IDEAL POWER Whitepaper

B-TRAN™ Devices in Solid-State Circuit Breaker Applications

Abstract

The increased electrification in our society is leading to increased demand on our circuit protection requirements. Circuit breakers are needed in power distribution systems to protect against power surges and short circuits caused by unplanned events such as lighting strikes, downed trees, and equipment failure. Applications include infrastructure upgrades to the existing alternating current (AC) grid, increased use of distributed generation such as solar and wind power, energy storage, electric vehicle (EV) and EV charging, and associated vehicle to grid (V2G) networks. Faults must be isolated before damage can cascade further throughout the system. Up to now, this critical function has been handled by mechanical circuit breakers. These devices exhibit several problems centered around the physical limitations of their operation, resulting in relative slowness to open the circuit when needed. This delay causes high fault currents and electrical arcs which wear the breaker contacts. A potentially superior solution is the solid-state circuit breaker (SSCB), which uses power semiconductors to quickly open a circuit with no moving parts subject to wear. Solid-state circuit breakers have not seen widespread deployment due to the comparatively high conduction losses of currently available Insulated-Gate Bipolar Transistor (IGBT) devices. It should be noted that all contactors switching AC power must inherently have bidirectional current flow capability. Fortunately, a significant advancement in power semiconductor technology called the Bidirectional Bipolar Junction Transistor (B-TRAN™) overcomes this problem by combining fast switching, low conduction losses, and bidirectional capability. For these reasons, solid-state circuit breakers could soon be more broadly adopted.

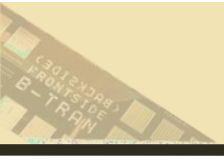
Keywords

Bi-directional, bidirectional, solid-state circuit breaker, SSCB, IGBT, MOSFET, grid protection, grid infrastructure, EV, AC circuit breaker, DC circuit breaker, vehicle to grid, V2G, B-TRAN

Circuit Breakers

Why we need them, and what makes a good one

A circuit breaker's purpose is to open a circuit, stop the flow of electricity, and contain high currents created by a fault. Typical situations that require circuit breaker protection include short circuits or



‘islanding’ when utility power is backed up by a generator or renewable energy source. They are also needed to isolate or power down various parts of the electrical distribution system during maintenance of the network. EVs also require circuit breakers as they have multiple power busses and power conversion nodes.

A circuit breaker should have as little impact on the circuit performance as possible when closed and provide effective isolation when open. The breaker might have to remain in the open or closed condition for extended periods of time, but react reliably when required, often to ensure personnel or equipment safety.

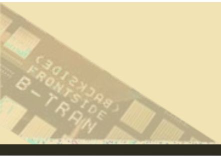
Circuit breakers represent a global market that is projected to reach nearly USD 26 Billion by 2027, growing at a forecasted compound annual growth rate of 6.6% [1]. Major existing applications are in small and medium size electrical substations, railway systems, and high voltage transmission and distribution. New installations are a market driver, but there is also a significant demand in updating the infrastructure around the world, with the U.S. power grid specifically in dire need of upgrade. Significant new markets have also appeared, such as renewable energy, direct current (DC) microgrids, energy storage, DC loads, and EV applications. In all circuit breaker applications, there are two important features that are critical for operation: fast switching and low conduction losses.

Fast Switching

The critically important role of a circuit breaker is to serve as a safety device by preventing damage to the downstream equipment, such as transformers and appliances, and reducing the risk of fire in high current situations. Fast switching is needed because currents rise rapidly in a fault situation. DC based systems such as wind, solar, and energy storage in particular have fault current rise times that require microsecond reaction times in the circuit breaker and may also require bidirectional capability to support current flow both to and from the grid. Ideally, opening the switch in microseconds is needed for optimum protection by dramatically reducing unwanted energy surge. Increasing the circuit breaker opening reaction time by 1 millisecond results in an order of magnitude increase in unwanted current in the system.

Low Conduction Losses

While the critical purpose of a circuit breaker is to open quickly, the majority of a circuit breaker’s lifetime is spent closed, allowing current to flow normally. In this closed state, circuit breakers are continuously conducting current, so it is important to minimize conduction losses that waste energy.



Traditional mechanical circuit breakers have very low contact losses but are incapable of switching as quickly as solid-state circuit breakers. On the other hand, solid-state circuit breakers can switch quickly but, until now, have come with high conduction losses that result in significant wasted energy that must be dissipated in the form of heat. The need to eliminate heat increases the cost, weight and complexity of solid-state circuit breakers using conventional semiconductor switches. In this paper we will examine a method of implementing a solid-state circuit breaker that achieves both fast switching *and* low conduction losses.

