Soft-Switched 4kV/100A Medium-Voltage Solid-State Circuit Breakers
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**Introduction**

In comparison with AC counterparts, DC power systems present higher efficiency in the same voltage levels, they need no AC synchronization, and reactive power compensation is not an obligation. Also, the possibility to integrate renewable energies is obtained. By eliminating AC/DC intermediate converters, the cost of establishing DC systems is reduced, and the reliability enhanced. Medium-voltage DC (MVDC) power systems have been under fully considerations for the newly established DC distribution systems.

There are a variety of factors contributing to the fast development of the DC systems during recent years. They can be divided into internal and external driving forces. Enhanced stability of the presented DC power supply, decreased corridor width of the DC distribution networks, higher power conversion efficiency, higher power capability, improved power quality, higher transmission efficiency, and being environmentally adaptive are the internal driving factors. While, fast growth of electric vehicles, growing number of installed wind farms, considerable number of DC loads, energy storage systems, fast growth of photovoltaic power, introducing more efficient material such as wide bandgap (WBG), and fuel cells stand for the external driving factors.

Among medium-voltage DC (MVDC) power systems’ equipment, circuit breakers (CB) are of great importance in disconnecting faulty sections from the network, enhancing the reliability, and obtaining an acceptable performance. Due to the high rate of rise of fault current and low inertia in DC systems, fast DC current interruption is an essential part of CBs design. Solid-state CBs (SSCBs) present fast response time and overcome the arc problems and noisy operation included in mechanical and hybrid CBs. In this research, the market of SSCBs, their applications, and the market segmentation are presented. Value proposition of the proposed SSCBs is also explained.

**End User Applications of DC Circuit Breakers**

DC circuit breakers have considerable applications from low voltage to high voltage levels. A few of these applications are listed as below:

- Aerospace
- Battery storage
- Data centers
- Electric power supply
- Electric vehicle charging stations
- Marine applications
- Mining
- Motor protection
- Oil and gas industry
- Particular Accelerators
- Radar
- Railway transportation
- Renewable energies
- Rolling stock
- Solar photovoltaics
- UPS systems

In the case of MVDC systems specifically as the emerging technology, the applications of circuit breakers can be categorized in six groups:
• Collection and distribution networks for PV plants
• Collection and distribution networks for wind parks
• Distribution networks of urban load centers
• Implementing MVDC systems in buildings
• MVDC distribution systems developed for electrified railways
• MVDC electric systems implemented on shipboard networks

The growing technology, HVDC systems, such as HVDC multi-terminal systems and macro HVDC grids are under fully developments worldwide. HVDC transmissions facilitate utilization of renewable energies and enable greater electricity exchanges among interconnected energy markets. Circuit breakers are the key technologies to guarantee the reliable operation of multi-terminal HVDC systems and HVDC grids.

**Major Players of DC Circuit Breakers Market**

DC circuit breaker products range from low voltage to high voltage levels. In the case of HVDC breakers, companies such as Hitachi ABB Power Grids ABB, Alstom, Mitsubishi, Siemens, and Diversified Technologies Incorporation have achieved remarkable progress in designing breakers up to 800kV. MVDC breakers range from 1.5kV to 100kV are under fully development with the recommended voltage ratings of ±50kV, 35kV, (±17.5kV), and ±10kV. In the case of LVDC breakers, which include the major number of manufacturers worldwide, the standard voltage levels are 1.5kV, 750V, 375V, 110V, and 48V. Table I shows a list of major players in designing circuit breakers.

Table I. A list of companies which are active in designing circuit breakers

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<thead>
<tr>
<th>Manufacturer</th>
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<tbody>
<tr>
<td>Hitachi ABB Power</td>
<td>Alstom</td>
<td>Sensata (Airpax)</td>
</tr>
<tr>
<td>Mitsubishi</td>
<td>Siemens</td>
<td>Ferraz Shawmut</td>
</tr>
<tr>
<td>Diversified Technologies Inc</td>
<td>Toshiba</td>
<td>American Electrical</td>
</tr>
<tr>
<td>ABB</td>
<td>Eaton</td>
<td>Franklin Electric</td>
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<tr>
<td>Changshu Switchgear</td>
<td>CHINT Electrics</td>
<td>LCB Corp</td>
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<td>ENTEC Electric &amp; Electronic</td>
<td>Powell</td>
<td>Carling Technologies</td>
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<td>Thycon</td>
<td>Yueqing Feeo Electric</td>
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<td>Astrol</td>
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<td>BRUSH Group</td>
<td>General Electric</td>
<td>APX group</td>
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<td>CG Power</td>
<td>Westinghouse</td>
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<td>Fuji Electric</td>
<td>Larsen &amp; Toubro</td>
<td>Shanghai Renmin</td>
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<td>Liangxin</td>
<td>Legrand</td>
<td>Bryant</td>
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<tr>
<td>Schneider Electric</td>
<td>Rockwell Automation</td>
<td>Federal Pioneer</td>
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Existing Technologies

Figures 1 through 3 show the most existing technologies introduced by ABB, THYCON, and Diversified Technologies, Inc.

