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Vacuum Switching Technology for Future of Power Systems

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ABSTRACT

Even though switching in vacuum is a technology with almost 100 years of history, its recent developments are still changing the future of power transmission and distribution systems. First, current switching in vacuum is an eco-friendly technology compared to switching in SF_6 gas, which is the strongest greenhouse gas according to the Kyoto Protocol. Vacuum, an eco-friendly natural medium, is promising for reducing the usage of SF_6 gas in current switching in transmission voltage. Second, switching in vacuum achieves faster current interruption than existing alternating current (AC) switching technologies. A vacuum circuit breaker (VCB) that uses an electromagnetic repulsion actuator is able to achieve a theoretical limit of AC interruption, which can interrupt a short-circuit current in the first half-cycle of a fault current, compared to the more common three cycles for existing current switching technologies. This can thus greatly enhance the transient stability of power networks in the presence of short-circuit faults, especially for ultra- and extra-high-voltage power transmission lines. Third, based on fast vacuum switching technology, various brilliant applications emerge, which are benefiting the power systems. They include the applications in the fields of direct current (DC) circuit breakers (CBs), fault current limiting, power quality improvement, generator CBs, and so forth. Fast vacuum switching technology is promising for controlled switching technology in power systems because it has low variation in terms of opening and closing times. With this controlled switching, vacuum switching technology may change the "gene" of power systems, by which power switching transients will become smoother.

1. Introduction

In China, enormous efforts have been dedicated to achieving a society of sustainable development and ecological civilization, by decoupling the air pollution from the marvelous economic achievement over the past three decades [1]. At the 21st session of the Conference of the Parties (COP21) occurred in Paris in 2015, China pledged to lower its carbon intensity by 60%–65% from the 2005 levels and to peak carbon emission by 2030 or earlier. Increasing the proportion of clean and low-carbon energy sources is important for a transition from relative to absolute carbon economy decoupling by 2030. Efforts to reduce the emission of greenhouse gas, particularly the usage of SF_6 gas in power industries, are inevitably interlinked along this path [2]. Although SF_6 gas is identified in the Kyoto Protocol as one of the most potent greenhouse gases, with a global warming potential of 22 200 to 23 900 times higher than that of CO_2, it is still extensively used in power transmission for robust electrical insulation and reliable arc quenching. Because there remains no environment-friendly gas medium, from the state of the art, was found could achieve both high insulation and high interruption performance at the same time like SF_6 gas, other than vacuum for various switching applications [3–5]. Vacuum itself provides nothing for current conduction in steady-state insulation and transient-state current switching [6]. The breakdown of a vacuum gap strongly depends on the inherent dielectric performance, which in turn depends on contact contours, materials, gap distance, and intrinsic transportation behaviors of macro- and microparticles [7–9]. Vacuum switching technology allows more compact designs (in terms of volume), provides high dielectric strength for a small contact gap, and is maintenance-free over its service life [6]. Table 1 shows a property comparison of the vaccum with SF_6 medium used in power-switching equipment [6,10].

Despite these advantages, vacuum switching technology has taken almost 100 years to dominate the switching equipment, which was based on media such as oils, airs, and SF_6, in power distribution networks. The history of vacuum switching dates back to the 1890s, when Enholm patented the first vacuum switch as a "device for transforming and controlling electric currents" [11].

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Table 1
Comparison of vacuum switching with SF_6 gas switching.

Switching in vacuum		Switching in SF_6 gas	
Advantages	Maintenance-free in entire serving life; neither affects nor does it affected by surrounding ambient; no danger of explosion.	Disadvantages	Need frequent maintenance during service; sensitive to ambient temperature; potential to explode in high current interruption.
	Components are environmentally benign and could be easily recycled.		Greenhouse gas, highly toxic decompositions; needed special recycling device.
	High breakdown voltage in small vacuum gaps but with relative high deviations.		Relative lower breakdown voltage in the same contact gaps but with lower deviations.
	High endurance of contact system to arc; attractive in applications require (very) frequent switching operations.		Relative lower endurance of contact in interrupters; frequent switching operations require special designs.
	Low driving energy required for the operating mechanism dues to much lower opening and closing stroke.		High driving energy required for the operating mechanism dues to higher opening and closing stroke, and high gas puffer pressure in current interruption.
	Easy switch aginst a very steep rising rate of transient recovery voltage, due to fast dielectric recovery property.		Difficult to switch aginst a steep rate of rising of transient recovery voltage, such as short-line fault switching.
	Low opening and closing time with low deviations; appropriate for controlled switching of fault/load current switching.		Relative high opening and closing time with high deviations; difficult in controlled switching of capacitive/inductive loads.
	Possible extreme low restrike probability in capacitive current switching when adopting controlled switching technology.		Require additional components like reactor, resistance to mitigate arc erosions of prestrike inrush current on contacts.
	Ability to interrupt high fault current even the movable contact in the open position.		Lossing current interruption ability when the movable contact approaches open position.
	Relative lower arc duration (typically 5–7 ms for the minimum arcing time) and voltage (typically tens of volt) in fault current interruption.		High arc duration (typically 10–15 ms for the minimum arcing time) and voltage (typically hundreds of volt) in fault current interruption.
Disadvantages	Challenge for a nominated current higher than 3150 A.	Advantages	Easy to realize a nominated current higher than 3150 A.
	Not practical to monitor the required degree of vacuum interrupter in service.		Easy to monitor the quality of SF_6 gas in the case of switchgear in service.
	Need multiple interrupters connected in series-connected for a high voltage application above 145 kV.		Single-break interrupter achieved 550 kV, has been put into service since 1994 and installed in many countries.
	X-ray emission, although within the standardized limits of 5.0 $\mu Sv \cdot h^{-1}$ under normal switching condition.		No X-ray emission in switching operation.
	Probability of spontaneous late breakdown in vacuum interruption, up to hundreds of milliseconds after current zero.		Quite a low possibility of late breakdowns, immediately breakdown in the rising phase of transient recovery voltage once SF_6 gas deteriorates.
	Relative high numbers of repeated re-ignitions in inductive load current switching dues to high interruption capability of high-frequency current followed re-ignitions.		Low numbers of repeated re-ignition in inductive current switching.

The technology was confined to low-voltage and low-current but high-frequency interruption applications before the 1920s, when the first vacuum switch was developed. The successful laboratory-scale demonstration of an interruption of 900 A at 40 kV in a vacuum tube in 1926 [12] stimulated considerable interest in the development of vacuum switches. Many researchers devoted themselves to vacuum arc physics and gained a preliminary understanding of current interruption in vacuum [13–17]. However, the limitations of metallurgy for gas-free electrodes and vacuum sealing technology slowed the pace of development. After solving these problems, Jennings Company developed a practically commercial vacuum interrupter (VI) for load current switching in the 1950s [18]. This achievement further increased interest in vacuum switching technology and contributed to a wide acceptance of vacuum switches. By the mid-1960s, General Electric (GE) Corporation (USA) developed a 15 kV/1.2–12 kA vacuum circuit breaker (VCB) which was the first VCB product worldwide. At the same period, Xi'an Jiaotong University developed the first three-phase vacuum switch in China in 1965, which was with 10 kV and 1500 A. Soon after, the Associated Electrical Industries (AEI) Company in UK developed its 132 kV, 15.3 kA VCB in 1967. Other companies, including Schwager, Pearson, and GE, started to develop their vacuum switching technologies. Although various vacuum switches were developed and applied in the United States, Europe, and Japan by the late 1960s [19], these switches were relatively expensive for widespread application because of their complicated manufacturing process, and thus switching equipment at that time was mainly dominated by bulk oil and minimum oil circuit breakers (CBs) [20–22]. It was not until the end of the 1970s, vacuum switching equipment gradually occupied a large scale market in power distribution systems and started to penetrate transmission-voltage systems [23–25]. Meidensha, in Japan, presented a 84 kV/2000 A-2–20 kA VCB in 1975. Later a series products of 145 kV/2000 A-2–25 kA, 154 kV/600 A-0.6–20 kA, and 168 kV/2000 A-2–31.5 kA were developed and installed in Japan. After 1980s, VCBs at transmission voltage got a rapid development all over the world, especially in China in 2000s [26], series products of 72.5–126 kV single-break VCB, and 72.5–363 kV multiple-break VCB were subsequentially developed, the rated current rose from 630 to 5000 A, the rated short-circuit breaking current rose from 25 kA to 63 kA. At the present time, vacuum switching technology spans all types of devices, from contactors, through disconnectors, reclosers, to CBs and accounts for a large fraction of the high-voltage switching market in AC power distribution systems.