Mechanical Circuit Breakers

Ubiquitous work horse, but too slow for new demands

Circuit breakers historically have been mechanical and have the benefits of low contact resistance and good isolation. However, they have considerable downsides as well: they are prone to wear and operate in milliseconds instead of microseconds. This means that after a short circuit is detected, the ‘let-through’ energy can be high before the circuit breaker opens, stressing or even damaging components, connections and the breaker itself.

Another significant problem is arcing. When a mechanical switch opens or closes an electrical spark, or arc, occurs. This degrades contacts, increasing resistance and the risk of the contacts being welded together. The time to break the circuit is also extended, particularly with DC, where there is no ‘zero-crossing’ to extinguish the arc, as there is with AC. The arc also produces a burst of electromagnetic interference (EMI) that can produce malfunctions in nearby electronics.

Complex schemes are needed to suppress the arc, such as vacuum sealing or gas-filling the breaker cavity, blasting away the arc with compressed air, or applying a magnetic bias field. All are expensive options and add further complexity and opportunity for failure. Mechanical circuit breakers therefore have a limited life and in critical systems need to be regularly serviced or changed-out with repeated labor and capital expenditure. The slow switching speed and short lifecycle of mechanical circuit breakers have led to development of an improved solution - the solid-state circuit breaker.

Solid-State Circuit Breakers

A faster solution, but held back by conduction losses

A solid-state circuit breaker solves the operating time and arcing problems present in mechanical circuit breakers. Instead of mechanical contacts, SSCBs use power semiconductors to quickly open a circuit with no moving parts. A semiconductor switch can open a circuit in microseconds, thereby dramatically reducing the energy that can cause damage in the system. Since SSCBs do not have mechanical contacts, arcing and its associated risks and countermeasures are eliminated. Additionally, SSCBs allow for a greater degree of control compared to electromechanical circuit breakers. SSCBs can be programmed to open at various current levels based on the differing needs of the system [2].

AC and DC Grid Infrastructure

Up to now, the power semiconductor switch that has been suited to the power levels of AC and DC grid SSCBs is the IGBT. However, IGBTs have significant conduction losses compared to a mechanical contact-based switch. At medium to high current, IGBTs are typically used for their low cost and proven ruggedness, but the physics of the device dictates that the voltage drop will be around 1.75 V per IGBT. Traditional IGBT circuits also require a series diode (in parallel with the reverse biased IGBT of a bidirectional module) which adds approximately 1 V, increasing the switch circuit voltage drop to 2.75 V.

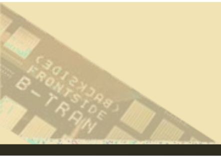
Typical SSCB implementation requires many switches in series, thereby increasing the aggregate voltage drop by 2.75 V for every switch in the circuit path. The aggregate voltage drop multiplied by the current equals the power lost. For the hundreds of amps seen in grid applications, this translates to hundreds of watts of energy lost, with a similar proportional increase in heat dissipation. Therefore, the conduction losses translate to considerable wasted energy and require the implementation of costly thermal management systems to cope with the excess heat.

EV and EV Charging

Electric vehicles have lower power levels than the grid infrastructure. For EV SSCB applications, in addition to IGBTs, another common alternative semiconductor device is the MOSFET. MOSFETs have a resistance to the flow of current that translates to high conduction losses and wasted energy in a circuit breaker application, particularly at high current conditions.

While efficiency is a concern in the grid infrastructure, it is particularly important in EV applications because the waste represents energy that could have been used to extend vehicle driving range or shorten charge time. Compounding the negative impact, the heatsinking required adds to the bulk and weight an EV has to haul around, further reducing its range.

Single MOSFETs are also much more expensive than IGBTs in the same voltage/current class. Although they can be paralleled for lower resistance, the cost becomes even more prohibitive and, for bidirectional current flow, two are needed in series to block their body diodes from conducting. In V2G



SSCB applications, the EV is essentially another node in the power grid, and bidirectional capability is needed for the flow of current between the EV and the grid.

None of the traditional options offer a good solution because of high conduction losses. With energy levels in many applications rising, the problem of high-power dissipation in SSCBs is only getting worse. There is therefore an increasing urgency to find a way to make and break high-current bidirectional connections with microsecond speed and lower loss.

