Review on Z-Source Solid State Circuit Breakers for DC Distribution Networks

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***Abstract*—DC technologies will be essential building blocks for future DC distribution networks. As in any DC system, these networks will face crucial threats imposed by short-circuit DC faults. Protection is thus of great interest, and it will likely rely on DC circuit breakers (DCCBs). Among available configurations, Z-source solid-state circuit breakers (Z-SSCBs) are promising candidates for protecting low and medium-voltage distribution networks, as well as DC equipment due to their structural and control simplicity and low cost. In this paper, start-of-the-art of Z-SSCBs topologies is reviewed. To set the context, the use of DC technologies for grid integration of renewables, DC power transmission, and the main types of DCCBs to protect DC transmission and distribution corridors are discussed. The Z-SSCB topologies are then classified into unidirectional and bidirectional. Advantages and disadvantages of different configurations are compared and analyzed based on existing research. Finally, a perspective on the future development of Z-SSCBs is discussed and potential challenges are elucidated.**

***Index Terms*—DC distribution networks, DC protection, solid state DC circuit breaker, Z-source.**

I. Introduction

OVER 40% of global energy-related carbon emissions come from electricity generation [1], [2]. Decarbonizing power systems has been sought by integrating widespread renewable sources to replace fossil fuel-based generation [3]–[5], using clean gas and other energy forms, and coordinating and optimizing generation, transmission, and distribution [6], [7]. This paradigm shift in the structure and operation of power systems is non-trivial and costly due to intermittency of renewables, the challenge of attaining stability in a system with reduced inertia and increased power electronics [8], and the infrastructure reinforcement needed [9], [10]. Not contributing toward meeting carbon neutrality is not an option, though [11].

Despite its cost, several manufacturers and operators favor high-voltage DC (HVDC) over conventional high-voltage AC (HVAC) transmission for integrating large-scale offshore renewables [12]. HVDC is cost-effective for transmission of bulk power as losses incurred in AC corridors increase with distance. This is compounded by a higher quality and more reliable wind resource farther away from shore [13]. Voltage source converter-based HVDC is preferred due to its black start capabilities and independent control of active and reactive power [8]. Its bidirectional power flow facilitates developing multi-terminal systems—expected to increase flexibility, redundancy, and economic viability of offshore transmission [12], [13]. In addition, an HVDC system enables provision of ancillary services, such as frequency support [14], [15] and damping of sub-synchronous oscillations [16]–[18].

At a distribution level, an urban power system is formed by distributed AC and DC loads and generators, including traditional AC power plants, renewable generation, and energy storage units. Modern systems will be embedded with AC/DC conversion and low-voltage and medium-voltage DC links [19]. Medium-voltage technology has attracted significant interest due to its enhanced transmission capacity, control flexibility and improved power quality compared to AC alternatives [20]–[22]

Irrespective of voltage level, a barrier preventing reliable DC grid development is protection [23]. Interruption of DC fault current is challenging due to the lack of natural zero-crossings and fast rate-of-rise in current due to low impedances [24]. Protection equipment includes power electronics components, such as DC circuit breakers (DCCBs) and converters with fault blocking capability. Their operation is facilitated by suitable protection schemes, which may differ depending on the type of fault experienced and its location [25]–[27]. Other power electronics-based devices may be incorporated into a DC grid to enable flexible power flow [28]. Power flow control units may be used to relieve transmission bottlenecks, prevent DC line breakdown, and reduce power losses [29]–[32].

DC links may enable the asynchronous interconnection of AC distribution systems without increasing their short-circuit capacity—mitigating the need for circuit breakers (CBs) or cables requiring current limitation [33]. In addition, the active power transmitted by DC lines and the reactive power consumed by power converters can be regulated with a control scheme, i.e., improving performance of the connected AC

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systems. Such advantages make DC systems promising alternatives for urban power systems. However, like higher voltage networks, DC distribution systems have low impedance and are fragile to short-circuit faults. They also contain several power electronic devices based on insulated-gate bipolar transistors (IGBTs) that cannot withstand overcurrents for a long duration [34]–[36]. Thus, a DC fault will cause an instantaneous rise in current that could be disastrous to any power electronics device if the fault current is not blocked quickly [37]. The widely acknowledged solution under these circumstances is to use DCCBs.

There are three main types of DCCBs: purely mechanical devices that open using mechanical switches, full solid-state DCCBs (SSCBs) based on power electronics (thyristors and IGBTs) [38]–[40], and hybrid CBs combining the first two [41] Mechanical DCCBs are inexpensive but have a large size and feature long switching times. Their proclivity to generate arcs is the most serious issue exhibited by these devices as this reduces their service life and may cause damage to surrounding equipment. Hybrid CBs combine the benefits of high-capacity mechanical devices with the fast response time of solid-state devices [42], and are also suitable for DC transmission networks. However, hybrid devices may be expensive and bulky for DC distribution networks in urban systems—particularly to protect end-use equipment. Development of advanced hybrid CBs exhibiting low losses, current flow control capabilities, and a reduced number of controllable devices to decrease their cost as in [43]–[46] may be attractive for distribution systems.

SSCBs have complex circuitries and thus more complex control schemes and higher cost [42], [47]. They exhibit a higher on-state loss and a lower interruptible fault current when compared to mechanical and hybrid CBs. Their on-state loss can be reduced by using a wide band gap device, and the magnitude of their interruptible current is determined by the voltage level carried by the power electronic device. As requirements for breaking capacity and speed increase, new SSCBs exhibiting high reliability must be researched further.

Recently, a new type of SSCB, the Z-source SSCB (Z-SSCB), has attracted attention. A Z-SSCB does not need additional control or detection circuitry when its triggering conditions are met, and has a simpler topology, faster response time, higher energy density, and reduced price compared to other CBs. While mechanical and hybrid CBs are appropriate for high voltage transmission, Z-SSCBs are better suited for medium and low voltages. However, utilizing Z-SSCBs to protect urban DC distribution networks and end-use equipment has not been investigated in detail and thus constitutes an interesting research direction [48], [49].

Following this line, this paper presents a detailed review of recent research on Z-SSCBs. For simplicity, the devices are grouped as unidirectional and bidirectional. Depending on their topologies, these are further classified, compared, and their advantages and disadvantages discussed. Recommendations are made for improving existing topologies in response to the current demand for Z-SSCBs. Problems encountered and prospects of these CB technologies are discussed.

