $\frac{1}{2}L_{\text{stray}}I^2$, we can safely transfer the loop inductive energy into the capacitor (however, the large RC time constant then increases the response time of the circuit breaker, needs to be addressed further). Table II compares the inductive energy in a DC loop versus a single SC's energy storage capability. However, given that the DC voltage ratings of a SC is very small (unlike an electrolytic, film or a ceramic) this is not easily implementable.

TABLE I: Characteristics of most common type of supercapacitors

C(F)	**V(V)**	**ESR (mΩ)**	**E_{C} (J)**	**P_{max} (W)**	**I_{s} (A)**	**Size D×L(mm)**
1	3	215	4.5	10	14	8×13
5	3	85	23	26	35	8×25
10	3	45	45	50	67	10×30
50	3	20	225	113	150	18×40
100	3	8	450	281	375	22×45
220	3	7.5	990	300	400	25×70
360	3	3.2	1620	703	938	35×62

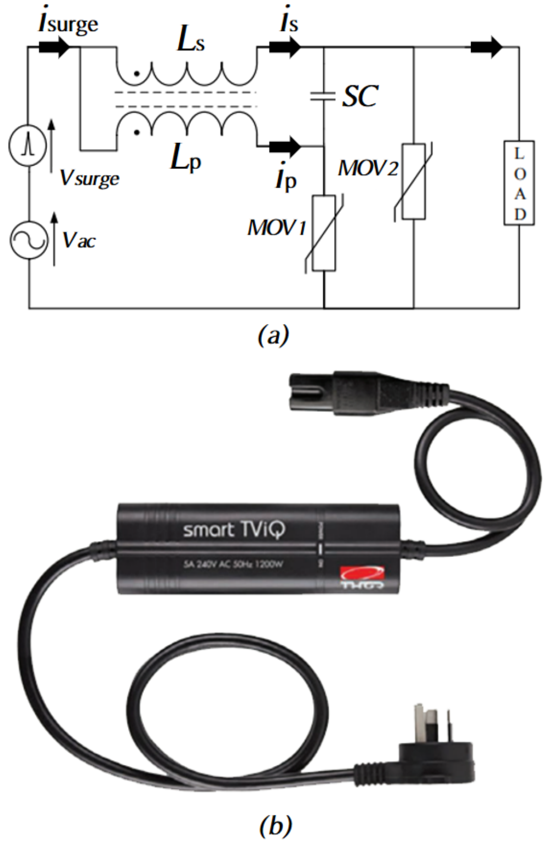
TABLE II: Stored energy in different parasitic inductors compared with the energy storage capability of different SCs

L (μH)	**$\frac{1}{2}LI^2$ at 100 A (J)**	**C(F)**	**$\frac{1}{2}CV^2$ at V (J)**
1	0.005	1	4.5
10	0.05	1	4.5
100	0.5	1	4.5
1000	5	5	23
L (μH)	**$\frac{1}{2}LI^2$ at 1000 A (J)**	**C(F)**	**$\frac{1}{2}CV^2$ at V (J)**
1	0.5	1	4.5
10	5	5	23
100	50	50	225
1000	500	220	990

Hence, we have commenced our research project on this SC assisted DC circuit breaker, to be practically and theoretically informed by our work on supercapacitor assisted (SCA) techniques [33–35] and the SCA loss management (SCALoM) theory [36]. In particular, our patented and commercialized SCA surge absorber (SCASA) technique has motivated us to go on this direction with adequate confidence [37–41].

V. ONGOING WORK AND EXPERIMENTAL OBSERVATIONS

Power electronics research group of University of Waikato has successfully implemented several unique SCA techniques, such as a low frequency DC-DC converter topology with higher efficiencies comparable with high frequency switch modes [42–47], surge absorber [37–41], DC LED lighting [33, 48–53] and rapid water heater [54, 55]. All these were



(a)

(b)

Fig. 9: Simplified schematic of SCASA technique for surge protectors (a) basic concept which overcomes the challenge of low DC voltage rating of a supercapacitor (b) a commercial implementation (courtesy of Thor Technologies)

based on unique properties of SC based long time constant circuits, coupled with some creative design approaches [33–55]. In our SC assisted surge absorber (SCASA) technique, we have overcome the challenge of absorbing a high voltage transient voltage impulse's energy into a SCA circuit, which we consider complimentary to the requirement in a DC circuit breaker. In a circuit breaker we need to absorb and extinguish the arc energy created by the DC loop current. In SCASA we successfully absorbed the transient energy in the high voltage impulse superimposed on a 230-V AC power line [26-30]. Fig 9(a) depicts a simplified schematic of our SCASA protector technique with a commercial implementation shown in Fig 9(b). Significant challenge in our SCASA technique was the very low DC voltage rating of the SC, which makes it impossible to place it across the live and neutral of the 230-V AC power rail, similar to a MOV usually used in a surge absorber. Therefore, the team had to invent a unique topology as shown in Fig 9(a), based on a coupled inductor [47]. Theoretically we plan to progress on the path of duality of current and voltage in these two approaches. In SCASA we absorb a voltage transient surge, compared to a current surge in a circuit breaker across the switch contacts.

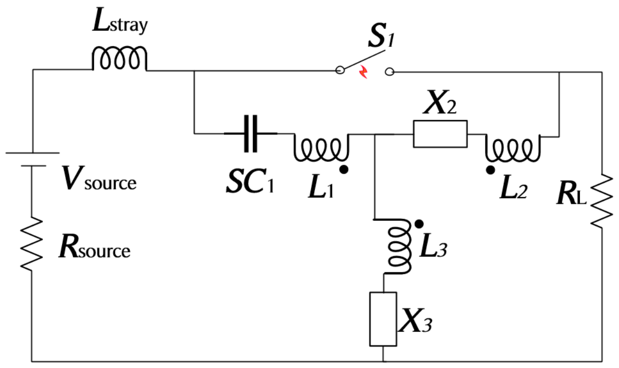


Fig. 10: New design concept of a supercapacitor-based DC circuit breaker

VI. CHALLENGES FOR PRACTICAL IMPLEMENTATION AND MITIGATION APPROACHES

The main challenge we face in our new design approach is the inability to place the energy absorbing SC permanently across the two contacts of the contact breaker - S in Fig. 1 (commutation path is the supercapacitor). We are challenged to invent a unique new circuit topology based on a combination of non-linear devices such as MOVs and/or bidirectional break over diodes (BBD), and inductors or coupled inductors as shown in Fig. 10. Given that there could be many more extensions to the basic topology in Fig. 10, which are not yet developed, we need to take significant risk and keep investigating our unique SC-based approach. X_2 and X_3 are nonlinear devices such as MOVs and/or BBDs. L_1 to L_3 are specially configured coupled inductors.

VII. CONCLUSION AND FUTURE WORKS

Given the major difference between an AC circuit breaker and a DC circuit breaker due to no zero crossing in a DC power supply, fundamental properties of a DC arc had been analyzed with simple experimental results during the project for developing a novel arc absorption technique for a DCCB. Based on the success of developing a supercapacitor assisted surge absorber, we have started investigating how circuit duality of current and voltage could be combined with duality of capacitor and inductor can be basis for developing supercapacitor assisted DC circuit breaker. Our research target is to develop a unique new topology dominated by passive components for higher reliability and lower cost.

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