Achieving the Best of Both Worlds

B-TRAN™ enables fast and efficient solid-state circuit breakers

The B-TRAN™ power semiconductor switch is a solution for SSCBs that achieves fast switching combined with low conduction losses. B-TRAN™ was developed by Ideal Power of Austin, Texas [3]. The device is similar to a symmetrical bipolar junction transistor with two controlling base connections, one for each direction of conduction. Ideal Power has 88 patents issued or pending related to the technology, covering its architecture, control methodologies and techniques, manufacturing methods and application-specific uses.

Figure 1 shows the simple and symmetrical internal structure of the device.

Figure 2 shows how it compares with an IGBT equivalent circuit.

Figure 3 shows that B-TRAN™ turn-off time, critical for an SSCB to open the circuit when a fault is detected, is even faster than IGBT turn-off time yet results in a voltage drop of only 0.6 V at 50 A. Compared with a bidirectional IGBT SSCB, the B-TRAN™ solution exhibits a 4x lower voltage drop.

The practical benefit is the B-TRAN™ solution dissipates just 360 W whereas an IGBT-based bidirectional circuit would dissipate over 1,500 W in a 12 kV 50 A SSCB. This is a significant energy savings and results in heatsinking that is a fraction of the size and cost, opening up applications such as EV battery isolation.