II. Unidirectional Z-SSCBs

The Z-source structure has attracted significant attention due to its characteristic electrical properties [50], [51]. It employs a unique passive network that allows semiconductors on the same bridge arm to turn on at the same time and thus realize its ramp-up/down conversion function, increasing the device's reliability while avoiding distortion in the output waveform caused by dead zones.

Z-source inverters are commonly used in applications where DC link voltage varies over a wide range [52]–[54]. Such structure was extended to be adopted in CBs, where an LC impedance network is used for post-fault thyristor current to achieve a zero-crossing, thus enabling turn-off of the thyristor. Because Z-SSCBs do not require complex control circuits, current research is centered on topologies enabling them to have faster operation times, simpler structures, and lower cost.

A. Conventional Unidirectional Z-SSCBs

Figures 1 to 3 depict the schematics of three types of unidirectional Z-SSCBs that differ in arrangement of their LC networks. These topologies are classified as Z-source crossed, Z-source parallel, and Z-source series. All three CBs follow a similar operating principle. In the event of a fault, current discharged by the capacitors compensates for fault current through a path formed by the LC circuit, so the current flowing through the thyristor is gradually reduced. The thyristor is then switched off when the compensation current is equal to the fault current [55].

Crossed unidirectional Z-SSCBs were first proposed in [56] and their schematic is shown in Fig. 1. In the event of a fault, the presence of inductors L_1 and L_2 in the circuit help limit the magnitude of fault current. However, the absence of a common grounding point between the source and load restricts their application in earthed systems due to the presence of L_2 in the return path. To solve this problem, a parallel unidirectional Z-SSCB was proposed [57], which includes a

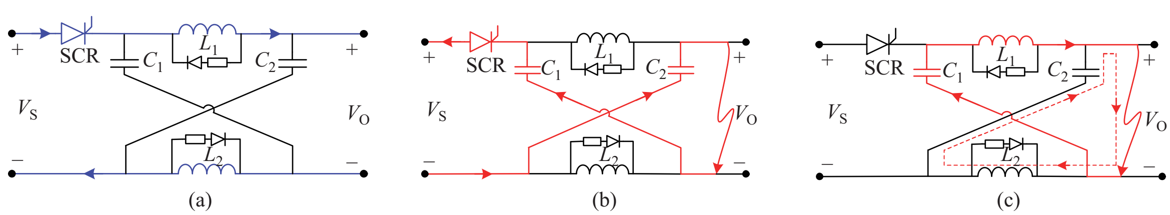

Fig. 1. Schematic of a crossed unidirectional Z-SSCB for: (a) normal working state, (b) fault occurring before the current of SCR decreases to zero, (c) fault occurring after the current of SCR decreases to zero.

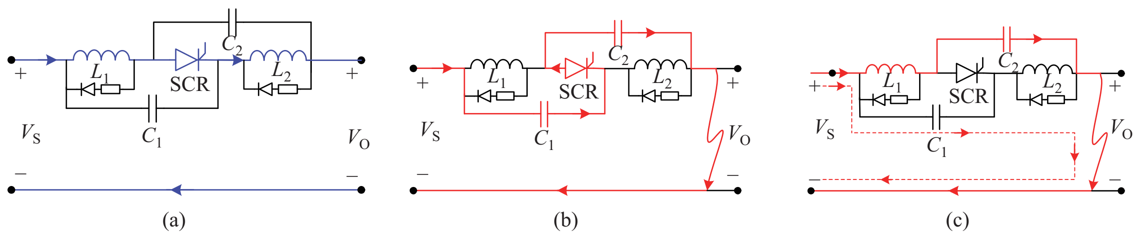

Fig. 2. Schematic of a parallel unidirectional Z-SSCB for: (a) normal working state, (b) fault occurring before the current of SCR decreases to zero, (c) fault occurring after the current of SCR decreases to zero.

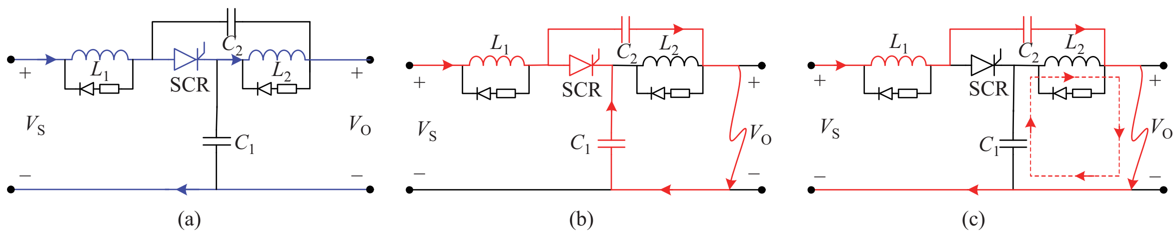

Fig. 3. Schematic of a series unidirectional Z-SSCB for: (a) normal working state, (b) fault occurring before the current of SCR decreases to zero, (c) fault occurring after the current of SCR decreases to zero.

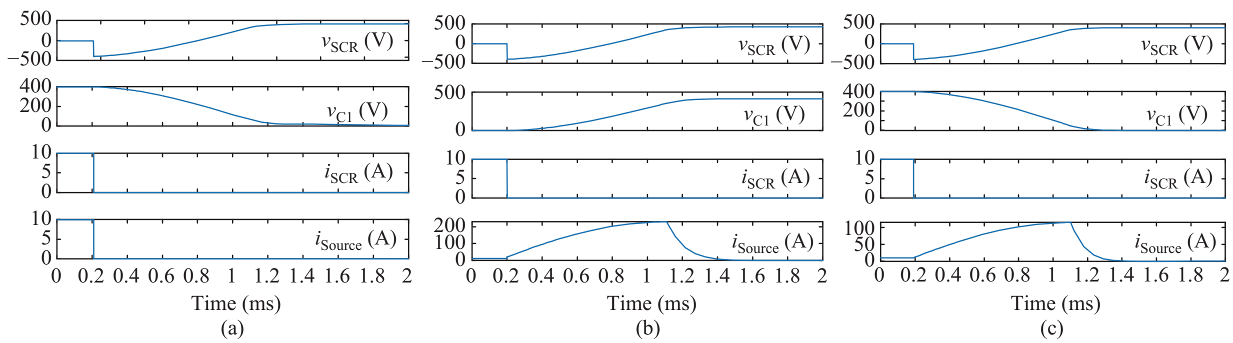

Fig. 4. Simulation waveforms of unidirectional Z-SSCBs for: (a) crossed, (b) parallel, (c) series.

common grounding point (see Fig. 2). However, once thyristor SCR turns off, two current pathways formed by V_S-C_1-V_S and V_S-L_1-C_2-V_S appear (where V_S is the voltage source), as shown in Fig. 2(a). Therefore, this topology exhibits a large fault current to the voltage source during removal of the fault current, which is prone to cause damage to the power supply.