Improvement in today's power system performance requires VCBs with higher interruption capacity and shorter interruption time. In achieving high interruption capacity, various vacuum arc control technologies, including those based on a transverse magnetic field (TMF) or radius magnetic field (RMF) [27,28], axial magnetic field (AMF) [29,30], or their combinations [31,32], were developed for interrupting currents of up to 100 kA [19] and rated voltages of up to 242 kV [10]. Progress in the operating mechanism, which releases energy to a mechanical driving system to move the contacts in VCBs to make or break a circuit on command, has led to a significant decrease in current interruption time from eight to five cycles of the power frequency current and further decreased to the common three cycles today [33–36]. Various types of operating mechanisms have been developed over the past century, including those based on pneumatic-type, spring-type, permanent magnetic type, digital controlled motor type, and electromagnetic repulsion type, and so on [37–40]. With the aid of electromagnetic repulsion actuators, vacuum switching technology can achieve fast-current-interruption, referred to as fast vacuum switching technology, which can reduce the interrupt time to a half-cycle of a fault current [34,41].

Power system performance can thus be further improved by applying fast vacuum switching technology. The shorter current interruption time of a fast VCB (FVCB) enables power equipment to have higher endurance of the peak current and short-time withstand current capability [42]. This could enhance the power transmission capacity of existing networks, especially extra-high-voltage (EHV) and ultra-high-voltage (UHV) networks, and considerably lower the cost of newly planned networks by permitting the use of equipment with low ratings. The application of fast vacuum switching technology in EHV or UHV networks requires multiple-break series-connected technologies, of which the feasibility has been demonstrated by installed direct current CB (DCCB) above 500 [43–46] and 252 kV alternating current (AC) bus-sectionalized FVCB [47], as well as a developed 363 kV FVCB [48,49]. Also, an envisaged 550 kV FVCB is under development in China. An FVCB has an opening time in orders of 1 ms and a closing time in orders of 10 ms. The deviation is 0.05 ms for the opening time and 0.1 ms for the closing time [34]. This allows a fast vacuum switch to perform accurate controlled switching of capacitive or inductive loads to smooth the switching transient of power systems. Today, fast vacuum switching technology is applied in the fields of DCCB, fault current limiting, power quality improvement, generator CBs, and so on. From this point of view, fast vacuum switching technology is changing the future of power systems.

This paper summarizes the state-of-the-art of vacuum switching technology. A brief history of vacuum switching at transmission voltage levels is given in Section 2, followed a review of recent research and development in fast vacuum switching technology in Section 3. The development and application of fast vacuum switches are described in Section 4, with DCCBs, fault current limiters (FCLs), power quality improvement, and generator CBs discussed in detail. A discussion of the future of vacuum switching technology is given in Section 5.

2. Vacuum switching at transmission voltage levels

Concerning the global warming potential of the greenhouse SF_6 gaseous, as well as the serving experience of the VCBs in the power distribution system, a strong impetus and extensive interest are drawn in researching and developing vacuum switching technology toward transmission voltage [50–52]. Here, a voltage of 72 kV or above is considered to be a transmission voltage. There are two approaches for developing VCBs for transmission voltages. In the first approach, a high voltage withstand capability is achieved by connecting multiple breaks in series [53,54]. With this approach, the breakdown voltage for the total contact gap length of several series-connected breaks is higher than that for a single-break with the same contact gap length. The challenges of implementing this approach include the synchronous operation among the breaks, homogenous distribution of stressed voltage on each break, and reducing the failure rate for multiple breaks. The rated voltage of single-break VCBs can also be increased by enlarging the contact diameter and the contact gap length [55,56]. This approach is useful for multiple-break VCBs with relatively few series-connected breaks. The challenges of implementing this approach include the nonlinear relationship between the breakdown voltage and contact gap, non-fluorinated-gas-based external insulation of the VI, controlling vacuum arcs at large contact gaps, and the trade-off between rated current and rated short-circuit breaking current.

An early transmission-voltage vacuum switch was a load switch in capacitor bank switching in 1956. Four VIs were connected in series for each phase to achieve a high withstand voltage of up to 232 kV [18]. Commercialized transmission-voltage VCBs were first developed by AEI in the United Kingdom in 1968, where eight series-connected VIs were used for a 132 kV application [25]. In the mid-1970s, much effort was devoted to the development of VCBs that included four VIs connected in series for application up to 175 kV to retrofit oil CBs in the United States; there were also plans for an 800 kV application with 14 series-connected VIs per phase [52]. In the 1990s, commercial VCBs up to 145 kV first became available [57]. Single-break VCBs for 72 kV and above and multiple-break VCBs for 168 kV and 204 kV were developed and commercialized in Japan; they were applied in some special applications [23]. Live- and dead-tank 145 kV single-break VCBs, with dry-air insulation, were developed by Siemens (Germany) in 2015. Products for 145 and 204 kV vacuum-type gas-insulated metal-enclosed switchgear (GIS) were subsequently developed in Germany and Japan. In 2018, Siemens launched 175 and 245 kV single-break VI products [26].

Over the past three decades, China has taken a strong lead in research and development of VCBs for transmission voltages [6]. Numerous local institutes, manufacturers, and power utilities are dedicated to researching and developing single-break VCBs from 72.5 to 126 kV. A conceptional design of a single-break 252 kV, 3150 A, 40 kA VI [55], and multiple-break 750 kV EHV VCBs were published in 2010 [58]. With support from Xi'an Jiaotong University, a series of eco-friendly products of live-tank single-break 126 kV VCBs and vacuum-type GIS, shown in Fig. 1, were commercialized by Baosheng Group and Pinggao Group Corporation, respectively. For the live-tank single-break 126 kV VCB, the external insulation medium of the VI is 0.2 MPa (gauge pressure) nitrogen [26]; for the vacuum-type GIS, it is 0.8 MPa (gauge pressure) CO_2. The rated current of the 126 kV VCB was increased from 2500 A in 2013 to 3150 A in 2018 while the rated short-circuit breaking current remained at 40 kA [50]. The development of a single-break 252 kV VI was recently launched by Xi'an Jiaotong University and Pinggao Group Corporation.

The required driving energy for the opening and closing operations of the VCB is lower than that needed for puffer- or self-blast-type SF_6 CBs. Various mechanisms, such as stepper motors with digital control and permanent magnetic actuators [59], have been developed for driving single-break transmission-voltage VCBs. The operation time, from the triggering of the operation to contact mating or separation, for existing mechanisms is typically 30 ms for the opening operation and 80 ms for the closing operation. The fault elimination time, from the initiation of a short-circuit fault to the interruption of the fault current, is typically three cycles of the fault current, taking into consideration a protective relaying time of 10 ms and an arcing time of 10–20 ms for the major loop of an asymmetric current interruption. Electromagnetic repulsion actuators can reduce the opening time of VCBs to less than 2 ms [34], which could limit the fault elimination time to the first half-cycle, which is within 20 ms in a 50 Hz power system. Although such actuators have not been applied in single-break transmission-voltage VCBs because of their long operation stroke requirement, they can be applied to transmission-voltage VCBs through multiple-break series-connected technology.

