A Survey on Configurations of Current-Limiting Circuit Breakers (CL-CB)

Chunyang Gu[1], Pat Wheeler[1], Alberto Castellazzi[1], Alan J. Waston[1], Francis Effah[2]

[1]The University of Nottingham
Tower Building, University Park,
Nottingham, UK, NG7 2RD
E-Mail: chunyang.gu@nottingham.ac.uk

[2]The University of Mines and Technology
Dept. Electrical & Electronic Engineering,
P. O. Box 237, Tarkwa, Ghana
E-Mail: fbeffah@umat.edu.gh

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Abstract

This paper presents a survey of topology configurations of current-limiting circuit breakers. Twelve different current-limiting topologies within four categories are detailed discussed and compared. It is concluded that active CL-CB may be a good choice for AC for its controllable reactive power capability to increase stability and multi-function protection.

Introduction

For power distribution systems, the most important responsibility is to protect equipments against overloads and short circuits. Circuit breakers are the effective measures of these protections. As the interrupting current rating becomes higher and higher, the fault current of AC distribution systems must be interrupted before it has reached the maximum value, or the terminal equipments and the destitution cable might to destroyed [1]. In a simple low-voltage system having a main power circuit breaker and several molded-case circuit breakers (MCCB), the main circuit breaker must be able to close and latch into a fault with limited current value until the MCCB clear the downstream fault, and the MCCB may be allowed to trip very rapidly to minimize the damage [2].

It is obvious that, from both technical and economical points of view, a device that reduces the short-circuit currents is needed [3]. Other common measures to limit the short-circuit current are increasing transformer reactance or using additional reactors which will influence the network under normal conditions. Thus, circuit breakers which could limit the current in fault conditions but normally work with no additional impedance are needed.

A current-limiting circuit breaker can be used to mitigate voltage sags caused by faults. The fault-current limiters are needed to provide a limited, but sustained short-circuit current through the fault for a sufficient time (e.g. 1s) to enable proper coordination of protection relays. In some cases, they may also be used to maintain sustained short-circuit current through a cable that has developed an intermittent fault to enable fault location [4]. A current-limiting circuit breaker allows equipment to remain in service even if the prospective fault current exceeds the rated short-circuit current [5].

General requirements of current-limiting circuit breakers may be: (a) Negligible influence (impedance) on the network under normal conditions; (b) High-speed limitation of fault currents; (c) Repetitive operation and short recovery time (good maintenance); (d) High reliability; (e) Low power loss in normal operation; (f) Simple structure with small size and low cost.

It is apparent that no single design concept can be used universally for current limiting with all applications. There are two kinds of current-limiting requirements: fast breaking at certain current limits and maintaining supply with a limited current. The former is for end facilities, and the latter is for grid circuit breakers (transmission or distribution).

Fast-breaking Circuit Breakers

Fast-breaking circuit breakers with fuses

A current-limiting fuse is a valuable method of current limiting which has the ability to interrupt large values and fault current, with interruption occurring before the fault current has reached the maximum value [1]. Primarily, the current-limiting fuse gives the short-circuit protection rather than an overload protection.
When the fuse element of a current-limiting fuse melts, it vaporizes, becoming an arc with considerable resistance. The fault current is then brought down to a current zero and to extinction. A current-limiting fuse usually has the continuous current ability of 12 to 16 times of rated current, and a melting characteristic of 30 to 40 times of current rating.
As the most developed current-limiting method, some standards and application guides have been made for circuit breakers with current-limiting fuses [7]. The time-current characteristics of fuses must be larger than that of the cooperating circuit breaker, so that it is a useful method for protect huge short-circuit current, but not for smaller amount of overload protection. Other drawbacks of current-limiting fuses are unclear breaking time (longer breaking time with lower current) and poor maintenance (the fuse must be replaced after breaking process). The supporter of current-limiting fuses announced that adding impedances to a system have the undesired effect of poor voltage regulation, poor power factor and added losses to a system. But as the advantage of this designation is acceded by fast-breaking circuit breakers with mechanical or solid-state switches, current-limiting fuses are becoming backups and even historical remains.