Series unidirectional Z-SSCB topologies were introduced in [58], which exhibit a common ground, as shown in Fig. 3. When a fault occurs, this topology is used to compensate the fault current through the combined action of capacitor C_1 and the voltage source V_S (Fig. 3(b)). After the thyristor is turned off, a portion of the fault current is consumed via the path formed by C_1 and inductor L_2, while the remainder of the current is returned to the V_S via inductor L_1 and capacitor C_2 (Fig. 3(c)). As a result, the reflected current to the source is smaller in comparison to that in the parallel structure.

Simulation waveforms at 400 V/10 A showing key variables for crossed, parallel and series unidirectional Z-SSCBs are shown in Fig. 4. When a fault occurs at $t = 0.2$ ms, current flowing through the thyristor (i_{SCR}) rapidly drops to zero. All three CB configurations exhibit the same forward-blocking voltage (v_{SCR}), which is equal to the voltage magnitude of the power supply (400 V). Capacitor voltage (v_{C1}) of crossed and series Z-SSCBs drops from the power supply voltage to zero, while for the parallel Z-SSCB it rises from zero to 400 V. When it comes to current flowing to the voltage source (i_{Source}) during removal of the fault current, the parallel Z-SSCB presents the largest magnitude while there is no current reflected for a crossed configuration. Time of operation of all devices is similar.

Transfer functions for the discussed unidirectional topologies are shown in Table I. Their filtering characteristics in a normal working state are equivalent to a resonator, a notch filter, and a low-pass filter [58]. Therefore, a series of unidirectional Z-SSCBs may naturally filter high frequency components generated by power electronics devices within the system. This reduces the need for additional filters.

When a fault occurs, these three topologies do not require additional control circuits to generate a triggering signal, as their thyristors turn off automatically once the fault current crosses zero. However, a new challenge arises. When the load suddenly changes, current also changes abruptly, which may lead to an incorrect triggering of the CB.

Note: To the knowledge of the authors, studies on the frequency characteristics of Z-SSCB topologies and the influence these topologies have on the reliability of DC systems under

TABLE I
TRANSFER FUNCTIONS OF THE THREE UNIDIRECTIONAL Z-SSCBS

Features	Transfer function	Characteristics
Crossed	$H_{\text{crossed}}(s)=\frac{-s^2+(1/LC)}{s^2+(2/R_{\text{load}}C)s+(1/LC)}$	Resonator
Parallel	$H_{\text{parallel}}(s)=\frac{s^2+(1/LC)}{s^2+(2/R_{\text{load}}C)s+(1/LC)}$	Notch filter
Series	$H_{\text{series}}(s)=\frac{(1/LC)}{s^2+(2/R_{\text{load}}C)s+(1/LC)}$	Low-pass filter

different frequency responses are not available in literature.

B. Unidirectional Z-SSCBs based on a coupled inductor

Coupled inductors or transformers have been introduced to unidirectional Z-SSCB topologies to solve the problem of incorrect triggering when the load changes. These coupled inductor-based Z-SSCBs are called T-shape [59]–[61], flipped Γ-shape [62], and Γ-shape [63], [64]. The turns ratio of the coupled inductor can be modified to make it capable of stepping down the load, which in turn decreases the risk of incorrect triggering when voltage or current of the circuit changes. At the same time, introduction of coupled inductors (or transformers) replaces the two inductors in conventional Z-SSCBs, which further reduces the size and weight of the unidirectional device.

Table II shows a schematic of a unidirectional Z-SSCBs based on coupled inductors just described. Their basic working principle is when a fault occurs, capacitor C in the CB will discharge to compensate the short circuit current. At this point, a secondary coil of coupled inductor L_2 will feature a large instantaneous current. Due to existence of the coupled inductance, an instantaneous current in the opposite direction of the current flowing through thyristor SCR will be produced at the primary coil of the coupled inductor L_1. This reduces the amount of current flowing through SCR to zero, and SCR is turned off under a reverse voltage. Because SCR is a semi-controlled power electronics component, it will not be turned on again without a triggering signal and a forward voltage, thereby realizing interruption and isolation of the short-circuit fault current.

The three presented coupled-inductor-based CBs have comparable architectures and a similar number of power electronic components in the main circuit. However, due to the varying physical location of the coupled inductors, there are some differences in their electrical characteristics. These are summarized in Table III [62].

TABLE II
UNIDIRECTIONAL Z-SSCBS BASED ON A COUPLED INDUCTOR

T-shape [59], [60]	Flipped Γ-shape [62]	Γ-shape [64]