3. Fast vacuum switching technology

Basu and Srivastava [60–62] proposed electromagnetic repulsion actuators in the 1970s. The introduction of these actuators

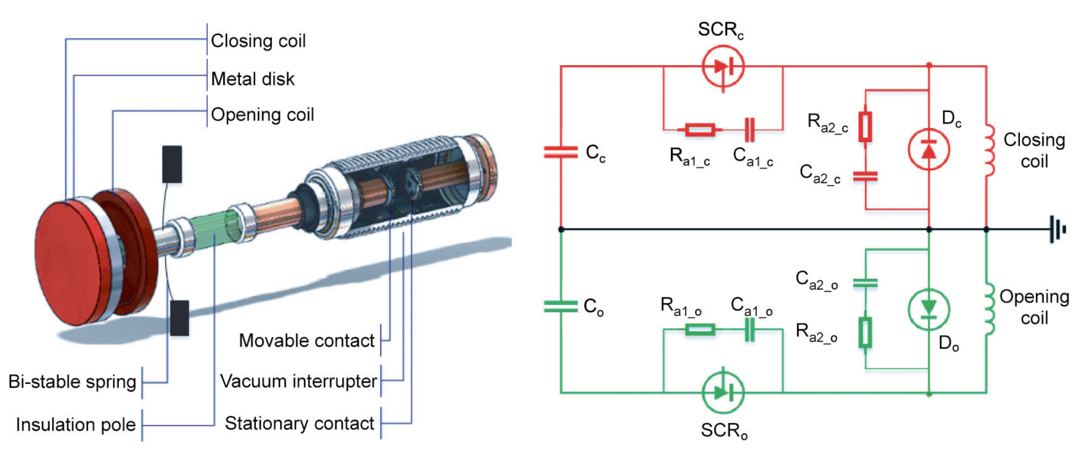
(a) (b)

Fig. 1. Eco-friendly 126 kV VCBs. (a) Baosheng Group (China), a product line of live-tank single-break 126 kV, 3150 A, 40 kA VCB with 0.2 MPa N_2 as the external insulation medium of the VIs; (b) Pinggao Group Corporation (China), 126 kV, 2500 A, 40 kA vacuum GIS with 0.5 MPa CO_2 as the external insulation medium of the VIs [26].

into vacuum switching technology, which comprised fast vacuum switches, resulted in an obvious decrease in opening time from tens of milliseconds to milliseconds. Power systems, especially EHV and UHV power networks, can greatly benefit from a fast elimination of short-circuit faults. The time required to recover from the instability of the transient power angle of a generator to equilibrium would be effectively decreased and the transmission capacity of the power lines would be increased. In addition, with a decreased operation time of fast vacuum switches, high-voltage power compensation equipment with fast switching becomes available. The required time interval for adjusting the active and reactive power of power networks can also be reduced. Besides, the influence of accessing clean energy on power qualities could be significantly moderated by a rapid interaction between the power sources and loads.

Fig. 2 shows a schematic diagram of a typical configuration of the fast vacuum switch and the topology of its control circuit. As shown in Fig. 2(a), the switch operates under the effect of electromagnetic repulsion force generated between an opening or closing coil and a metal disk. Taking the opening operation as an example, charged capacitor C_o in Fig. 2(b) discharges through the opening coil, generating an impulse electromagnetic field; simultaneously, an eddy current is induced in the counter metal disk, resulting in an inverse magnetic field. A repulsion force is generated between the opening coil and the metal disk. Thus, the movable contact in the VI moves towards the open position of the VCB. This configuration of a fast vacuum switch eliminates the contact spring component, which is placed between the insulation pole and the movable contact in a conventional VCB. Instead, a parallel-connected bi-stable spring is used to provide the latching force for the switch in the open or closed position. Thus, the opening time of the switch is significantly decreased. Two free-wheeling diodes, D_c and D_o, connected in parallel to the closing or opening coil are used to achieve high driving efficiency. The energy-absorbing circuit branches, R_{a1} and C_{a1} for the silicon-controlled rectifiers (SCRs) and R_{a2} and C_{a2} for the diodes, are essential for stabilizing operation by protecting the electronic switches from reverse overvoltage.

The latching and holding components, as well as opening and closing buffering components, are essential for fast vacuum switching to achieve reliable operations. The latching and holding components are not only adopted to keep the fast vacuum switch in a stable open or close position but also provide a required compressing force for the contacts of a VI in a close position. Generally, the technology involved the spring-type and the permanent-magnetic-type latching and holding technologies. The spring-type is geometrically simple and widely used in fast vacuum switches, which involve unidirectional spring compressing and latching type [63], biostable columnar spring-type [64], bidirectional disk spring-type [65], and so forth. However, the spring-type latching and holding components in the fast vacuum switch require careful dimension designs and force adjustment to avoid contact bounces in opening or closing operations. The permanent-magnetic-type is more compactable in volume, which geometrically removes the opening and closing coils in the permanent magnet actuator [66]. However, the iron core structure inevitably increases the moving masses of the dynamic transmission system for the fast vacuum switch compared with the spring-type. The opening and closing buffering components in the fast vacuum switches are adopted to lower down the opening and closing velocities and moderate the impact force when the movable contact of the VI approaches the open or close position. Thus, the mechanical endurance of fast vacuum switches could be significantly promoted for frequent switching operations. Various buffering technologies were also developed, which included spring buffers [67], air pressure buffers [68,69], oil buffer [70], polyurethane buffers [71], electromagnetic buffers [72], and so on. The air pressure buffers permit an integrated design with the repulsion actuator but require a deliberate arrangement of the exhaust vent, which is similar with the carefully designed orifices for the oil buffer. The electromagnetic buffer could provide an ideal damping force theoretically by adjusting the discharging current in a real-time opening or closing operation.



(a) (b)

Fig. 2. Schematic diagram of a typical configuration of fast vacuum switch and topology of its control circuit. (a) Configuration; (b) control circuit. C_C and C_O are energy storage capacitor banks; SCR_C and SCR_O are controlled thyristors; D_C and D_O are free-wheeling diodes; branches R_{a1}/C_{a1} and R_{a2}/C_{a2} are energy-absorbing components for SCRs and diodes; subscript "o" and "c" is the acronym of "open" and "close", respectively.

An obvious decrease in the opening or closing time of FVCB results in a limited deviation of the operation time. This contributes to the parallel or series synchronous operations of multiple-break FVCBs in high-voltage and high-current rating applications. Fig. 3 shows a prototype of a recently developed single-phase 363 kV, 5000 A, and 63 kA multiple-break FVCB. The rated lightning impulse withstand voltage is 1175 kV, not taking the stressed voltage value of 215 kV across the open switching device into consideration. The rated short-time power frequency withstand voltage is 510 kV.

The feasibility of the prototype has been validated at the Chinese National Quality Supervision & Inspection Center for High Voltage Apparatus [48,49]. As shown in Fig. 3(a), each phase of the prototype comprises two circuit branches in parallel; each branch consists of three series-connected breaking units (BKs), each of which is two series-connected modular 40.5 kV FVCBs. A minimum grading capacitance of 4.0 nF is connected in parallel to each modular FVCB to achieve a relatively uniform distribution of stressed voltage. The determination of the essential grading capacitors obeys such a sequence: analyzing the stray capacitance of the multiple-break FVCB with an entire model; determining the influence of grading capacitors on voltage distribution ratios of each break; and choosing an appropriate value (4.0 nF) for the grading capacitor to achieve a low deviation (typical 0.24% for the 363 kV FVCB) uneven voltage distribution ratio of each break. Each BK is first connected in series and then in parallel. A uniform distribution of the carried current can then be easily achieved by evaluating the total conducting reactance of each branch, instead of focusing on the reactance deviations of each modular FVCB. In Fig. 3(b), each BK is placed on an insulating platform, which comprises three layers of 126 kV bushings. Conductors connect each layer of the platform to ensure equal voltage potential. The opening time of the prototype FVCB, from the trigging of the opening operation to the separation of the last break contacts, was verified to be 1.18 ms. The short-circuit breaking current of the prototype was verified to be 80 kA [49,69].

From the point of view of high-voltage insulation, an improvement in the voltage rating of single-break FVCBs could effectively decrease the number of essential modules for EHV FVCB. Table 2 shows the required number of single-break FVCBs with different voltage ratings for various kinds of high-voltage multiple-break FVCB. The chosen voltage ratings are recommended by the Chinese Standard GB/T 11022–2011 following a higher recommended value. The voltage ratings also take into consideration the stressed voltage across the open switching device. In Table 2, U_d is the rated short-time power frequency withstand voltage and U_P is the rated lightning impulse withstand voltage. When the rated voltage of a single-break FVCB increases from 40.5 to 72.5 kV, the required number of series-connected breaks decreases from seven to four for a multiple-break 363 kV FVCB; when the rated voltage further increases to 126 kV, the required number of breaks decreases to three. For a 72.5 kV single-break FVCB, six series-connected breaks are sufficient for a 550 kV multiple-break FVCB.

A conceptional design of a dead-tank 550 kV multiple-break FVCB is currently under development. Fig. 4 shows the configuration of the single-phase dead-tank FVCB. Similar to the topology of the 363 kV FVCB, the 550 kV FVCB consists of two parallel-connected circuit branches for a high rated current-carrying capacity of 5000 A and a high prospective short-circuit breaking current of 80 kA. Each circuit branch contains six series-connected modular tanks of a 72.5 kV FVCB. A grading capacitance of 6 nF is required for each 72.5 kV modular break to achieve a uniform distribution of stressed voltage across each break. The determination of the grading capacitors of the 550 kV FVCB follows the same method as that for the 363 kV FVCB. The inner tank of each module is primarily filled with 0.4 MPa (gauge pressure) SF_6 gas to ensure external insulation of the VI. Fig. 4(b) shows a 1/3 structure unit of a single-phase 550 kV FVCB being prepared for a dielectric test. The short-circuit current interruption performance of the FVCB was validated using terminal fault test duty T100s(b) for a modular 72.5 kV FVCB at the National Quality Supervision & Inspection Center for High Voltage Apparatus. A test current of 80 kA was successfully interrupted against a recovery voltage of 126 kV in peak. The minimum, maximum, and middle arcing times were verified to be 2.5, 11.8, and 8.9 ms, respectively.