Fast-breaking mechanical circuit breakers

Fast mechanical switches can be used to replace current-limiting fuses [8, 10, 11]. With the action time of several hundreds of microseconds, it is possible to break a 50Hz/60Hz AC current before it has reached the maximum value [12, 16].
Reference [9] gives a brief operation introduction of molded-case circuit breaker (MCCB) with normal mode as well as with current-limiting mode. An MCCB is usually made up of several important elements: (a) contacts; (b) moving contact arms; (c) an arc chamber to extinguish the arc; (d) an opening mechanism tripped by a latch. The current-limiting MCB operates in a slightly different mode: clear short circuits independently of mechanism operation, that is, contacts will open, clear the circuit, and remain open without any action from the mechanism. The mechanism will de-latch and open independently of the faster contacts [2]. The arcing phenomena of low voltage current-limiting miniature circuit breakers (MCB) were presented in [13, 14]. The arc is forced rapidly away from the contacts through an arc chamber and into a set of splitter plates. The motion of the arc is dependent on a complex interaction of the anode and cathode root and the arc plasma motion.
Reference [15] gives a predicting method of let-through arc-flash energy of current-limiting circuit breakers. This evaluation proposes a better method to predict the arc-flash performance of current-limiting circuit breakers.
Fast-breaking mechanical switches are the fundamentals of mechanical parts of hybrid circuit breakers.

Fast-breaking hybrid circuit breakers

In 1994, Japanese experts proposed a current-limiting circuit breaker for 400V class electric power systems [16]. As shown in Fig. 1, the equipment consists of high-speed mechanical switch paralleled with solid-state switch (GTO), snubber circuit and voltage limiting element (ZnO arrester), which is a typical topology of hybrid circuit breaker. The drive system of the high-speed mechanical switch uses an electromagnetic repulsion force to open the circuit at high speeds. GTO is chosen as the solid-state part of the circuit breaker to obtain a large interrupting capacity. When a fault occurs in the system, current increases suddenly. The fault is detected and the GTOs are turned on. The mechanical switch is open at the same time. As a result, an arc is generated between the contacts and the arc voltage forces the current to commutate from mechanical switch to the solid-state switch. When the fault current is completely commutated to the GTO, GTO interrupts the fault instantly. The time from fault occurrence to current interruption is less than 1ms which is about 100 times as fast as that of mechanical circuit breakers.

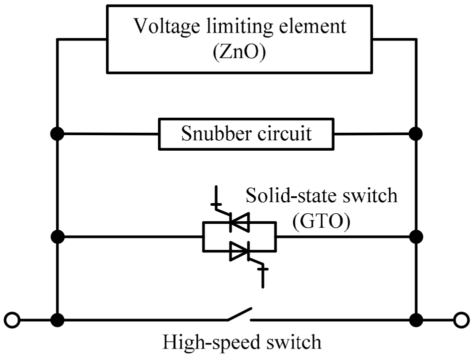


Fig. 1: A current-limiting circuit breaker for 400V class electric power systems in 1994.

Current-limiting Circuit Breakers with Switched Resistive Components

Current-limiting circuit breakers with ordinary resistors

In 1980, EPRI had proposed a switched impedance method for current limiting with resistor and vacuum current limiter (mechanical switch), as shown in Fig. 2. The vacuum current limiter contains separable contacts that are normally closed and carry the continuous current [17]. When a fault occurs, the contacts are rapidly separated during the rise of the fault current, which results in a rapid rise in the arc voltage of the vacuum current limiter. This arc causes the current to be diverted from the vacuum current limiter into the parallel capacitance, thus extinguish the arc. Then the current continues to flow into the parallel capacitor and resistor, which limits the fault current.

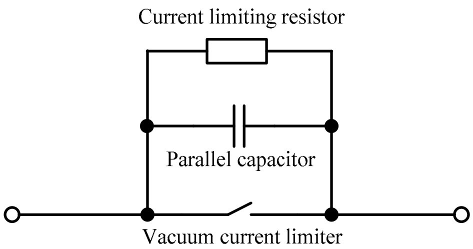


Fig. 2. EPRI switched impedance method with resistor and mechanical switch in 1980.

In [18], a high speed switch (HSS) with an electromagnetic repulsion mechanism and a new spring mechanism was developed with the open time less than 1ms. Reference [18] also proposed a current-limiting device with HSS, as shown in Fig. 3. The device consists of the HSS, a counter pulse circuit, and a limiting resistor. A forced current zero is made by a superposition of a counter pulse current on the short-circuit current. The current is interrupted by HSS at the forced current zero and commutated to the limiting resistor. The transfer of fault current from mechanical switch to the parallel resistor in the middle of a current loop is more complex than it seems, so that instead of mechanical switch, semiconductor switches with snubber circuits and arrestors are with better performance.