![Hybrid HVDC Breaker](image)

Figure 1. Hybrid DC Circuit breaker developed by ABB [1]

Figure 1. shows the hybrid DC circuit breaker developed by ABB. The technology implemented in this structure is employing two paths to interrupt the fault current using ultra-fast mechanical switch and IGBT semiconductor devices.

The hybrid HVDC breaker includes two parallel paths: 1) main breaker which is made of series connected IGBT modules and nonlinear resistor arrestor banks; 2) load path consists of lower number of matrix connected IGBT modules and an ultra-fast disconnector which is called load current path.

In normal operation mode, the current passes through the load current path. In fault condition mode, the IGBT based load commutation switch turns off, and the fault current commutates immediately into the main breaker path. Then, the mechanical ultra-fast disconnector (UFD) opens to disconnect the load commutation switch from the main circuit. this process takes around 2 ms.

After commutating current to the main breaker, the main breakers IGBT cells open to force the fault currents to the nonlinear resistors designed by arrestor banks. The arrester banks reduce the fault current to zero by dissipating the energy of the fault. The total protective level of the arrester banks is chosen to be 1.5 times the nominal DC voltage. In addition, the arrester banks provide an over-voltage protection for IGBT modules in the main breaker [1].

Figure 2 indicates the solid-state circuit breaker using forced commutated thyristor developed by THYCON company. This circuit breaker uses the auxiliary injection circuit technology to provide an artificial zero-crossing-current in the main switch during DC current interruption.

In figure 2, V\_dc indicates the supply voltage; L1 represents the equivalent inductance of the source and transmission line; L3/R1 shows the load; and the short circuit fault is modeled by S1 switch at the load side.

In the normal operation mode, the normal load current passes through the thyristor Thy1. When the short circuit fault current is detected, Thy2 turns on to apply the voltage on the precharged capacitor C1 to the cathode of Thy1. In this case, the fault current in the main path is forced to zero through inductor L2.
The fault current commutates from Thy1 to Thy2, and capacitor C1 begins to charge in the opposite direction of what is shown in figure 5. After charging the capacitor C1, the current in the auxiliary branch including Thy2 reduces to zero. Then, Thy2 turns off to interrupt the fault current completely. Also, the energy stored in the inductor L1 is transferred to C1.

An auxiliary power supply is required to keep the voltage on C1 constant before DC current interruption process. This power supply also helps to discharge this capacitor after DC current breaking process. The values of capacitor C1, inductor L1, and the initial voltage on capacitor C1 are determined according to the maximum value of the fault current aimed to be interrupted.

Figure 2. DC circuit breaker developed by THYCON [2]

Figure 3 shows two types of solid-state circuit breakers and their simplified circuit topology developed by Diversified Technologies, Inc. The first circuit breaker is 4.5kV/600A solid-state DC circuit breaker. Also, conceptual design of the 8 MW solid-state DC circuit breakers is represented in this figure. In this structure, IGBTs are connected in series and parallel to handle the electrical ratings of the DC system, and the switch arrays are built with at least 20% redundancy margin.

4.5 kV, 600 A Solid-State DC Circuit Breaker comprising of two 4.5 kV IGBTs in series.

8 MW Solid-State DC Circuit Breaker comprising of two 10 kV, 8 MW interrupters

Figure 3. DC circuit breaker developed by Diversified Technologies, Inc. [3]-[4]
A simplified circuit topology of the solid-state circuit breaker developed by Diversified Technologies Incorporation is shown in Figure 4. The solid-state current interrupter includes a series string of solid-state devices to satisfy the DC bus voltage. The gate-drive signals for the solid-state switches are prepared by the fast-inverse-time controller. The trip signals can be generated manually, by the other breakers in the system, or from the breaker itself by detecting the fault current using the sampled fault currents. The gate-drive signals are applied to the semiconductor devices simultaneously.