4. Applications of fast vacuum switching technology

In the field of fast switching technologies, power electronic switching devices were considered to be the best available technology over the past decades. The emerging fast vacuum switching technology provides a competitive alternative, with higher switching capacity, much lower power loss, lower cost of reliability, availability, maintainability, and safety (RAMS). Nowadays, the fast vacuum switches, applied as a switching element in various power equipment, are penetrating the field of DCCB, FCL, power quality improvement devices, and generator CB, contributing to improving the stability of the power system.

4.1. Direct current circuit breaker

High-voltage direct current (DC) power transmission technology has advantages over AC technology in terms of more flexible power allocation, access to clean energy, and long-distance

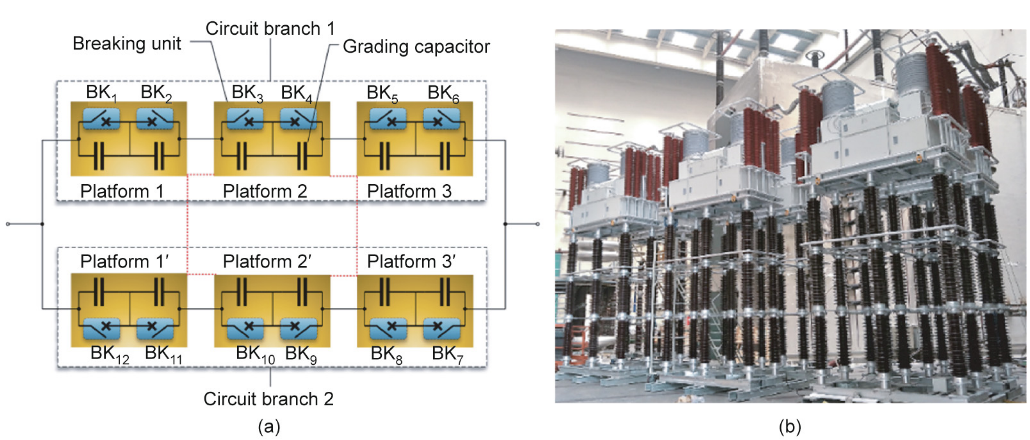


Fig. 3. Prototype of a single-phase 363 kV, 5000 A, 63 kA FVCB. (a) Topology; (b) configuration. (b) Reproduced from Ref. [69] with permission of IEEE, © 2021.

Table 2
Required number of series-connected single-break FVCBs for various kinds of multiple-break FVCB.

Rated voltage of single-break	Voltage ratings for multiple-break FVCBs							
	252 kV		363 kV		550 kV		800 kV	
	U_d = 460 (+146) kV	U_P = 1050 (+206) kV	U_d = 510 (+210) kV	U_P = 1175 (+205) kV	U_d = 740 (+318) kV	U_P = 1675 (+315) kV	U_d = 960 (+462) kV	U_P = 2100 (+455) kV
12 kV U_d = 48 kV; U_P = 85 kV	13	15	15	17	22	24	30	31
40.5 kV U_d = 118 kV; U_P = 215 kV	6	6	7	7	9	10	13	12
72.5 kV U_d = 160 (+42) kV; U_P = 380 (+59) kV	3	3	4	4	6	5	7	6
126 kV U_d = 230 (+73) kV; U_P = 550 (+203) kV	2	2	3	3	4	3	5	4

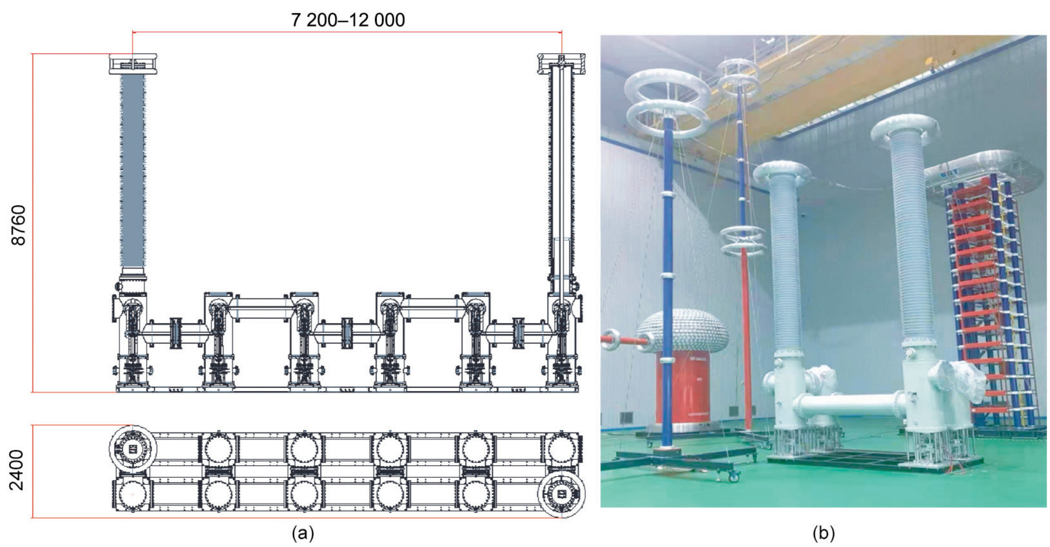


Fig. 4. Conceptional design of single-phase dead-tank 550 kV, 5000 A, and 80 kA FVCB. (a) Cross section of 550 kV FVCB configuration; (b) 1/3 structure unit of single-phase 550 kV FVCB being prepared for dielectric test.

transmission and is thus receiving extensive attention all over the world. Of particular interest is the development of DCCBs in the DC power system, which are responsible for normal current-carrying, abnormal current interruption, and fault isolations. Unlike in AC power switching, the fault current in a DC system has no natural current zero, which results in three different kinds of DC switching technologies regarding the fast elimination of the DC fault. These technologies involve solid-state DCCBs, mechanical DCCBs, and hybrid DCCBs [43]. In the latter two kinds of DCCB technology, the fast vacuum switches are partially used and engaged to pass through a nominated working current, or commutating fault current into other circuit branches, or act as disconnectors to switch against no arc and no voltage. Fig. 5 shows three different kinds of typical DCCBs topologies relating to the application of fast vacuum switching technology.

Fig. 5(a) shows a traditional topology of mechanical DCCB with forced current zero technology, in which the function of the fast vacuum switch is to carry and commutate the rated or fault current in normal or fault conditions of the DC systems, respectively. On a normal state of the DC system, the fast vacuum switch in the main circuit keeps in a close position, carrying the load current and causing little conducting losses. Once a short-circuit fault occurs, the fast vacuum switch is triggered to open on command; as the movable contact is approaching the open position, the pre-charged capacitor bank C is forced to discharge through an inductor L to generate a high-frequency-inverse current; the inverse current superimposes on the main circuit current to create a current zero for the fast vacuum switch to extinguish the DC vacuum arcs; the metal oxide varistor (MOV) does not conduct until the established transient recovery voltage rises exceeding its protecting voltage; then it dissipates the residual energy stored in the inductance of the DC system until the total fault current flowing through the DCCB decreases to zero. The application of a fast vacuum switch in this mechanical DCCBs with forced current zero is more appreciable than any other switching technology, which dues to its high-frequency current interruption performance. The simplicity of the topology and mature current commutating technology results in a low cost, and large power capacity configuration of the DCCB product. This brings out a series of commercial DCCBs with ratings ranging from 10 kV/40 kA to 50 kV/16 kA [43,73]. The auxiliary circuit in the topology, as shown in Fig. 5(a), must withstand a high voltage in the normal state of the DCCB to maintain a charged voltage on capacitor bank C, which limits its application towards a higher voltage level. An improved topology could be found in Ref. [74], where a coupled transformer is proposed. Based on the improved topology, series 160 and 535 kV DCCB products with installed of 40.5 kV fast vacuum switches were developed and put into service in flexible DC systems.