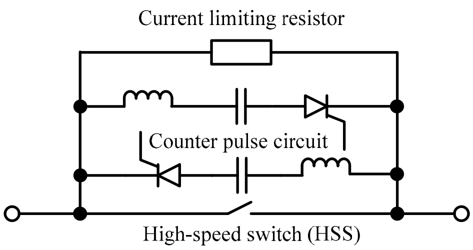


Fig. 3: Current limiting device with high-speed switch and resistor in 1998.

In [19], a current limiter with resistive components was proposed for 22kV distribution system with almost the same topology of Fig. 3. The mechanical switch is called as a commutating unit. The commuting unit is activated by the electromagnetic force of the fault current, which is designed with compactness, cost reduction and repeated usage.

Fig. 4 shows a hybrid current-limiting circuit breaker with separated current limiting path for two current flowing directions [20] which consists of two high-speed mechanical switches connected in series to carry main current under normal conditions. For a fault current interruption, depending on the current direction, one of the mechanical switches is open. The current is commutated to one of the current-limiting impedances (usually resistors).

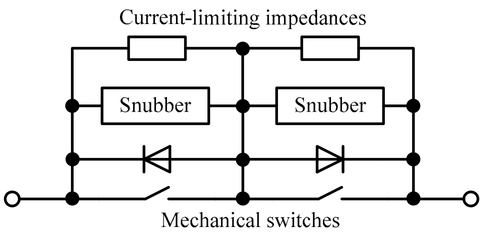


Fig. 4: Hybrid current-limiting circuit breaker with separated current-limiting path in 2009.

Current-limiting circuit breakers with PTC thermistors

In 1996, a hybrid configuration of current limiter with PTC resistor is proposed [2], which is developed on the basis of Fig. 1, as shown in Fig. 5. The mechanical contact is used to provide the main current path. When a fault occurs, the contacts are separated. This results in an arc which forces the current to the parallel path provided by GTO devices with a PTC thermistor in series. As the current continues to increase through the PTC resistor after commutation completion, PTC resistance increases which results to current limitation. After the circuit interruption, PTC thermistor cools down and attains the conductive state.
In 2003, a hybrid current-limiting circuit breaker with PTC resister is propose in [21], as shown in Fig. 6, which consists of a mechanical fast-opening transfer switch (FTS), mechanical fast-opening disconnecting switch (FDS), a bi-directional semiconductor switch with four diodes and a GTO, a PTC element and a mechanical load switch (LS). When a fault occurs, FTS open which causes an arc voltage of several tens of volts which forces the current to commutate to semiconductor switch where GTO and FDS are already turned-on. After complete current commutation, the GTO is turned-off, forcing the current to the PTC resistor. The large current flowing through PTC resistor leads to large power dissipation in it causing huge increase in its resistivity and voltage drop across it. The limited current is finally interrupted by opening LS.

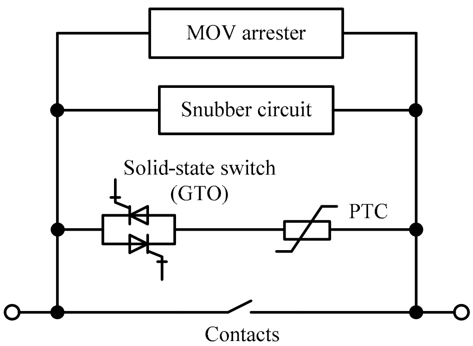


Fig. 5: Hybrid current limiter with PTC resistor in 1996.

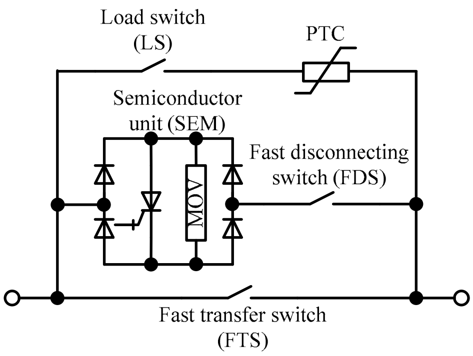


Fig. 6: Hybrid current-limiting circuit breaker with PTC in 2003.

Current-limiting circuit breakers with superconductors

In 1995, high critical temperature superconductors are introduced as fault current limiters [3]. The outstanding electrical properties of superconductors are zero resistivity below a critical temperature and a critical current density; and the resistivity increases rapidly when the temperature and current density surpasses. Although the superconductors are complicated and expensive, it may be good choice for power distribution network applications [22-24].
An HVDC hybrid superconducting circuit breaker with current limiting capability is proposed in [25], as shown in Fig. 7. When a fault occurs, the fault current is automatically limited by the superconductor fault current limiter (SFCL). After a trip signal, the line commutation switch (LCS) is open and causes the fault current to flow through the main circuit breaker (MCB). Once all the current flows through the main path, the ultrafast disconnector switch opens. Finally, the main circuit breaker will break the fault current with the help of arrester.