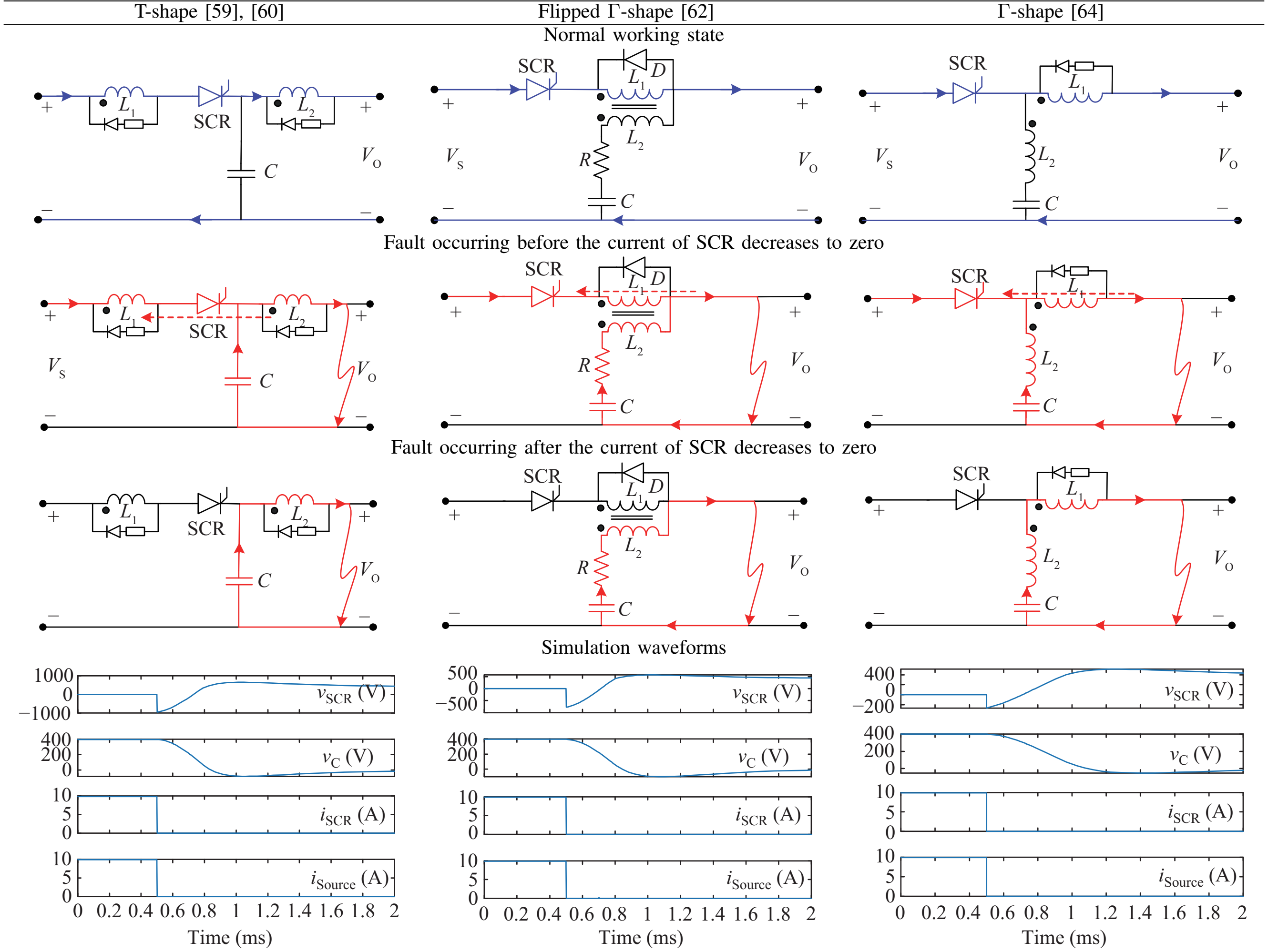

TABLE III
COMPARISON OF THREE COUPLED-INDUCTOR BASED UNIDIRECTIONAL Z-SSCBS

Features	Common ground	Reflected current to source	Overload protection	Surge current during fault	Required thyristor voltage rating
T-shape	Yes	No	Yes	Low	Highest
Flipped Γ-shape	Yes	No	Yes	Low	Low
Γ-shape	Yes	No	Yes	Low	Lowest

As observed from the simulation waveforms in Table II and differences in their electrical characteristics summarized in Table III, all three CBs have a common grounding point. There is no reflected current to the source (i_{Source}), and a low surge current (i_{SCR}) is exhibited when a fault occurs. All three capacitors in the topologies are subjected to a negative voltage (v_{C}) during the discharging process, so selecting a non-polarity capacitor should be considered when implementing unidirectional Z-SSCBs based on a coupled inductor. Meanwhile, Γ-shape CBs require the lowest voltage rating of thyristors as they have the lowest forward-blocking voltage (v_{SCR}) during fault removal.

The common grounding point discussed here refers to when the Z-SSCB is used in series with the circuit to play a protective role. In this case, the negative electrode of the capacitor in the Z-SSCB must be connected to the current return path of the load. Regardless of which grounding mode is adopted in the DC grid (e.g. TN, TT, or IT, where T represents a ground connection, N a neutral connection, and I isolation from both neutral and the ground [65]), the Z-SSCB will not be affected as long as the input and output of the Z-SSCB coincide with the input and output of the DC load to be protected. Additionally, the way the transformer is connected on the AC side has no effect on the Z-SSCB's operation.

Additionally, when designing the coupled inductor in the Z-SSCB, a suitable turns ratio must be chosen to ensure protection while withstanding sudden changes in load. Similarly, a suitable magnetic inductance must be chosen based on the magnitude of the current during normal operation and following a fault. This will prevent magnetic saturation and in turn failure during the fault removal process. Given that there are no special design requirements for the coupled inductors, the selection of insulation materials only needs to adhere to standard design process.

III. BIDIRECTIONAL Z-SSCBS

Increase of distributed energy sources, microgrids, energy storage devices, and electric vehicle charging stations in urban systems has created a demand for bidirectional protection equipment as power flows bidirectionally. Unidirectional devices described in Section II are not suitable for bidirectional protection and, instead, bidirectional Z-SSCBs are needed.

Bidirectional Z-SSCBs have, in general, a similar structure as unidirectional devices; however, their power electronics switches are connected differently. This is shown in Fig. 5. Combinations of thyristors and diodes are employed to achieve bidirectional power flow and hence the devices can interrupt currents flowing in both directions.

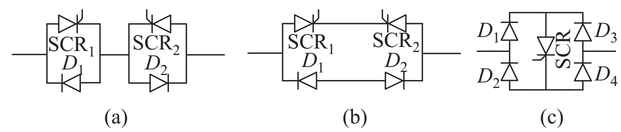

Fig. 5. Connection of power electronics devices for bidirectional CBs. (a) Anti-parallel 1. (b) Anti-parallel 2. (c) Bridge.