Fig. 5(b) shows the topology of a hybrid DCCB based on a coupled negative-voltage commutation circuit and cascade crossover diode bridge structure [43,75]. The function of the fast vacuum switch in this topology is similar to that in the mechanical DCCB. When the DC power system is in a normal state, the fast vacuum switch remains in a close position. The power electronic switches remain in the off-state and the DCCB has small conducting losses. Once a short-circuit fault is detected, the fast vacuum switch is triggered to open, and the power electronic switches turn on. When the contact gap of the fast vacuum switch approaches a certain gap distance, the trigger switch T_c in the negative-voltage commutation circuit is triggered; simultaneously, a negative voltage is induced in the commutating circuit. The fast vacuum switch extinguishes the fault current arc and transferred it into the commutating circuit. The contact gap distance of the fast vacuum switch keeps increasing until it approaches a contact gap that could withstand the transient interruption voltage of the DCCB, the power electronic switches turn off, and the fault current further commutates into the energy dissipation circuit and decays to zero. The advantages of this topology over fewer fully controlled semiconductor elements and double overvoltage protection structures allow the development of DCCB equipment with relatively low cost and high reliability. Moreover, the fast vacuum switch is appreciable to be applied in this topology attributing to its fast dielectric recovery property comparing with other switching technologies, like SF_6, air blast, and so on. A prototype 535 kV hybrid DCCB with this topology was developed and installed in the Zhangbei flexible DC grid in 2019. The feasibility of the DCCB was validated by three field tests in 2020 [43]. The DCCB successfully interrupted a short-circuit current of 25.6 kA within 3 ms and performed successful reclose operations.

The fast vacuum switch in the above DCCB technology must extinguish an arc to transfer the fault or work current into the commutating circuit. In many other kinds of DCCB, the fast vacuum switch is used as a disconnector (i.e., it does not need to switch any current or voltage). Fig. 5(c) shows the typical topology for this kind of modular cascade hybrid DCCB [76]. The topology is based on diode bridge rectifiers. Under normal conditions, the main circuit branch conducts the load current of the DC power system. When a short-circuit fault is detected or the system operation mode is adjusted, the insulated-gate bipolar transistor (IGBT) full-bridge modules interrupt the main circuit current on command and completely transfer it into the current commutating circuit; simultaneously, the fast vacuum switch opens to withstand almost the voltage that impressed on the commutation circuit and then on the energy dissipation circuit, as the vacuum gap has higher resistance than the insulated-gate bipolar transistor full-bridge modules. The diode full-bridge rectifier interrupts the commutation current and transfers it into the energy dissipation circuit. The MOV dissipates the energy stored in the inductance of the DC system and suppresses increases in the recovery voltage. Because there is no arcing during the entire switching process, this topology increases the operation reliability of DCCBs. The modular design of the cascade full-bridge electric switches makes the DCCB capable of scaling for various voltage applications. The fast vacuum switch is also appreciable to be applied in this kind of DCCBs, as a small vacuum gap has a relatively high breakdown voltage level than many other switching media, like SF_6, N_2, CO_2, and their mixtures. A series of DCCB products with this topology was developed and installed in DC power systems [77,78]. A typical 535 kV, 26 kA hybrid DCCB, has already been installed in the Zhangbei ±500 kV four-terminal DC grid since 2017 [43]. The interruption time, from the initiation to the elimination of a short-circuit fault, was validated to be 2.7 ms.

4.2. Fault current limiting

The rapid growth of power generation and the enhanced connectivity of the power grid have increased high-amplitude fault currents in power systems. Networks are approaching or exceeding their design limits concerning their short-circuit current withstand capabilities. Various short-circuit current limiting technologies have been developed to increase the transient stability of power systems [79–81]. With an FCL, power equipment can remain in service even if the prospective fault current exceeds the rated short-circuit breaking current of the serving CBs. There is renewed interest recently in introducing fast vacuum switching technology into economical FCLs.

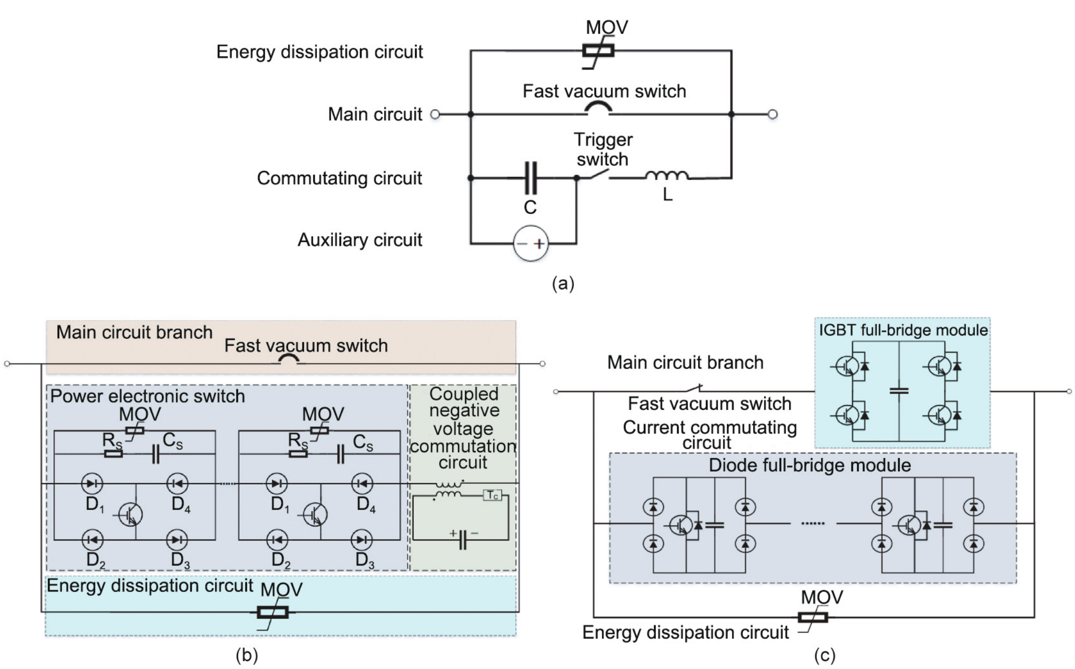


Fig. 5. Three different kinds of DCCB. (a) Topology of the traditional mechanical DCCB; (b) topology of hybrid DCCB based on coupled negative-voltage commutation circuit and cascade crossover diode bridge structure [45,65]; (c) topology of hybrid DCCB based on diode full-bridge rectifiers [45,66]. MOV: metal oxide varistor; R_s: resistance; C_s: capacitance; D1–D4: diode; L: inductor; C: capacitor bank; T_c: trigger switch; IGBT: insulated-gate bipolar transistor.

4.2.1. EHV economical fault current limiters

The local exceeding short-circuit current of power substations can be effectively decreased by installing an FCL in EHV power networks. A fast-vacuum-switch-based FCL is more economical than existing current limiting technologies such as those based on superconductivity, solid-state devices, and series resonance. There are two kinds of FCL for EHV networks. One is a fast vacuum switch connected in parallel to a current-limiting reactor [82–84] and the other is a fast vacuum switch connected to a highly coupled split reactor (HCSR) [85]. Fig. 6 shows the two kinds of modular fast-vacuum-switch-based economical FCL. For a given short-circuit fault, the fast vacuum switch in the former FCL has to interrupt and transfer the total fault current into the current-limiting reactor and withstand the transient recovery voltage generated by the reactor, whereas in the latter FCL the fast vacuum switch has to switch against double transient recovery voltage that results from the current-limiting winding of the HCSR if a conventional topology is used, but the interrupting current is decreased to half of the fault current. Besides, a commonly used reactor is appropriate for the former FCLs, which could render considerable cost savings for their applications; while for the latter FCL, the HCSR requires deliberate designs in terms of the coupled physics of thermal, insulation, and structure strengths.