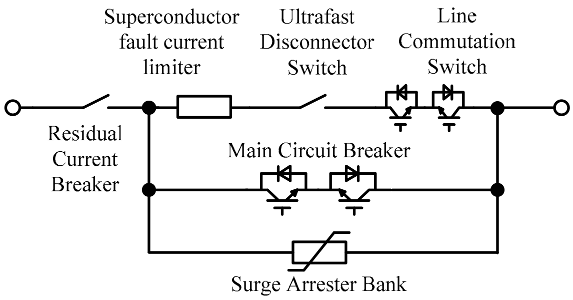


Fig. 7: HVDC hybrid superconducting circuit breaker with current limiting capability in 2015.

Superconductors, as a variable resistor, could be either used to limit fault current itself by absorb the energy or used as an automatic current-commutating switch to transfer the current from main path to an auxiliary path [26].
Superconductors, as a main part of current-limiting devices, could be also operated in inductive mode, as described in [43, 44], which is not introduced in this paper in detail.

Current-limiting Circuit Breakers with Other Switched Components

Inductive components are commonly used in power systems for reduction of the short-circuit power. However, when they are activated rapidly by the solid-state switch, significant over-voltages occur in the grid until the short-circuit current is commutated to the inductor.
In contract to that, no over voltage occurs with capacitive limitation, since the current can instantaneously commutate to the capacitor. However, the current is not limited properly directly after the switching. Consequently, longer and deeper voltage sags occur with capacitive limitation.
Both mentioned disadvantages can be avoided when a proper combination of inductor and capacitor is applied. Other advantage of L-C combination components is that switched resonant circuit could be formed with the impedance from negligible to very big, which is suitable for current limiting.

Current-limiting circuit breakers with inductive components

Inductive components are the first thought to limit fault current [27]. As the fault protect devices are usually placed in series with the load, reactor is more appropriate choice rather than a capacitor. As no active power loss was added to the system, the reactor was added to the distribution systems with no switches [27], which had the undesired effect of poor voltage regulation.
In 2008, a complex superconductor fault current limiter was proposed in which superconductor works as current-commutating element and inductors work as current-limiting elements [26]. As shown in Fig. 8, the superconductor element offers negligible impedance to the normal current path. The inductance of L2 is larger than that of L1. In case of a fault, the fault current is mostly going through superconductor. When a fault occurs and the current increase, the superconductor resistance increases rapidly and forces the current to commutate to the path of inductors. After sensing the complete separation of mechanical contact, the semiconductor switches will be turned off and the fault current is limited by the large impedance of L2. This is actually a complex structure with both inductive and superconductor components, which is too complex for real applications.

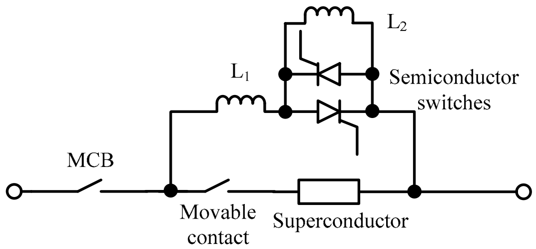


Fig. 8: A complex superconductor fault current limiter in 2008.

Fig. 9 shows a bridge type solid state fault current limiter based on AC/DC reactor[28]. In normal operation mode, T1, T2 are off, and T3, T4 are on, the configuration is a DC reactor type with negligible effect on the network power quality. In fault operation mode, T1, T2 are on, and T3, T4 are off, the configuration changes form DC reactor type to the AC reactor type. Then the reactor's AC impedance decreases the amplitude of the fault current.

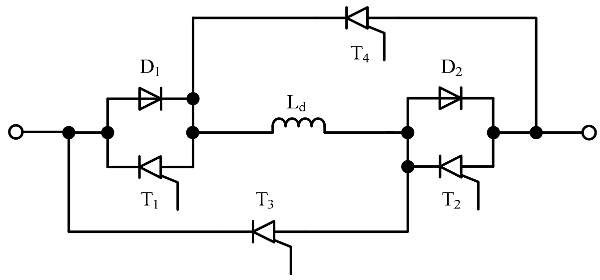


Fig. 9: Solid state fault current limiter based on AC/DC reactor in 2015.