In this structure, IGBTs are connected in series and parallel to handle the electrical ratings of the DC system, and the switch arrays are built with at least 20% redundancy margin. In the topology shown in the right side of figure 3, water cooling system with comparatively compact size is used to cool the equipment during operation.

**Novelties of the Developed Solid-State Circuit Breaker**

The proposed solid-state circuit breaker is designed for MVDC. To present the state-of-the-art technology to market, many factors are included in the final design. These are:

- Artificial zero-crossing-current during turn-off process is achieved.
- Auxiliary branch is protected from high short-circuit fault currents.
- Auxiliary circuit is design to have a fast response time to satisfy the operation of SiC MOSFETs in the main branch.
- High isolation gate-drive power supplies are included to handle medium-voltage DC voltage value.
- Multiple SiC MOSFETs are placed in parallel to achieve high efficiency and handle high fault currents.
- Multiple SiC MOSFETs are placed in series to satisfy DC system voltage.
- Silicon carbide (SiC) MOSFETs are used due to their decreased on-state resistance, high electrical ratings, and fast response time.
- The final design is compact.
- The final design is electrically scalable.
- Voltage oscillations is decreased to increase the lifetime and improve the reliability of the SiC MOSFETs.
The response time of the designed circuit breakers is fast enough to compensate the low inertia of the DC System during fault conditions.

According to the presented innovations, a new circuit topology is proposed with a novel topology shown in figure 5. The proposed circuit topology includes two main branches. The main conduction branch is responsible for conducting the load current with high efficiency. The other path is an auxiliary circuit named as active resonant branch connected in parallel. This branch is responsible for generating a resonant current during DC current interruption and achieve soft switching turn-off.

Regarding figure 6, the DC power typically is transferred from the DC grid to the load through the DC breaker (the red arrow in figure 6). When the DC breaker needs to turn off, another current (the black arrow in figure 6) needs to flow through the DC breaker with the same amplitude but in the opposite direction to have zero current switching of the DC breaker.

The active resonant branch generates the short-period constant current pulse (the black arrow in figure 6) for the main conduction branch to turn off. The short-period, defined as $t_{sw}$ would be the switching time for the main conduction branch.
The designed circuit for the active resonant branch is shown in Figure 7 which is based on boost converter and operates on-shot. The working principle is as follows:

During 0-t₀: SW turns on and the DC voltage charges the inductor L, \( i_{ac} \) increases linearly to the peak desired current level.

During t₀-t₁: SW turns off; the relatively constant \( i_{ac} \) flows through the diode D, capacitors, and the main conductor branch.

The main conduction branch would have zero current turn-off during t₀-t₁, which is \( t_{sw} \).

In addition to the explained working principle above, two points are of importance:

- There would be parasitic inductance in the branch that consists of diode D, the capacitors, and the main conductor branch. The current flowed in this branch would start from zero and ringing exists. This problem is solved by the damping resistor.
- When the main conduction branch has been turned off. The rest part of \( i_{ac} \) (t₁ and t₂) could go to MOVs directly instead of flowing through the capacitors. Thus, the maximum voltage for the HV switch stack is decreased.

**Main Conduction Branch of the Developed Solid-State Circuit Breaker**

Figure 8 shows the 3D design view of the main conduction including five layers of SiC MOSFETs in series. In each layer, four SiC MOSFETs are connected in parallel to achieve high efficiency. Also, to provide high isolated gate-drive power supplies, inductive power transfer system is used to provide isolated power supplies for each SiC module in the main branch. Figure 9 indicates the implemented main conduction branch. Also, figure 10 shows the implemented main conduction branch and inductive power transfer supply in a whole DC test system.

Figure 11 shows the second developed main conduction branch where three layers of SiC modules are connected in series, and in each layer, three module are connected in parallel to achieve a high efficiency and reliability. Also, figure 12 indicates the circuit breaker consisting of the developed main conduction branch of figure 11 and the wireless power supply.

Figure 13 indicates the third version of the main conduction loop which resistive-capacitive-diode (RCD) snubbers are used to slow down the transient voltage across the solid state circuit breaker. The full implementation of the RCD based main conduction branch in conjunction with the wireless power supply is presented in figure 14.
Figure 8. The 3D design view of the main conduction branch including five layers of SiC MOSFETs in series, each layer consists of four SiC MOSFETs in parallel. In the figure, the wireless part to supply the gate drivers are also included.

Figure 9. Implemented the main conduction branch including five layers of SiC MOSFETs.