Fig. 6(a) shows the former FCL's modular topology, where a fast vacuum switch is connected in parallel to a current-limiting reactor, for EHV application. In a normal state of the power system, the load current flows through the closed fast vacuum switches and generates small conducting losses. In the presence of a short-circuit fault, the protective relay control unit identifies the fault and commands the fast vacuum switch to open to break the fault current. When the instantaneous current is zero, the fault current is transferred into the current-limiting reactor. A high transient recovery voltage, caused by the increasing fault current in the reactor, is established across the breaks of the fast vacuum switch. To avoid the breakdown and reignition of the fast vacuum switch, an resistance (R_s)–capacitance (C_s) damping circuit is used to suppress the rising rate of the recovery voltage. All the devices are placed on an insulating platform, where a capacitive voltage transformer (CVT) provides the required power from the ground to the fast vacuum switch and the control unit on the platform. The current-limiting reactor requires neither a special design nor a special manufacturing process, which reduces the cost of its topology. The modular topology can be scaled for various high-voltage applications by connecting various numbers of modules in series. The current limiting ratio can be varied by adjusting the inductance of the reactors. The required number of fast vacuum switches can then be adjusted according to the current limiting ratio. Fig. 6(b) shows a developed 330 kV EHV FCL with this topology [83]. Three modules connected in series were manufactured for one-phase application, with each module comprising two series-connected 12 kV fast vacuum switches and a 1.9 mH current-limiting reactor. A current limiting ratio of 40% was validated by a field test [82]. A prototype of an economical 800 kV EHV FCL is currently under development, where six modules, with each of the three are connected in series, are used for each phase. In each module, two 63 kV fast vacuum switches are used. The nominal carried current is 5000 A; the prospective short-circuit limit current of 100 kA; and the current limiting ratio is more than 50%.

Fig. 6(c) shows the latter FCL's modular topology for EHV application, where the fast vacuum switches are used to connect with an HCSR. When the power grid is in a normal state, the load current flows through the closed fast vacuum switch and both windings of the HCSR. The HCSR has a small conducting impedance because the magnetic fluxes generated by its anti-coupled coil structures counteract each other. When the coupling coefficient of the two windings exceeds 0.95, the HCSR impedance is less than 2.5% of the single-winding impedance. Once a short-circuit fault is encountered, the fast vacuum switches open on command to break the fault current in a branch. The HCSR is decoupled at the simultaneous current zero to generate a high impedance to limit the fault current. Because of the arrangement of switches on both sides of a single winding of the HCSR, the stressed voltage imposed on the HCSR could be effectively depressed, instead of twice the voltage generated by the current-limiting winding. Thus, the requirement for winding insulation designs of the HCSR could be moderated. A series of products, ranging from a 126 kV, 5000 A, 80 kA device to a 252 kV, 100 kA device, with this topology were developed and put into service. An economical 550 kV EHV FCL

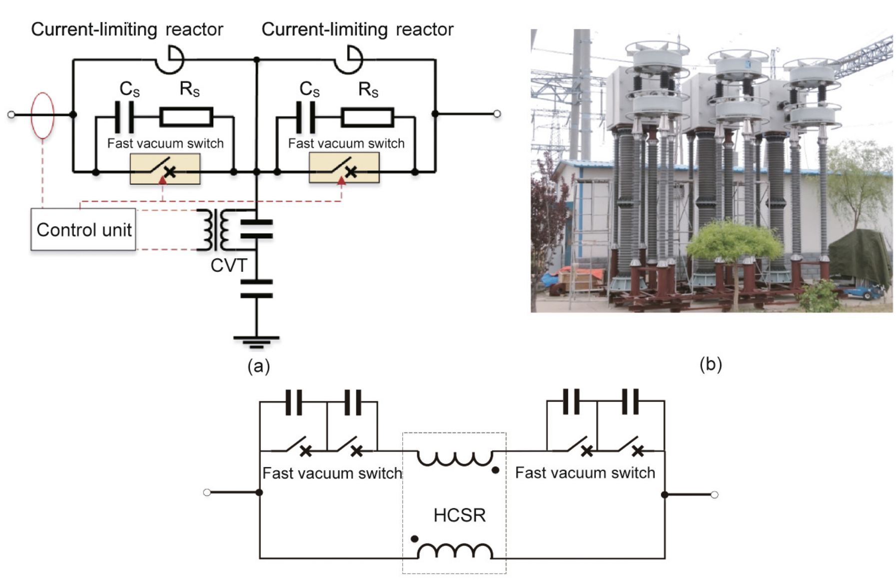


Fig. 6. Two kinds of modular fast-vacuum-switch-based economical FCLs. (a) Modular FCL topology of fast vacuum switch connected in parallel to current-limiting reactor [74]; (b) 330 kV EHV fast-vacuum-switch-based economical FCL [74]; (c) modular FCL topology based on fast vacuum switch and HCSR [75]. CVT: capacitive voltage transformer.

is currently under development. Its prospective short-circuit limiting current is 90 kA, its nominal carried current is 3150 A, and its nominal current limiting ratio is 40% [85]. Two modules with this topology were applied to 550 kV FCLs, with eight breaks of 40.5 kV fast vacuum switches in total. The inductance of the HCSR in the current limiting state was determined to be 8.5 mH [85]. The high coupling coefficient of 0.98 was achieved by careful manufacturing, which indicated a negligible conducting loss when it is in service.

4.2.2. Fast vacuum switches in other current-limiting devices

There are various kinds of fast-vacuum-switch-based current-limiting devices for different scenarios of power applications, including variable-impedance transformers [86] and bus-coupler FVCBs [87]. In these applications, a fast vacuum switch acts as a switching element that changes the impedance or operation mode of the local power network. Fig. 7 shows two schemes of variable-impedance transformers. A parallel-connected fast vacuum switch with a current-limiting reactor can be integrated into a newly designed low-impedance transformer, as shown in Fig. 7(a), or externally added to the output terminals or neutral point of an existing transformer, as shown in Fig. 7(b). The working principle of the fault current limiting of the variable-impedance transformer is identical to that shown in Fig. 6(a). The power losses of a variable-impedance transformer are significantly lower than those of a high-impedance transformer, which is commonly used for current limiting; simultaneously, the peak and short-time withstand current performance of a variable-impedance transformer can be further enhanced compared with that of a low-impedance transformer. Fig. 7(c) shows a newly developed and installed 63 MVA, 110 kV variable-impedance transformer. A parallel-connected fast vacuum switch and a current-limiting reactor are integrated into the transformer. A three-phase double-break fast vacuum switch is used. The inductance of the integrated reactor was determined to be 54.6 mH and a high short-circuit limiting ratio of more than 40% was achieved [87].

Another typical application of the fast-vacuum-switch-based current limiting devices is to take the fast vacuum switch directly as a bus-coupler CB [47], which is a system-level current limiting solution. In most substations of 220 kV or below, the busbar commonly operates in forms of splitting conditions. A bus-coupler CB engages to connect each busbar in the closed position to improve power supply stability. When a short-circuit fault occurs, the bus-coupler CB is expected to open on command and rapidly interrupt the fault current contributed by other busbars. The fault current is efficiently decreased because the short-circuit fault is isolated from the normal operating busbars, as shown in Fig. 8(a). Theoretically, a faster interruption of the bus-coupler CB leads to a lower impact of the fault busbar on the normal operating busbars and improved transient stability and power supply flexibility. Fig. 8(b) shows an installed three-phase 252 kV, 2500 A, 40 kA bus-coupler FVCB in a 220 kV power grid. The configuration of the FVCB is similar to that of the 363 kV FVCB shown in Fig. 3(b), except for the lower-rated voltage of the insulating platforms and fewer breaks (four series-connected breaks per phase). A 40.5 kV, 2500 A, 40 kA VI was applied to each break. The opening time of the bus-coupler FVCB is 1.15 ms, with a deviation of ±0.12 ms after 2000 operations [47]. The feasibility of the bus-coupler FVCB was validated by a series of type test duties and field tests, which showed that the FVCB can effectively limit the fault current to 60% of the prospective value within 20 ms.

4.3. Fast vacuum switches applied for improving power quality

The high-end manufacturing industry requires a high-quality power supply. Fast vacuum switches could improve the power quality and transient stability of the power grid through their fast opening and closing characteristics. There have been various brilliant applications benefitting the power systems from a stable power voltage, power supply continuity, and improved clean energy access capability. In all these applications, such as dual-power fast switching equipment, line series compensation equipment, fault arc and resonance elimination equipment, and so forth, the fast vacuum switches act as a core switching element [88–90].