A. Conventional Bidirectional Z-SSCBs

Table IV shows three bidirectional Z-SSCB topologies and their corresponding simulation waveforms. Arrows in the diagrams represent the direction of current flow, whereas the red dashed line in the fault state is used to highlight the SCR current tends to decrease to zero. Key features of these bidirectional topologies are compared in Table V. The topology introduced in [66] and [67] was modified from a conventional crossed unidirectional Z-SSCB and retains the benefits of not exhibiting a reflected current to the source (i_{Source}). However, it employs additional thyristors, which may be reduced in number by replacing two of them with diodes.

The bidirectional topology presented in [68] has characteristics of both the crossed and parallel unidirectional Z-SSCB topologies, respectively reported in [56] and [57], but still exhibits a large reflected current to the source (i_{Source}) and a high peak forward-blocking voltage of the thyristor (v_{SCR1}). This high voltage is caused by LC resonance during short-circuit fault interruption. The higher the thyristor's peak forward-blocking voltage is, the higher the voltage stress on the thyristor becomes. Under these circumstances, a thyristor able to withstand higher voltage levels is required at the expense of increasing the overall cost of the Z-SSCB.

Topology 3 proposed in [69] outperforms the other two topologies as it exhibits a moderate reflected current to the source (i_{Source}) and a reduced peak forward-blocking voltage (v_{SCR1}) in the thyristor. The downside is that its on-state losses are relatively high. C_1 in topologies 1 and 3, as well as C_0 in topology 2 are subjected to a negative voltage which is similar to that from topology 2 during the discharging process.

B. Bidirectional Z-SSCBs Based on Coupled Inductor

By adopting the bridge structure shown in Fig. 5 in unidirectional Z-SSCBs based on a coupled inductor, a bidirectional power flow can be achieved, as well as bidirectional interruption and isolation of short-circuit faults.

Several bidirectional topologies have been presented in literature [70]–[86], with the most representative being reproduced in Fig. 6. Fig. 6(a) shows a bidirectional Z-SSCB based on coupled inductors and a bridge structure as introduced in [70], [71]. This device is made up of two diodes and two thyristors, as well as two coupled inductors. To simplify this

TABLE IV
THREE CONVENTIONAL BIDIRECTIONAL Z-SSCBS

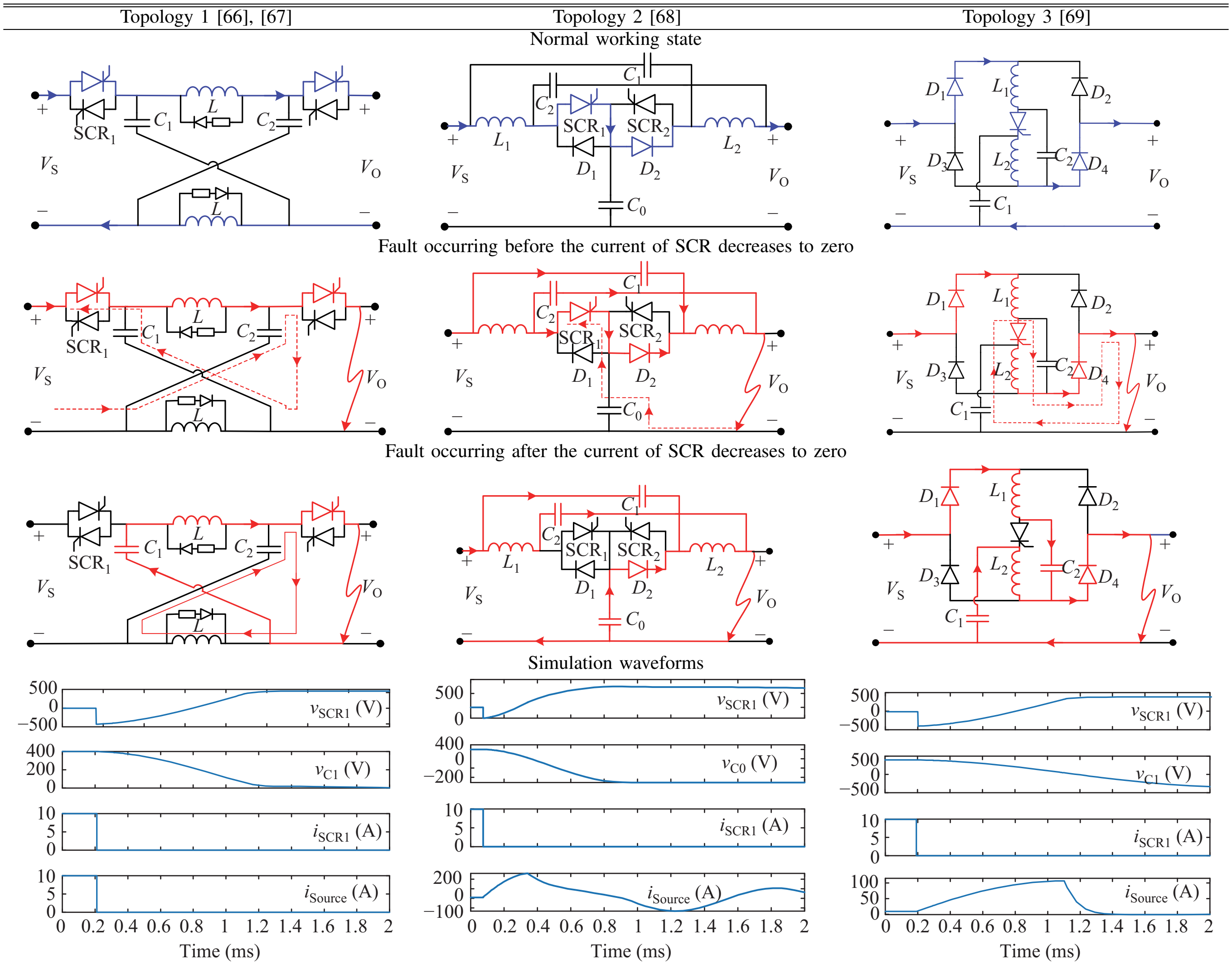

TABLE V
COMPARISON OF THREE CONVENTIONAL BIDIRECTIONAL Z-SSCBS

Features	Topology 1	Topology 2	Topology 3
Number of passive components	4	5	4
Number of thyristors	4	2	1
Reflected current to source	Zero	High	Moderate
Common ground	No	Yes	Yes
Peak forward-blocking voltage of thyristor [69]	$> V_S$	$> V_S$	V_S
Number of semiconductor devices when conducting	2	2	3
Power loss when conducting	Moderate	Moderate	High
Overall cost	Highest	High	Moderate

arrangement, a topology based on a three-coil transformer was presented in [72]. In [73], a topology based on two-coil coupled inductors is presented, which reduces the volume of the bidirectional device even further. However, it features three semiconductor components on the main circuit during its normal operating state, and on-state losses are high.