Figure 10. The fault current breaking test setup. The main conduction loop with the discrete SiC MOSFETs and the wireless gate driver supply are included in the figure. The SSCB is tested under pulse current test condition.
Figure 11. The main conduction branch including three layers of SiC MOSFETs in series, each layer includes three SiC MOSFETs module in parallel.

Figure 12. The fault current breaking test setup. The main conduction loop with the SiC MOSFET modules and the wireless gate driver supply are included in the figure. The SSCB is tested under pulse current test condition.
Figure 13. The main conduction branch with RCD snubbers. The branch includes three layers of SiC MOSFETs in series, each layer includes three SiC MOSFETs module in parallel.

Figure 14. The fault current breaking test setup. The main conduction loop with RCD snubber and the wireless power supply are included in the figure. The SSCB is tested under pulse current test condition.
Figure 15. The captured screen shot of the 520A current interruption process. (a) Complete turn-off process waveforms, (b) Measured transient voltage on the breaker, (c) Measured transient voltage distribution among various layers.
It should be noted that each of these main connection branch has been fully tested to interrupt 500A DC currents in a pulse current test system. Figure 15 shows the captured screen shot of the 520A current interruption process. The voltage balance between layers is shown in this figure. The proposed solid state circuit breaker presents scalability.

**Active Resonant Branch of the Developed Solid-State Circuit Breaker**

The active resonant branch successfully generates the 100 A while clamping the maximum voltage around 5 kV in order to cancel out the original current in the main conduction branch to achieve zero current switching. Figure 16 shows the final design of the hardware overview. The full voltage and full current test to demonstrate the proof-of-principle of the proposed topology has been successfully done.

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**Figure 16. An overview of the finalized hardware design of the active injection circuit.**

The components included in figure 14 to generate 100A resonant current are as follows:

- **DC Voltage=300V:** which is smaller than 600V in the original specification in the statement of work.
- **L=300μH** by an air-gapped inductor built with an amorphous core: which doesn’t saturate to at least 100A.
- **High Voltage (HV) Switch Stack** uses two IGBT half-bridge modules in series with isolated gate driver design and parallel protection devices: which could carry 100A and standoff 5kV.
- **High Voltage (HV) Diode Stack** uses four SiC diodes in series with parallel protection devices.
- **Coupler Reset** resets the energy of the coupler for next activation of the active resonant branch.
- **Damping Resistor** is used to damp out the undesired resonance of the 100A.
- **Controller** commands the active resonant branch and communicates with the main conduction branch.
- Current sensor: which measures the generation of 100A. The system is well characterized so that for a pre-programmed current level, the current sensor is not necessarily needed.

The hardware design implementation of the active injection circuit is shown in figure 17 with components listed above. Some components are hidden in figure 17. Also, Figure 18 shows switch stack and the gate driver with more details. The whole set up of the active injection circuit is indicated in figure 19.

Figure 17. The active resonant branch circuit implementation.

Figure 18. High voltage (HV) switch stack. Isolated gate driver board (left) and series IGBT half-bridge modules (right).
DC Circuit Breakers Market Segmentation

To get a deep understanding of the DC circuit breaker market in the world, the existing market is evaluated under several factors including the circuit breaker type, voltage type, end-use application type, and geographical region.

In the case of circuit breaker type, the market of circuit breaker is segmented into two groups including solid state DC circuit breakers and hybrid DC circuit breakers. From voltage aspect, DC circuit breaker market is divided into three distinct categories: low-voltage DC circuit breakers, medium-voltage DC circuit breakers, and high-voltage DC circuit breakers. Considering end-use applications, the market of DC circuit breakers can be categorized by power generation, transmission, distribution of electrical energy, and others including specific applications such as rolling stock. In term of geography, the DC circuit breaker market is divided by five regions: North America, Europe, Asia-Pacific, South America, and Middle-East and Africa. [factmr.com: DC Circuit Breaker Market Forecast, Trend Analysis & Competition Tracking - Global Market Insights 2019-2029], [Mordorintelligence.com, “DC Circuit Breaker Market - Growth, Trends, And Forecasts (2020 - 2025)]]
Renewables energies as a dominant application in DC circuit breakers Market

Renewable energy resources are witnessing a considerable growth in developing countries. Significant progress with renewable energies among total electricity generation, growing number of renewable projects, and rising demand for clean energy all are driving factors [Mordorintelligence.com, “DC Circuit Breaker Market - Growth, Trends, And Forecasts (2020 - 2025)].