Fig. 9 shows a typical application of the fast vacuum switch in dual-power fast switching equipment, where the fast-current interruption of the fast vacuum switch plays a significant role. In Fig. 9(a), three fast vacuum switches are integrated with a dual-power fast switching device. It is used to decrease the severity of voltage sag and the duration of power interruptions caused by a short-circuit fault. In a normal operating state, fast vacuum switches I and III are in the closed position, and fast vacuum switch II is in the open position. When a short-circuit fault occurs in the grid of the serving power source, switch I is commanded to interrupt the fault current and isolate the fault grid. Then, switch II is commanded to close and connect the prepared power source grid to recover the power supply of busbar I. Compared with traditional dual-power switching equipment, the voltage sag durations of busbar I are significantly decreased from more than 50 ms to less than 20 ms. The fast-vacuum-switch-based equipment can also decrease the risk of a split of the connected set with clean power energy caused by the long duration of the low-voltage ride

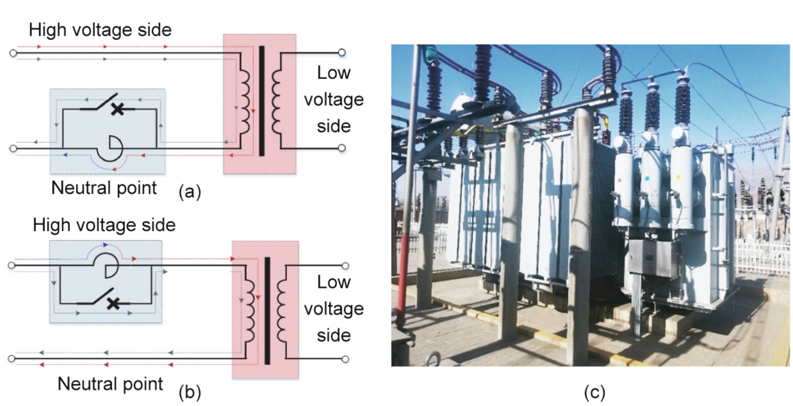


Fig. 7. Schemes and application of fast-vacuum-switch-based variable-impedance transformer. (a) Schematic diagram of variable-impedance transformer with parallel-connected fast vacuum switch and reactor installed at neutral point of the transformer; (b) schematic diagram of variable-impedance transformer with parallel-connected fast vacuum switch and reactor installed at high-voltage side of the transformer; (c) installed 63 MVA, 110 kV variable-impedance transformer [76,77].

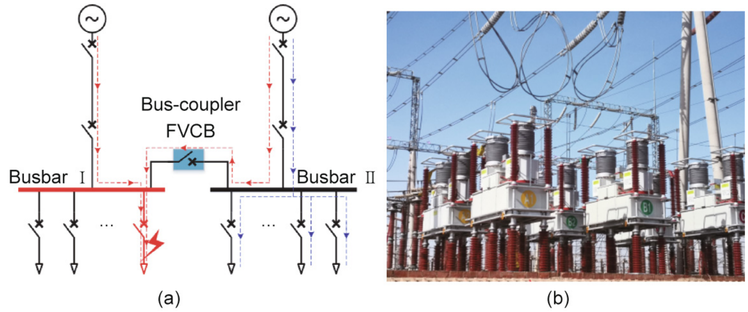


Fig. 8. Schematic diagram and application of bus-coupler FVCB. (a) Schematic diagram of bus-coupler FVCB; (b) installed 252 kV, 2500 A, 40 kA bus-coupler FVCB [49].

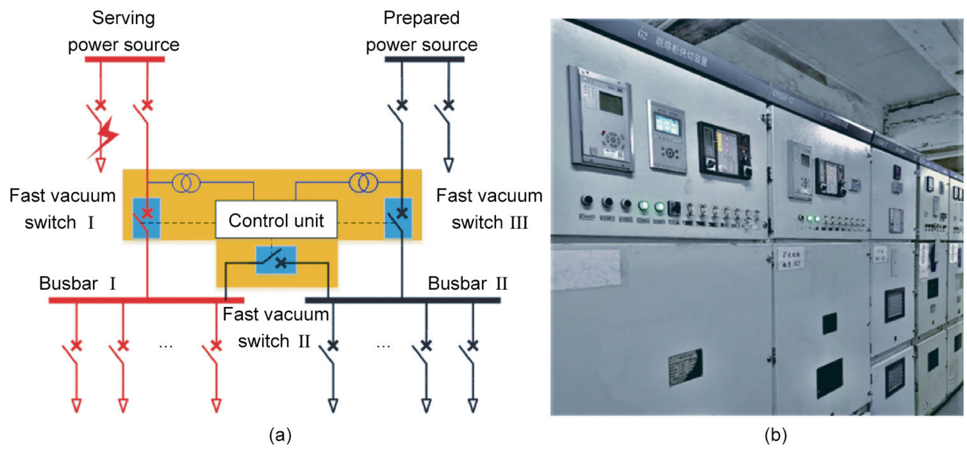


Fig. 9. Schematic diagram and application of dual-power fast switching devices. (a) Schematic diagram; (b) installed 12 kV dual-power fast switching device.

through. The power supply interruption time can be decreased from almost 100 ms to less than 30 ms, which would benefit local sensitive industrial loads that require a stable power supply. Fig. 9(b) shows an installed 12 kV dual-power fast switching equipment that can recover the power supply within 20 ms.

Fig. 10 shows another typical power quality enhancement device with fast-vacuum-switch-based line series compensation, where the fast closing characteristic of fast vacuum switches is used. Fig. 10(a) shows the topology of the device, in which the fast vacuum switch is in the open position under normal working conditions. The capacitor bank C are connected in series in the power grid to provide the required reactive power. When a short-circuit fault is detected, the fast vacuum switch is commanded to rapidly close and bypass the circuit branches of the MOV and C. The fast vacuum switch replaces the spark gap or electronic switches in a traditional series compensation device. A specially arranged bypass switch, which is connected in parallel to C in a traditional device, can also be eliminated. Thus, the fast-vacuum-switch-based line series compensation device has significant advantages in terms of cost savings, operation reliability, and compact designs. It permits the application of series compensation devices in rural power grids, where the radius of the power network is so large that the voltage at the end of power lines is often less than 90% of the nominal value. Series fast-vacuum-switch-based line series compensation devices with the above topology, ranging from 10 to 110 kV, were developed. Fig. 10 shows an example of an installed 110 kV device, in which a 12 kV fast vacuum switch is used to protect 84 μF compensation capacitor banks. When a fault is detected, the fast vacuum switch can bypass the compensation capacitor banks within 12 ms.

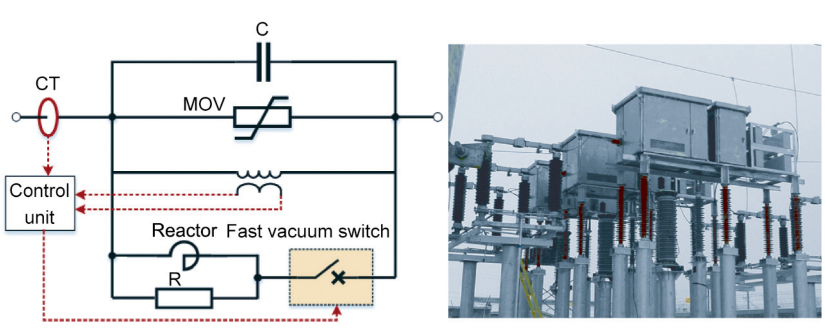


Fig. 10. Topology and application of fast-vacuum-switch-based line series compensation device. (a) Topology. PT: potential transformer; CT: current transformer. (b) Installed 110 kV fast-vacuum-switch-based line series compensation device.

4.4. FVCB applied as generator CB

From the point of view of a vacuum arc, fast vacuum switches are suitable for application as generator CBs. A high initial opening velocity of a VCB can rapidly drive the initial constricted vacuum arc into a diffuse arc during high-current interruption. This moderates the erosion of the contact surface and decreases the minimum arcing time of the VCB [33,34]. Moreover, a vacuum arc has a positive volt-ampere characteristic during current interruption. This permits the fast vacuum switches to be connected in parallel to comprise a generator CB. In this case, a high nominal carrying current and high ratings of the short-circuit breaking current can be achieved without any additional current-balancing devices. Fig. 11 shows topology and a photograph of a developed 15 kV, 8000 A, 63 kA fast-vacuum-switch-based generator CB. In Fig. 11(a), to avoid the late breakdown or non-sustained disruptive discharge that occasionally occurs in vacuum interruptions, two fast vacuum switches are connected in series to achieve a high recovery voltage withstand capability. In achieving a high nominated current-carrying capability and a high rated short-circuit breaking current of the generator CB, three 12 kV, 3150 A, 40 kA VIs are connected in parallel. Thus, there are six fast vacuum switches in each phase of the generator CB. The total resistance of two series-connected modules of the fast vacuum switch per circuit branch is 26.7 μΩ, and keeps the same to each of the other two phases with a tolerance of less than 1 μΩ. Fig. 11(b) shows a photograph of the single-phase generator CB with this topology. Controlled switching technology with a short arcing time was adopted. The prototype was commanded to open at 3 ms before the fault current zero and interrupt the fault current within an arcing time of 2.5 ms. The feasibility of the fast-vacuum-switch-based generator CB was validated by a series of type test duties performed at the Chinese National Quality Supervision & Inspection Center for High Voltage Apparatus.