To reduce on-state losses in the topology presented in [73], three bidirectional Z-SSCBs based on a diode bridge and a coupled inductor were introduced [74]–[77]. These are shown in Fig. 6(d)–(f). During normal operation, these topologies have two semiconductor components on the main circuit where the current flows, which reduces on-state losses. When the topology in [76], [77] is used for bidirectional protection, the turns ratio of the coupled inductor should be equal to one, and the threshold current of the fault on both sides should be the same [78]. This prevents from adjusting the turns ratio of the coupled inductor for a load step.

Although on-state losses of bidirectional Z-SSCBs can be reduced by using wide bandgap materials, their price would inevitably rise. Reducing on-state losses by limiting the number of semiconductor devices on the main circuits of the devices has been the preferred approach. References [78] and [79] introduced two simpler bidirectional topologies, termed O-Z and Q-Z. During normal operation, they have a single semiconductor component in the main circuit, which reduces on-state losses significantly. Particularly, the Q-Z CB improves sensitivity of the magnetic coupling coefficient present in the

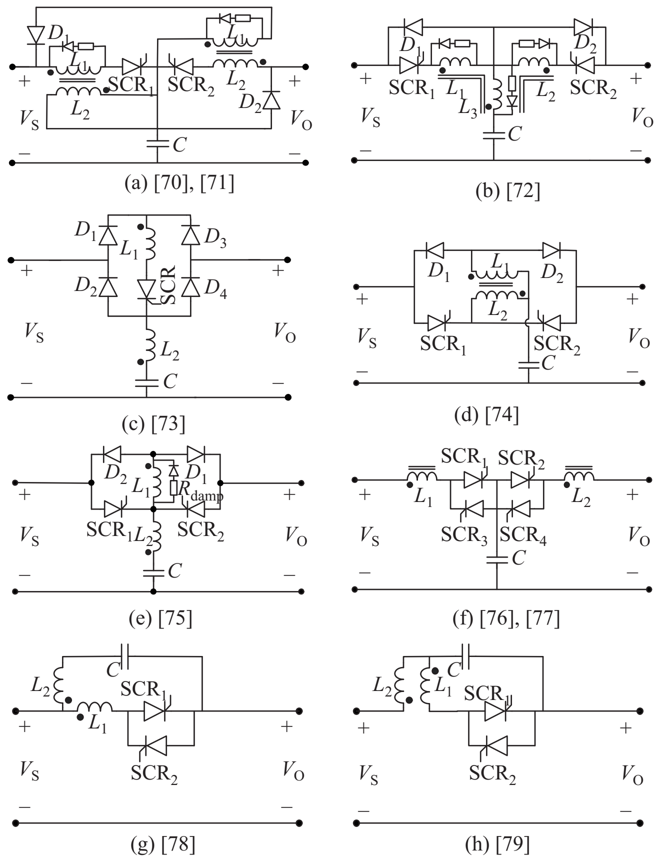

Fig. 6. Bidirectional topologies based on coupled inductors [70]–[79]. ©[2022] IEEE. Reprinted, with permission, from [70]–[74], [76]–[79].

O-Z topology. Also, the Q-Z CB requires less capacitance for practical applications with non-ideal magnetic coupling coefficients, which can translate to a lighter weight and lower cost [79]. However, when these devices eliminate a short-circuit fault, they still feature a reflected current to the source.

IV. Discussion on the Improvement of Z-SSCB Topologies

A. Manual Triggering

Z-SSCBs only work for small impedance short-circuit faults with a specific fault current ramp rate and magnitude, and the triggering conditions are too strict to protect against large impedance short-circuit faults [49], [87], [88]. In response to this, a manual triggering approach may be used to resolve the issue. This is illustrated in Fig. 7.

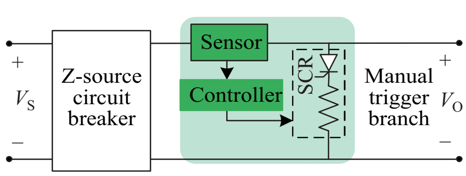

Fig. 7. Auxiliary turn-off of Z-SSCBs.

As shown in Fig. 7, a manual triggering branch could be added directly to the Z-source structure for unidirectional Z-SSCBs, as well as a current sensor and a control circuit. In this upgraded configuration, when a sensor detects a current greater than a predetermined threshold, the controller enables the manual triggering branch to generate a transient short-circuit fault, enabling the Z-SSCBs to interrupt and isolate the short-circuit fault current.

Two methods for manually triggering the unidirectional series Z-SSCB were presented in [58] and are shown in Fig. 8. In Fig. 8(a), a manual triggering branch (for an external artificial fault) was added at a location where short-circuit faults frequently occur. The branch consists of a controllable switch and a current-limiting resistor, and the size of the fault current can be controlled by adjusting the size of the resistor. The presence of D_{block} reduces the amount of current required to trigger the CB by limiting the inflow of capacitive load current.

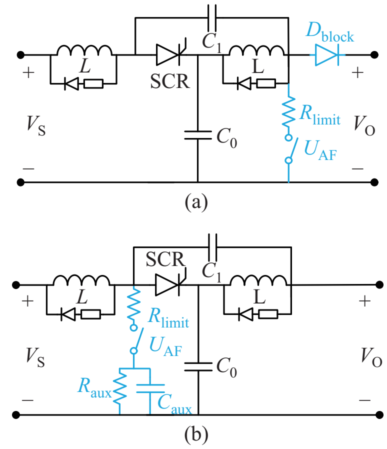

Fig. 8. Two ways to manually trigger a Z-SSCB: (a) external artificial fault near the output, and (b) internal artificial fault within the CB [58]. ©[2022] IEEE. Reprinted, with permission, from [58].