Current-limiting circuit breakers with L-C components

In 1980, EPRI had proposed a tuned impedance current limiter, as shown in Fig. 10. Under normal load condition, the switch is open, each of the two parallel branches represents a series L-C circuit with an essentially zero impedance (resonant frequency is 60Hz). When a fault occurs, the switch is closed which adds a resistor between the two parallel tuned L-C circuits. The resulted impedance is resistive so that the fault current is in phase with the voltage [17].

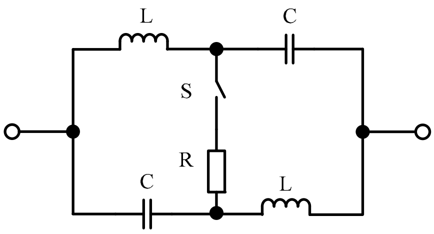


Fig. 10: EPRI tuned impedance current limiter in 1980.

The experts in Technical University of Gdansk proposed their hybrid current-limiting interrupting device (HCLID) in 1998, with the configuration of L-C counter current injection circuit [29, 30], as shown in Fig. 11. The HCLID consists of a very fast mechanical contact opened by electrodynamic repulsion force, two diodes, an inductor, a pre-charged capacitor and two thyristors. To limit and interrupt a current, depending on the current direction at the instant of start of operation, one of the thyristors is gated-on. With pre-charged C, it drives a counter-current in the opposite direction to the main current and flowing through the mechanical switch. This results in reduced current and then the mechanical contact is opened at a fast rate with limited arcing. The current will then commutate to the corresponding semiconductor elements, which are with L and C in the current flowing path. Nevertheless, the pre-charged capacitor and additional passive elements increase the complexity, size and cost of this topology. The authors suggest that it could be one of the most effective configurations available for low voltage current-limiting and interrupting devices.

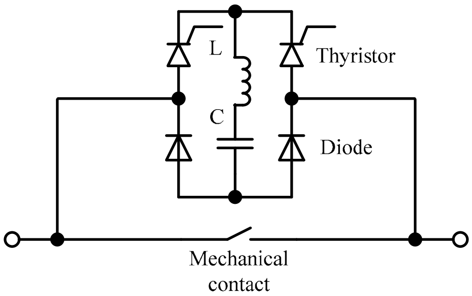


Fig. 11: Hybrid current-limiting interrupting device (HCLID) in 1998.

Reference [31] proposed a solid-state current limiter with L-C current-limiting elements for medium-voltage systems in 2002. With L-C components connected paralleled with the GTO solid-state switches, current can still flow through the reactive element when turning off the switches. The limited current is chosen to be lower than the short circuit current of the grid but higher than the nominal current of that path.

Fig. 12 shows a hybrid current-limiting circuit breaker with very complex tuned L-C elements [32]. Under normal condition, the current flows through the mechanical switch and series-connected leakage inductor of the transformer and C2, which form a resonant circuit with negligible impedance. In case of a fault current, the mechanical switch is open with little arc and forces the current to commutate from main path to the series connection of S1 and C1, where S1 is a bi-directional controllable semiconductor switch (e.g. thyristor, GTO, IGBT and IGCT). The series combination of C1 with the remained circuit results in a very high impedance with significant current limitation. The current-limiting capability is strengthened by close S2 to add more resistance and inductance. A power dissipative element is used to absorb the remaining circuit energy when the circuit breaker is turned-off to interrupt the current.

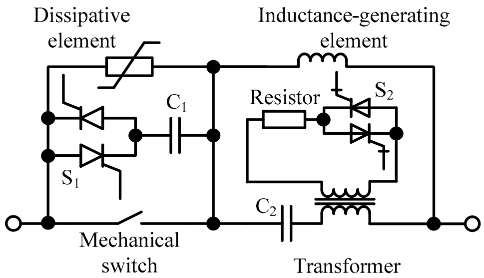


Fig. 12: Hybrid current-limiting circuit breaker with complex tuned L-C elements in 2012.

Fig. 13 shows a solid state fault current limiting circuit breaker (SSFCLCB) using resonant L-C tank for medium voltage network applications [33]. Because of the series configuration of the resonant structure, the SSFCLCB is with negligible impedance during normal operation mode. In fault conditions, the SSFCLCB topology change to a rectifier bridge and feeds the resonant structure with rectified AC voltage. As a result, the fault line is opened and the fault current is limited. In normal operation mode, T1, T2 are on, and T3, T4, T5 are off, the current go through the L-C tank with a small impedance. In fault operation mode, T1, T2 are off, and T3, T4, T5 are on, the rectified AC voltage is applied to the L-C tank. The SSFCLCB can return the system to the normal state after fault removal.