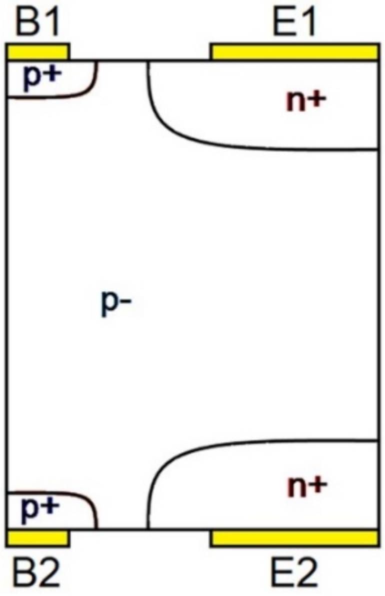


Figure 1: The internal structure of a B-TRAN^{TM} device

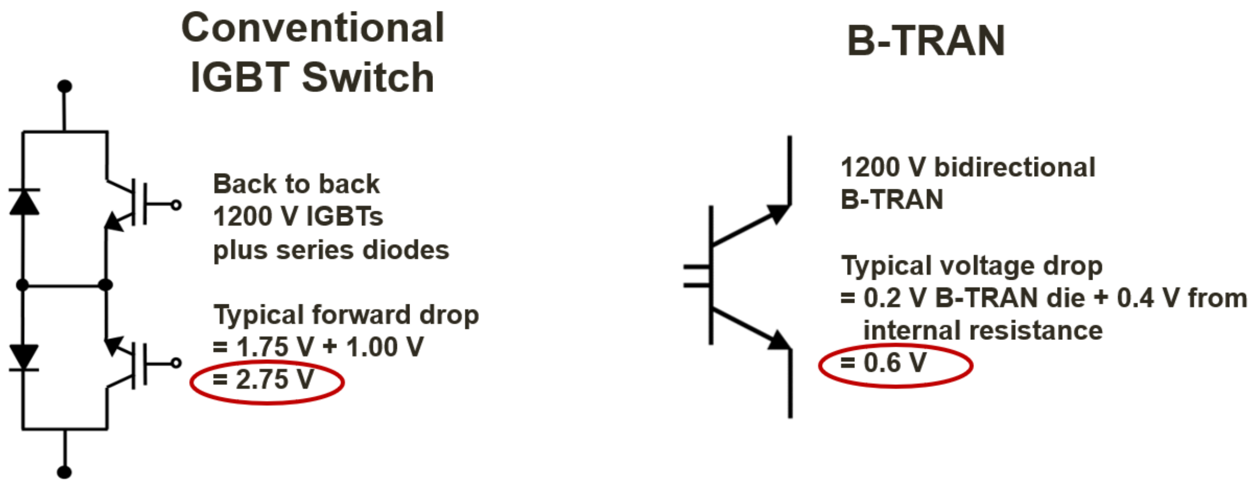


Figure 2: B-TRAN^{TM} lower conduction loss compared with an IGBT-based circuit

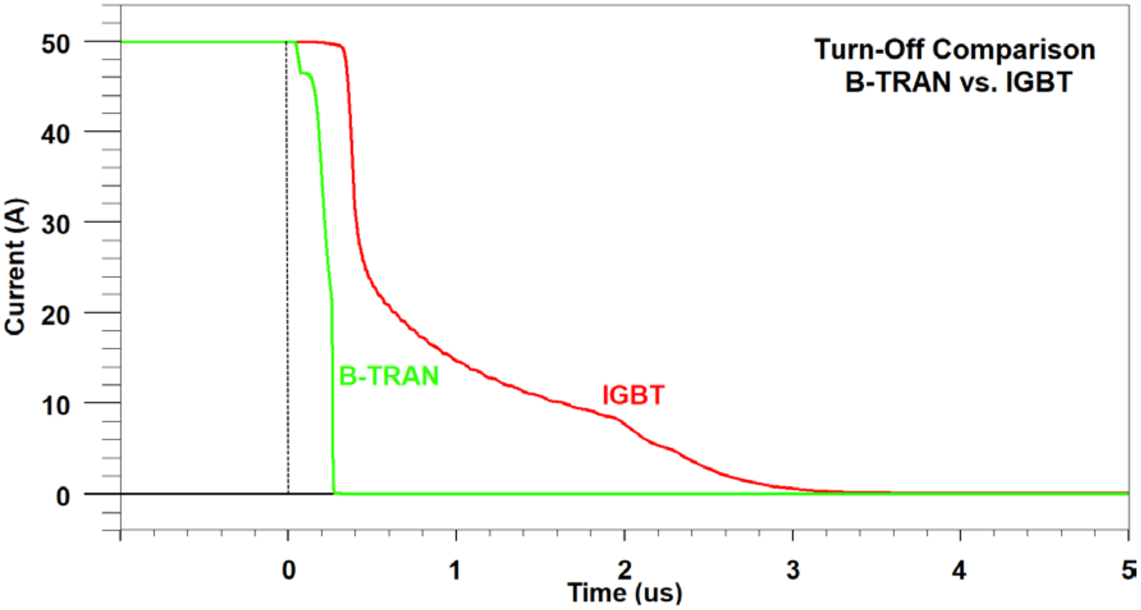


Figure 3: B-TRAN™ turn-off switching is faster than IGBT

Bidirectional Benefits

Reduced component count with B-TRAN™

In addition to the lower conduction losses of a B-TRAN™ compared to an IGBT, there is an additional benefit of reduced component count in a B-TRAN™ based SSCB. For a bidirectional AC or DC circuit breaker, two IGBTs in series are required, with parallel diodes, resulting in four semiconductor devices needed per switch.

Figure 4 is a bidirectional SSCB block diagram showing the component reduction achieved using one B-TRAN™ instead of two IGBTs and two diodes. Lower component counts lead to smaller system size, greater reliability, and lower system level costs.

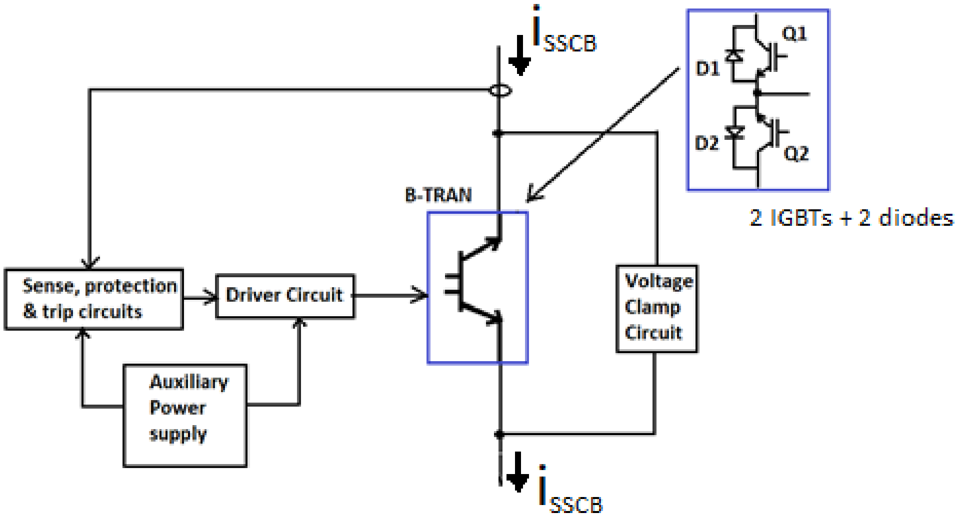
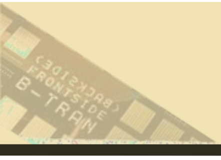


Figure 4: In a bidirectional SSCB circuit, one B-TRAN™ replaces two IGBTs and two diodes

In a typical SSCB, the circuit shown in Figure 4 is implemented multiple times, in series and/or parallel configurations, in order to achieve the needed high power handling capability. Therefore, the benefit of the reduced component count B-TRAN™ circuit multiplies as the scale of the SSCB increases, also contributing to further reduction in overall conduction losses compared to an IGBT-based SSCB. As an illustration of the benefits of the B-TRAN™, **Table 1** shows dissipation at 50 A compared with IGBTs from two major suppliers. All devices are rated at 1200 V/50 A. Figures are given for single devices in a low-voltage application (columns 4 and 5) and for 12 devices in series for a 12 kV unidirectional application (column 6). In the 12 kV bidirectional application (column 7), the IGBT losses must now include the additional reverse blocking diode.