Figure 8(b) shows a method for introducing an internal artificial fault by modifying the position of the auxiliary turn-off branch. When the auxiliary thyristor U_{AF} is turned on, capacitor C_0 and the capacitive load discharge, resulting in formation of paths C_0-SCR-C_{aux} and C_{load}-C_1-C_{aux}. This causes the current flowing through the main circuit thyristor SCR to drop to zero and, thus, enables the main branch thyristor to be turned off. When the manual triggering branch selects an additional thyristor to control the opening and closing actions, capacitor C_{aux} will be charged after U_{AF} is closed [58]. Once C_{aux} is fully charged, the thyristor in the manual triggering branch turns off naturally in preparation for subsequent auxiliary closing.

These two artificial triggering methods require twice the rated load current but ensure that unidirectional Z-SSCBs are correctly triggered to isolate the power supply. This means that a fault current-limiting resistor can be half the size of the load resistance [68]. In practice though, fault current can rise further due to delays in sensors or control signals, so it should be decreased further. This may be achieved by reducing the resistance value of the fault current-limiting resistor.

Similarly, to ensure bidirectional protection in bidirectional Z-SSCBs, the simplest and easiest method to achieve this is to add a manual triggering branch at both the input and the output of the device, as shown in Fig. 9.

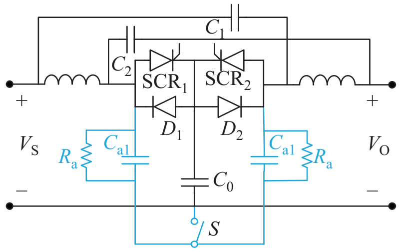

Fig. 9. Manually triggering method presented in [68]. ©[2022] IEEE. Reprinted, with permission, from [68].

Furthermore, those methods in [58] and [68] allow Z-SSCBs to be used as a switch when required, thus enabling control of the circuit's opening and closing. In any case, while these methods improve reliability of the CBs, addition of the control circuit complicates their construction and control.

To further simplify the structure of the manual triggering branches and to reduce their number, bidirectional Z-SSCBs topologies may be combined. As shown in Fig. 10, a method of combining the bidirectional structure with a manual triggering branch is used [74]. This configuration combines the branch with the bridge structure, and manual triggering can be achieved regardless of whether the CB is operating in a forward or a backward energy flow—thus simplifying circuit structure and reducing complexity of its control.

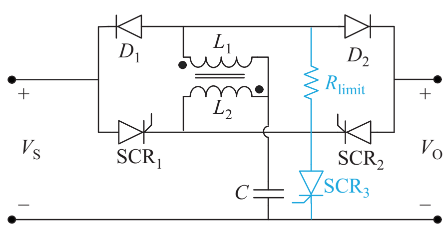

Fig. 10. Manual triggering method for bidirectional protection by one manual triggering branch. ©[2022] IEEE. Reprinted, with permission, from [74].

When coupled with a manual triggering branch, the turn-off logic of Z-SSCBs is similar to that of mechanical and hybrid CBs, both of which isolate short-circuit faults after receiving a turn-off signal. The main difference is these CBs need to open their mechanical switch after receiving a signal, whereas a Z-SSCB triggers the manual triggering branch (consisting of a thyristor and a resistor in series) to isolate faults. As a result, the Z-SSCB with a manual triggering branch still exhibits faster response than mechanical and hybrid CBs despite the additional components.

Given that CBs automatically respond to fault current and interrupt it in the event of a low impedance short-circuit fault, it is difficult to coordinate operation of Z-SSCBs with protection schemes of distribution networks. However, by integrating a manual triggering branch to the Z-SSCB, this issue can be circumvented as triggering control logic can be considered directly by the protection scheme. This way, a coordinated operation to remove loads or short-circuit faults as required, can be achieved.

B. Safe Re-start and Re-breaking

The discussed references so far, whether on unidirectional or bidirectional Z-SSCBs, do not consider the device's safe re-start and re-breaking functions [89]. These refer to re-conduction of the thyristor in the main circuit when a short-circuit fault still exists and the CB can still isolate the fault current instantaneously.

One of the most critical issues is recharging the capacitors in CBs in enough time following a discharge to allow the breaker to be turned off again. This issue can be solved by making structural changes to existing topologies. Fig. 11 shows improvements for the topologies presented in [59], [60], as well as topology reported in [74], [75].

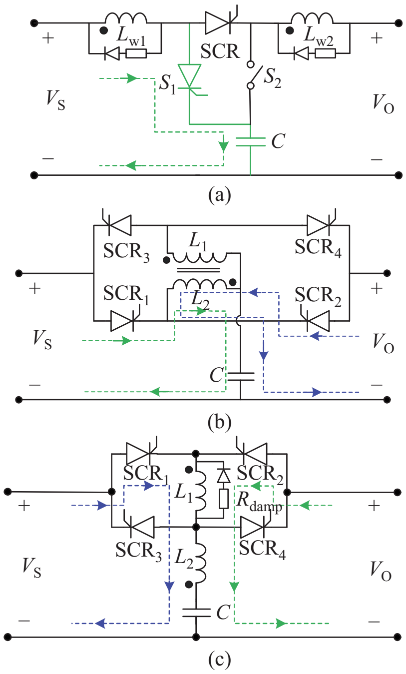

Fig. 11. Modification of Z-SSCB topologies for a safe re-start function. Improvement for topologies presented in: (a) [59], [60], (b) [74], (c) [75].

As shown in Fig. 11, capacitor C is connected to the voltage source through a thyristor to ensure a safe restart of the CBs by pre-charging C. After a short-circuit fault occurs, C is discharged to achieve short-circuit interruption and isolation, and its voltage is reduced to zero. After thyristor SCR in the main circuit is turned off, C is recharged by the voltage source, ensuring the thyristor in the main circuit conducts again before the short-circuit fault is completely cleared to achieve another instantaneous discharge of C—thus isolating the fault current against a short-circuit once more.

C. Integration of Z-SSCBs with DC Converters

DC converters and DCCBs are two essential devices in DC systems. Normally, these elements are used in series to separately perform energy conversion and short-circuit protection, but their physical location may affect their respective performance. During normal operation, power quality is affected due to the presence of a DCCB —particularly reflected with an increase in voltage and current ripples of the converter output.