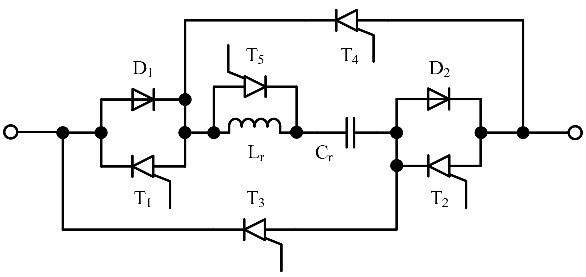


Fig. 13: Solid state fault current limiting circuit breaker using resonant L-C tank in 2015.

Current-limiting Circuit Breakers with Controlled Semiconductors

Current-limiting circuit breakers with semiconductor switches and energy absorbers

A solid-state fault-current limiting and interrupting device (FCLID) is proposed in [4], as shown in Fig. 14. The FCLID consists of bi-directional semiconductor switches (e.g. IGBT, MOSFET) paralleled with RC snubber circuit and a varistor (nonlinear resistor). The semiconductor switches are controlled in PWM mode to limit the fault current. When the switch is on, the current increases rapidly. When the switch is off, the current decreases and the energy of the line inductor is absorbed by the varistor (e.g. an MOV arrest). Discontinuous line current is achieved by using this control method.

A very important thing is that when with short-circuit conditions, the fault current is limited with a value larger than nominal rating, and a power loss larger than path nominal rating must be absorbed by the MOV. The ultimate reason of this big power loss is that the certainly big active power (input voltage, big input current with almost unity power factor) must be absorbed by some resistive elements. As a result, huge MOV components are need for long term operation.

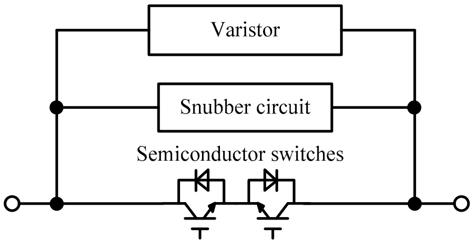


Fig. 14: Solid-state fault-current limiting and interrupting device (FCLID) in 2006.

A multifunction hybrid solid-state switchgear is proposed in [35], as shown in Fig. 15. When a fault current is detected, the fast mechanical switch can be quickly turned off. The current can then be transferred to the solid-state switch for fault limiting and clearing operations. The gate signal of the controllable semiconductor device (e.g. GTO or IGBT) can be a PWM mode signal or a linear current mode signal which goes to zero exponentially. With the limited fault current, the fault can be cleared properly.

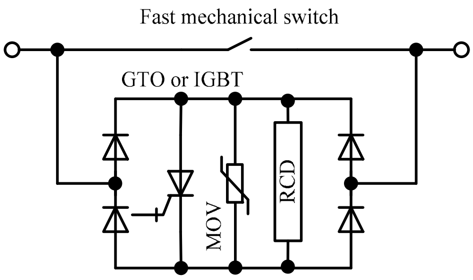
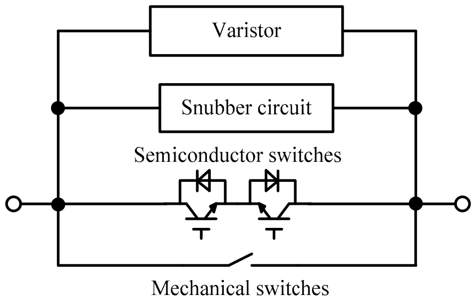


Fig. 15: Multifunction hybrid solid-state switchgear in 2008.

A hybrid current-limiting circuit breaker with the same principle of [4] is proposed in [34] in which a mechanical circuit breaker is added in parallel, as shown in Fig. 16. An alternative bi-directional semiconductor switch can be used to replace the common-emitter configuration. Detailed modelling and control is discussed in that paper, and the simulation results are no different from that of Fig. 14.