5. Future of vacuum switching technology

Fast vacuum switches have a fast operation response and low deviation of the operation time, making them suitable for accurate controlled switching operation. The switching transient of power systems can be smoothed by controlled switching of the load or fault currents. From this point of view, the controlled fast vacuum switching technology might be changing the future of power systems. However, further development of corresponding control strategies for the fast vacuum switches is required. These strategies must consider the pre-breakdown arc extinguishing mechanisms during high voltage making process, the determination of the boundaries of the controlled switching arcing time windows for a reliable current interruption, the equilibrium between the suppression of the magnetizing inrush current and the making overvoltage in energizing of no-load transformers, and the influence of operation conditions (e.g., operation time, control voltage, and environmental compatibility) on variation of opening and closing times of the fast vacuum switch.

The controlled fast vacuum switching of capacitive or inductive loads could effectively minimize the electromagnetic stresses on power systems and their components. Regarding the controlled switching of capacitive loads, such as shunt capacitor banks, filter compensation capacitor banks, no-load overhead lines, and cables, the making operation at a voltage-zero-point is preferred to avoid a high-amplitude and high-frequency inrush current with bank-to-bank capacitor switching and low local or remote overvoltage with other capacitive load switching. For de-energizing capacitive loads, a long arcing time is recommended for fast vacuum switch, ensuring a large arc-extinguishing contact gap, to decrease the probability of restrikes. For the controlled switching of inductive loads, such as shunt reactors, motors, and no-load transformers, the prospective voltage making phase angle should generate a prospective magnetic flux density that is equal to the residual flux density in the inductive loads to avoid the inrush current during the energization of these loads; in this case, the making operation at a voltage-peak-point is preferred for energizing the shunt reactors because there is no correlated residual flux. For the controlled switching of no-load transformers, the amplitude of energizing inrush current strongly depends on the estimation of the residual flux density in the transformer cores, which is determined by the interruption of the no-load transformer current. For de-energizing inductive loads, a long arcing time is recommended for fast vacuum switch to avoid repetitive reignitions and induced escalation overvoltage.

Fig. 12 shows an example of the controlled switching of a no-load transformer. Fig. 12(a) shows an installed 126 kV, 2500 A, 31.5 kA double-break fast vacuum switch, which is engaged to switch a no-load 65 MVA, 110 kV transformer. Fig. 12(b) shows a comparison of the test records of the no-load transformer switching. Compared with the energizing inrush current of the transformer with random switching, that with controlled fast vacuum switching is obviously suppressed; where the amplitude of the inrush current is limited to less than 10% of the rated current of the transformer.

For controlled switching of a fault current, a rapid short-circuit fault identification algorithm, particularly in fast prediction of the fault current zero, is essential for fast interruption of the fault current by the fast vacuum switch. The fast vacuum switch should open and interrupt a fault current with a short arcing time before current zero. In this way, the short-circuit fault elimination time can be decreased from more common three cycles for the existing switching technologies to less than half a cycle. Thus, both the structural and thermal effects caused by the short-circuit current

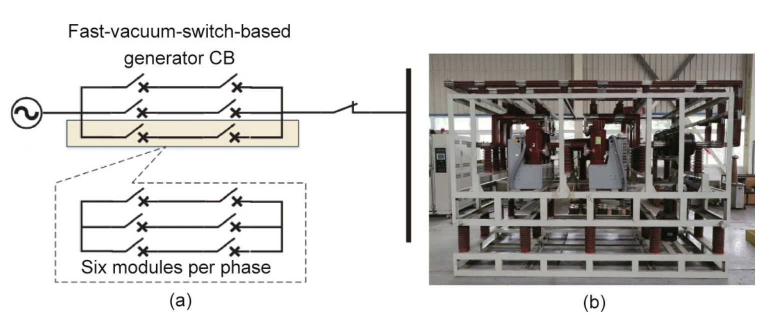
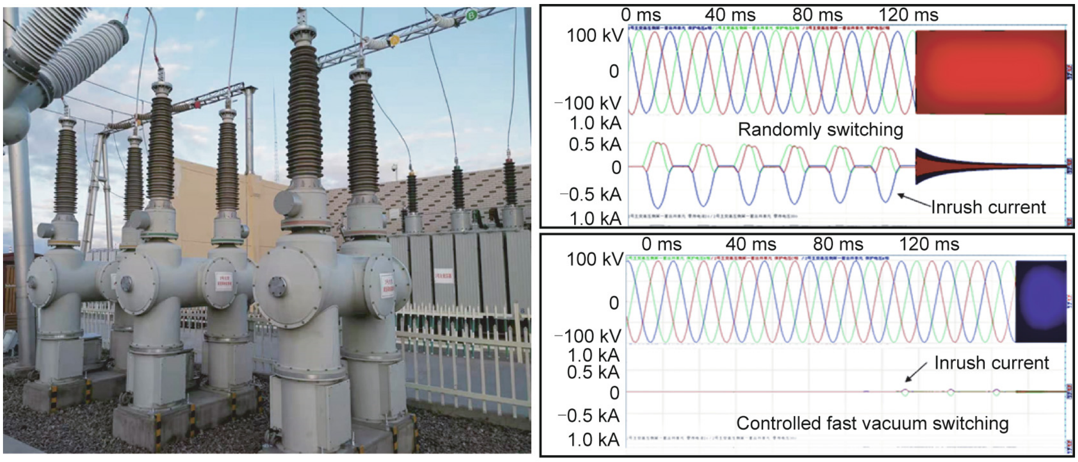


Fig. 11. Topology and photograph of developed 15 kV, 8000 A, 63 kA fast-vacuum-switch-based generator CB. (a) Topology; (b) photograph of the single-phase fast-vacuum-switch-based generator CB.



(a) (b)

Fig. 12. Photograph and test results of controlled fast vacuum switching of 65 kVA, 110 kV no-load transformer. (a) Photograph of 126 kV, 2500 A, 31.5 kA double-break FVCB for no-load transformer controlled switching; (b) comparison of no-load transformer performance with (top) random switching and (bottom) controlled fast vacuum switching.

on other power equipment can be moderated. The reduction in arcing energy during current interruption could also increase the electrical endurance of the fast vacuum switch.

6. Conclusions

China pledged to reduce its carbon intensity, peak carbon dioxide emission in 2030, and achieve carbon neutrality in 2060 at COP21 in 2015. As part of this effort, the use of SF_6 gas in the power industry is being reduced. As vacuum itself provides nothing for current conduction in both steady-state electrical insulation and transient-state switching, vacuum switching technology is a preferred alternative for the SF_6 gas switching in power transmission voltage. This paper reviewed the history of vacuum switching technology and presented the state-of-the-art of fast vacuum switching technology, which can be summarized as follows:

(1) China has taken a strong lead in researching and developing VCBs towards transmission voltage. A series of products, such as the eco-friendly live-tank 126 kV VCB and vacuum-type GIS, were developed. Based on the fast-current-interruption characteristics of vacuum switching technology, a series of EHV FVCBs, including 363 kV, 5000 A, 63 kA, and 550 kV, 5000 A, 80 kA FVCBs, are under development. The application of these products will significantly improve the transient stability and power transmission capability of networks.

(2) The fast opening and closing operations of fast vacuum switches make these switches suitable for integration into many applications, including DCCBs, FCLs, power quality improvement devices, and generator CBs. Power systems can benefit from these devices in terms of improved operation reliability, lower losses, lower cost, and higher power quality.

(3) The low deviation in the opening and closing times of the fast vacuum switches is appropriate for controlled switching equipment in power systems. The transient electromagnetic impact from a short-circuit current making or breaking, capacitive or inductive load current switching in power systems can be effectively moderated. The vacuum switching technology is changing the future of power systems.

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Compliance with ethics guidelines

Xiaofei Yao, Jianhua Wang, Shaogui Ai, Zhiyuan Liu, Yingsan Geng, and Zhiguo Hao declare that they have no conflicts of interest or financial conflicts to disclose.

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