Among renewable energy resources, solar energy capacity, and wind power capacity have been witnessing a significant growth during last decade. Solar energy capacity has increased by 1300% from 41.54 GW, in 2010, to 586.43 GW, in 2019. Also, wind energy capacity grew by over 240% from 180.85 GW, in 2010, to 622.7 GW, in 2019. The relaying utility requires DC circuit breakers to protect the equipment from short circuit faults [Mordorintelligence.com, “DC Circuit Breaker Market - Growth, Trends, And Forecasts (2020 - 2025)].

Another factor that increases the share of renewable energies in total generation energy is the considerable decrease of the cost of renewable energy infrastructures. For example, the cost of solar photovoltaic modules has dropped about 99% in the last four decades. Another example is decreasing the cost of wind turbines around 30-40% since 2009 [Mordorintelligence.com, “DC Circuit Breaker Market - Growth, Trends, And Forecasts (2020 - 2025)].

Regarding the fast growth of renewable energies, it is expected that the markets of DC circuit breakers as the inseparable part of DC systems increases accordingly.

Solid-state circuit breakers and their growing rate

Growing investments in transmission and distribution of electrical energy, especially in the Asia Pacific region, are expected to increase the solid-state DC circuit breakers market. Also, developing economies in Asia Pacific region are the fastest growing markets for this segment. In addition, technological advancements in power electronics devices is another factor to increase the market of DC solid state circuit breakers [marketsandmarkets.com, DC Circuit Breaker Market by Voltage, Type, Insulation, End-User, and Region - Global Forecast to 2024]

Medium voltage DC circuit breakers as the major part in DC circuit breakers Market

According to the DC circuit breakers market, they can be categorized in term of voltage to low-voltage, medium-voltage, and high-voltage groups. Medium-voltage part is expected to cover a major part of the market share by 2024. Increasing electrical infrastructure development, increasing investments in renewable integration projects, demand for efficient, and stable power supply all are the driving factors [marketsandmarkets.com, DC Circuit Breaker Market by Voltage, Type, Insulation, End-User, and Region - Global Forecast to 2024]

Value proposition assessment

According to value proposition canvas, the value proposition for the proposed solid-state circuit breakers is as follows:

A. Customer jobs

1) The electrical ratings of the target application need to be determined.
2) The maximum value of the fault current in the DC system need to be decided.
3) Overload conditions need to be defined.
4) Maintenance needs to be done in a proper routine.
5) Enough space needs to be provided to install the circuit breaker.
6) Equipment accompanied by circuit breaker such as cooling systems are required.

B. Customer pains
1) Due to the development of the DC system, determining the nominal electrical ratings is not straightforward.
2) The maximum value of the fault current depends on the fault condition and DC system topology.
3) Routinely maintenance accompanies by spending time and cost for customers.
4) Due to the cost of space, the cost of infrastructures will be high.
5) Cooling systems and other required equipment increase the overall cost of the product.

C. Customer gains
1) The DC system and related equipment are protected from short circuit faults.
2) The reliability of the DC system is increased.
3) Intelligent protective relaying can be connected to the circuit breaker to protect the DC system.
4) In the case of routinely maintenance of a specific part of the DC system, that part can be deenergized and isolated from the rest of the DC system without completely turning the whole DC system off.
5) The sources can be protected form overload condition by programming the circuit breaker.
6) The circuit breakers automatically dissipate the stored inductive energy of the voltage source reactor and transmission lines of the DC system during DC current interruption.

D. Products and services
1) Medium-voltage solid state circuit breaker.
2) User-friendly developed software for setting the circuit breaker’s operating parameters.
3) 24/7 availability of the product support services team.

E. Gain creators
1) Higher reliability and increased lifetime are achieved due to the soft switching operation of the proposed circuit breaker. In this case, medium-term and long-term costs of the infrastructure are reduced.
2) Higher efficiency not only decreases the power loss of the circuit breaker during normal operation mode, but it reduces the cost of the cooling systems as well.
3) Fast response time is proposed to compensate the low inertia feature of the DC system. In this case, fault currents in the system is removed before entering to an unsafe range.
4) Scalability and compactness are provided.
5) The circuit breaker can be used for in-door applications without the concern of arc problems and noisy operations.

F. Pain relievers
1) DC system analysis and fault condition evaluation are performed by the product expert engineers and the required parameters are recommended to customers.
2) 24/7 availability of the product support services team is proposed to customers for a given period.
3) Product support team takes care about the routinely maintenance and gives technical advice.
4) The proposed design is compact with high-power density. This leads to a considerable decrease in the cost of space required to install the circuit breaker.
5) Scalability provides a great chance for customers to develop their system in the future.
6) High efficiency decreases the cost of cooling system infrastructure.

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