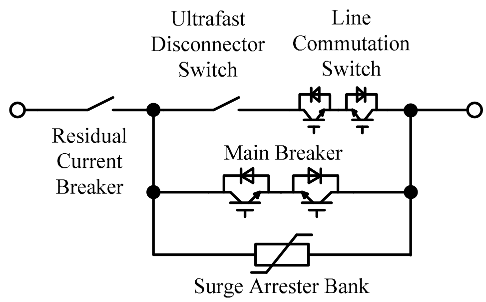
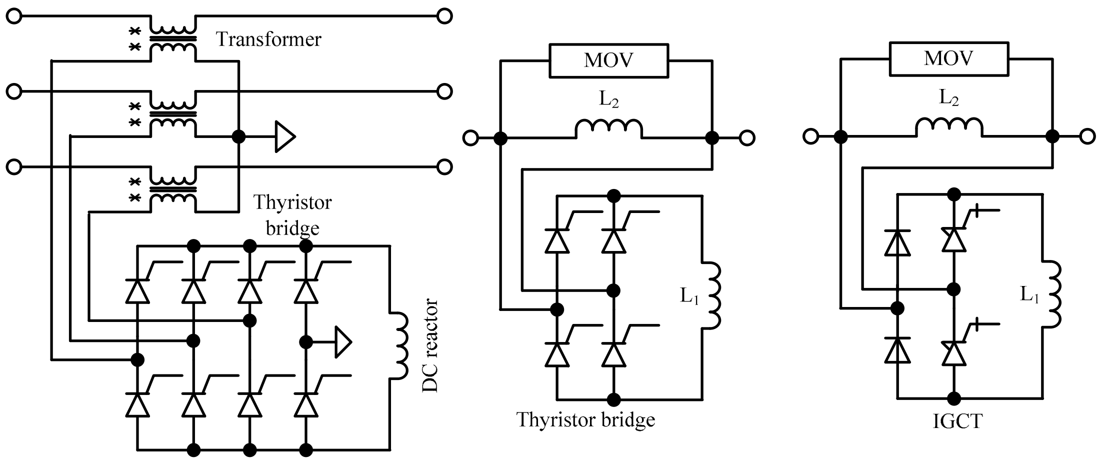


Fig. 16: Hybrid current-limiting circuit breaker in 2012. Fig. 17: ABB hybrid HVDC circuit breaker in 2011.

ABB, in 2011, proposes a hybrid HVDC breaker with either low power loss and no-arcing when interrupting [45], as shown in Fig. 17. The advantage of this hybrid circuit breaker is that no-arcing on the mechanical switch and little on-state loss of the semiconductor switch.

Bridge configurations of current-limiting circuit breakers (active CL-CB)

A bridge type solid state fault current limiter for medium voltage AC transmission systems is proposed in [36]. As shown in Fig 18, the solid state current limiter consists for three-phase series connected isolation transformer and a three-phase thyristor-type bridge with a reactor on the DC side. It is shown that in normal operation condition, the limiter has no obvious effect on loads. However it will insert an impedance automatically without delay to limit the short circuit current when fault happens. The thyristor bridge is controlled with variable trigger angle which limits the fault current.



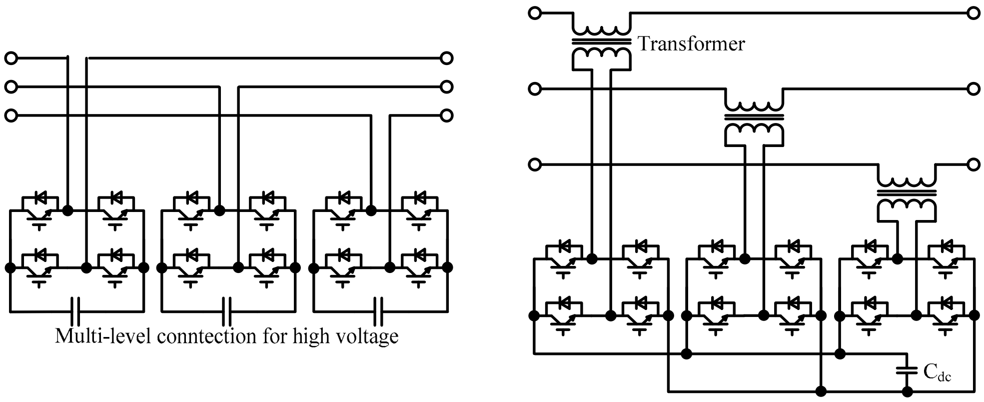
(a) Three-phase bridge with transformers. (b) Single-phase bridge. (c) Half-controlled IGCT bridge.

Fig. 18: Reactor-bridge type solid state fault current limiters.

By removing the transformers in Fig. 18(a), a single-phase fault current limiter is proposed in [37] with single-phase thyristor bridge and a DC reactor, as shown in Fig. 18(b). The idea is that a let-through reactor and thyristor bridge work together. The let-through AC reactor is to increase the high-level over-current ability. A MOV arrestor is required to clamp the voltage across the bridge. The topology can work at inverter state to make the reactor current controllable.