Conversely, during a fault condition, the converter influences whether the breaker can be switched off normally [90]. These are examples of issues to be considered in the design and application of DCCBs.

The utilization rate of a DCCB within a DC system is expected to be low, so its inclusion needs to be considered with care. However, by integrating a DCCB with DC converters which share common components, the overall number of elements can be reduced, which in turn may decrease costs. In addition, it is possible to improve power quality while guaranteeing system protection.

Figure 12(a) shows a buck converter integrated with a Z-SSCB as proposed in [91]. Similarly, Fig. 12(b) shows a boost converter integrated with a Z-SSCB reproduced from [92]. To interrupt a short-circuit current following a fault, both converter configurations consider additional thyristors in the main circuit and their inductors are replaced by coupled inductors. During normal operation, the converter charges capacitor C to the power supply voltage. When a short-circuit fault occurs, C discharges and the thyristor is turned off by using the induced current of the coupled inductor, which is similar to the operating principle of a Z-SSCB. Thus, energy conversion during normal operation and fault current isolation during short-circuit faults can be performed with fewer components.

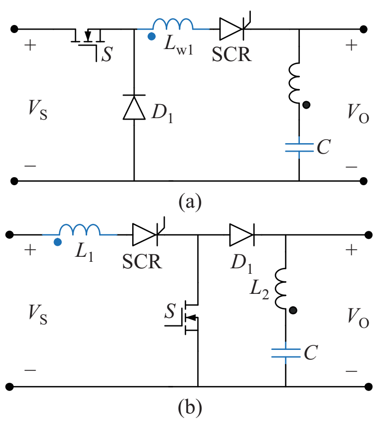

Fig. 12. Power converters integrated with Z-SSCBs: (a) buck converter, (b) boost converter. ©[2022] IEEE. Reprinted, with permission, from [91] and [92].

D. Discussion on Power Rating, Cost, and Reliability

The maximum power rating of a Z-SSCB is primarily determined by the power rating of the power electronics device within the CB. As a result, the difference in power rating between the presented topologies is determined by the type of thyristor employed and, in practice, all that is required is selecting the appropriate type based on available levels for voltage and power rating.

A comparison between conventional topologies for unidirectional Z-SSCBs reveals that all use the same number of passive components and thyristors, with each consisting of two inductors, two capacitors, and one thyristor. Similarly, almost all unidirectional Z-SSCBs based on a coupled inductor have three components: a coupled inductor, a thyristor, and a capacitor. Therefore, unidirectional Z-SSCBs based on a coupled inductor have the fewest components and are likely to be more economical than conventional unidirectional topologies for equivalent power ratings.

Similarly, bidirectional Z-SSCBs, based on a coupled inductor, are less expensive than traditional bidirectional devices for an equivalent power rating, with the O-Z and Q-Z topologies offering the simplest constructions and thus lowest prices [79].

With regards to reliability, Z-SSCBs based on a coupled inductor can be made more reliable by adjusting the turns ratio of the coupled inductor so it is capable of withstanding sudden changes in load. At the same time, by adding manual triggering branches, all Z-SSCBs will be able to handle effectively high impedance short-circuit faults and achieve a controllable turn-off, which increases their reliability [58]. Having said that, an in-depth comparison on reliability of Z-SSCBs (e.g. with regards to success rate per a given number of cycles) is missing in literature.

V. Future Trends

As a critical protection device for prospective DC distribution systems and DC power loads, additional research is required on Z-SSCB topologies. Research should be extended to their re-opening and manual triggering controls, and it could consider a coordinated control of multiple CBs.

Because current in the main branch always flows through a semiconductor device during normal operation of Z-SSCBs, reducing on-state losses is a concern. One approach is to replace silicon devices with wide bandgap devices as these exhibit lower on-state losses [93]–[95]. However, this approach is currently limited by the development of wide bandgap devices such as silicon carbide (SiC) based switches. Further increase of their voltage ratings would be needed, and synchronization of the turn-off of SiC switches would be critical and challenging due to their fast switching. Another alternative is to optimize topology of the Z-SSCB further so the main branch current flows through the fewest possible semiconductor devices.

Considering the relatively low utilization rate expected from a Z-SSCB, integrating this device with DC converters constitutes a promising area of research which should be developed further. An integrated design would optimize the utilization of common components, as well as maximizing power quality of the converters while guaranteeing short-circuit protection performance.

DC distribution grids may adopt various configurations including radial, ring, and double circuit radial topologies. To achieve full protection of grids with multiple nodes, suitable Z-SSCBs should be selected, or redesigned for protecting multiple nodes. Based on existing structures, integrated Z-SSCBs may be developed to protect multiple nodes and hence reduce costs by sharing key components.

VI. Conclusion

The need for DC transmission technologies within the context of grid integration of renewable energy sources for the decarbonization of electrical power systems, their application in transmission and distribution networks, and the classification of DCCB topologies for their protection was discussed. Following this introductory context, this paper examined the current state-of-the-art of Z-SSCB configurations and summarized key characteristics of their various topologies. For simplicity, these have been classified as unidirectional and bidirectional. Unidirectional topologies based on coupled inductors offer the best reliability and power density. For bidirectional Z-SSCBs, the Q-Z structure is the simplest and exhibits the lowest on-state losses.

Methods for manual triggering of Z-SSCBs were also reviewed. Such methods ensure successful triggering of the device when the system impedance is high by adding additional manual triggering branches. This is because a failure of triggering may occur for systems with increased impedance. Simplification of the manual triggering branches is viable for bidirectional Z-SSCBs, reducing their overall cost and volume.

A safe re-start function of Z-SSCBs was discussed. A method was presented to ensure re-conduction of the thyristor of the CB if different fault events occur.

Finally, challenges faced by Z-SSCB devices and future development directions were discussed. The most critical challenges are to reduce power loss of the device and their adoption for protecting DC grids with multiple nodes. Potential solutions are to use wide-bandgap devices and develop integrated Z-SSCB topologies which share key components of the currently available options.

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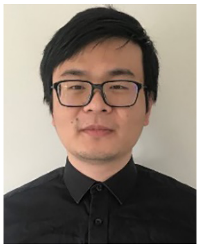

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