To improve the performance of bridge type fault current limiter, a similar topology is proposed in [38] using two diodes and two IGCTs instead of four thyristors, as shown in Fig. 18(c). For three phase systems, 6 IGCT devices, three bypass reactor, three DC current limiting reactors are needed. In normal condition, all the IGCT devices are gated on and remain conduction. The current flowing through L1 is a DC constant value, so that the voltage drop of L1 is zero. The existence of the fault current limiter has no harmful effect on the power system. When a fault occurs, simply open the IGCTs and the DC reactor current will flow through diodes, and the fault current is limited by bypass reactor L2. With the controlling of gate signal of IGCT instead of just switching, the fault current of this fault current limiter can also be controllable.

From 2000 until now, static synchronous series compensators (SSSC) is mentioned in several papers a fault current limiter [39-42] for power transmission and distribution. SSSC is a similar configuration of static synchronous compensator (STATCOM). But instead of paralleled in the system, SSSC is place series to the distribution line [46], as shown in Fig. 19. The SSSC is a serial connected reactive power compensator, which can provide controllable compensating voltage over an identical capacitive and inductive range [47]. Acting as serial-connected variable impedance, SSSC is a proper choice as multi-functional controllable fault current limiter with no resistive loss.



(a) single-phase H-bridge. (b) Three-phase bridge with transformer.

Fig. 19: An SSSC type fault current limiter in 2000 and 2012.

Table II. Assessments of current-limiting methods

Categories			Methods	Advantages	Disadvantages
Fast breaking	Single-use devices		Fuses [1, 6]	Small size and low cost	Poor maintenance, unclear breaking time
	Reusable devices		Fast mechanical switches [2, 7-15]	Relatively small size, low loss in normal operation	Electric arc with contact erosion, long operation time
			Fast hybrid switches [16]	Fast interruption, no arcing (depends on configuration)	Complex structure, relatively high cost
Current limiting	Devices with switched passive components	With resistive components	Switched resistor [17-20]	Relatively low cost, CL with constant resistive current	High power dissipation in CL mode
			Switched PTC thermistors [2, 21]	working with smoother current change and automatic limiting	High power dissipation in CL mode
			Switched superconductors [3, 22-26]	Automatic limiting with resistive current	High cost, large size for temperature care
		With other components	Switched reactors [26-28]	No additional heat, constant limiting current	Sensitive to frequency
			Switched L-C elements [17, 29-33]	Low impedance in normal mode, no additional heat,	Very sensitive to frequency
	Devices with controlled passive and semiconductor elements	With semiconductor switches and energy absorbers	PWM controlled semiconductors with discontinuous line current [4, 34]	Relatively simple structure, CL with resistive current	High power dissipation of MOV arrester in CL mode
			Linear region controlled semiconductors with continuous line current [35]	Relatively simple structure, CL with resistive current	High power dissipation of semiconductors in CL mode, complex control
		Other controlled configurations	Controlled bridge with reactor as FCL [36-38]	Controllable limited current, no additional heat	high current harmonics with SCR
			Static synchronous	Multi-functional , no	Relatively complex

			series compensators (SSSC) as FCL [39-42]	additional heat, controllable capacitive or inductive current	structure, capacitor charging problems

Conclusions

Table I gives the assessments of all 12 types of current-limiting methods discussed in this chapter.
It is apparent that for fast breaking requirement, current-limiting fuses are no longer a good choice. Fast mechanical circuit breaker with the capability of interrupting fault current in a few hundred of microseconds is a proper alternative. But improved mechanical structure is needed to be investigated. Hybrid circuit breaker is a good choice for medium and high voltage power grid with the capability of no-arcing interrupting. Superconductor type current limiting device is expensive and complex, which may only be used for HVDC systems and grid interconnection conditions.
For switched and controlled current limiting configurations, more or less semiconductor devices are used which influence the performance of current limiting. Resistive current limiters are with good performance but high power dissipation, so that they cannot be used for long-time limiting. Inductive or L-C current limiters could generate reactive power to limit the line current without additional heat, but their performance is sensitive to frequency change. Static synchronous series compensators (SSSC), as a multi-functional controllable fault current limiter with no resistive loss, are with great performance. Controllable capacitive or inductive current could be generated with PWM of active bridges.
Active CL-CB with SSSC may be a good choice for AC systems for its controllable reactive power generation capability to increase power system stability and its multi-function of short-circuit protection as well as over-load protection.

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