Device	Transistor Forward Drop @ 50 A(V)	Diode Forward Drop @ 50 A (V)	Unidirectional loss (W)	Bidirectional loss (W)	12 kV application* unidirectional loss (W)	12 kV application bidirectional loss (W)
B-TRAN™	0.6	NA	30	30	~ 360	~ 360
IGBT – Manufacturer A	1.75	1	87.5	137.5	~ 1050	~ 1650
IGBT – Manufacturer B	2.2	1	110	160	~ 1320	~ 1920

Table 1: SSCB conduction losses compared



The results in Table 1 show a reduction in power loss in the unidirectional application of nearly 66% compared with the better of the two IGBTs and 78% for the bidirectional case. Along with energy savings, heatsink sizing, weight, and cost are dramatically reduced.

Performance Demonstrations

SSCB implementation with B-TRAN™

As validation of the performance breakthrough of B-TRAN™, Diversified Technologies, Inc. (DTI), in collaboration with Ideal Power, was awarded a contract with the U.S. Navy/Naval Sea Systems Command (NAVSEA) to develop a B-TRAN™ based solid-state DC circuit breaker rated at 12 kV, 500 A (6 MW) for mission-critical technology in the Navy's ship electrification program. The contract is funded by the U.S. Department of Defense's Rapid Innovation Fund designed to accelerate the commercialization of high-value, high-impact new technologies. Further funding has also been received from the U.S. Department of Energy (DOE) for an AC version of a B-TRAN™ based SSCB.

In Phase I of the DOE project, DTI will:

- design a 50 MW, 13.8 kV-class SSCB utilizing B-TRAN™
- build and demonstrate B-TRAN™ switch modules to interrupt AC power
- confirm the efficiency and speed of the B-TRAN™ devices in AC operation.

The B-TRAN™ based SSCB is expected to limit fault energy by orders of magnitude compared to conventional mechanical circuit breakers. If successful and awarded a Phase II grant, DTI will build and test a full 50 MW AC SSCB using Ideal Power B-TRAN™ devices.

The funded development programs are set to generate performance data, validating the use of B-TRAN™ based SSCBs in wider applications in the power distribution grid, renewable energy microgrids, energy storage, electric vehicles, and future development of the overall smart energy infrastructure.

In these applications, bidirectional conduction capability of a breaker is increasingly required to enable energy feed-in to the grid in growing applications, including V2G and renewable energy with storage, to allow charge/discharge of high current batteries.

Other markets for B-TRAN™ can also be addressed, such as for circuit breakers and high-frequency switches in uninterruptable power supplies for data centers and switches in off-board/stationary electric vehicle chargers, grid-tied inverters, and military systems.

Solid-State Circuit Breaker Market is Finally Enabled with B-TRAN™

The SSCB market can now be realized as B-TRAN™ has addressed the conduction loss obstacles of IGBTs. Semiconductor switching speeds that outperform legacy mechanical switches, combined with low conduction losses of B-TRAN™, allow for a solution that offers greater protection without sacrificing system efficiency. In addition to performance gains, B-TRAN™ lowers costs by reducing the component count when compared to IGBT-based SSCBs, while also reducing associated heatsinking costs of complex cooling systems, particularly in bidirectional applications.

The energy saved is a compelling cost benefit over time and, compared with IGBTs, the smaller, lighter system solution confers user benefits such as longer range in EVs. Compared with mechanical circuit breakers in the power grid, the dramatically extended life, reliability, and low maintenance attributes of B-TRAN™ make it an attractive solution for AC and DC circuit breaker applications.

All of the SSCB applications discussed in this paper will be interconnected as society moves towards increased electrification and requires bidirectional capability for V2G, energy storage, renewable energy, and DC microgrids. Bidirectional SSCBs with fast switching and low conduction losses are needed for this new infrastructure, and B-TRAN™ devices are the solution which can help enable the market.

References:

[1] Fortune Business Insights – Circuit Breaker Market Size: report FBI100765

[2] M. Kempkes, I. Roth and M. Gaudreau, "Solid-state circuit breakers for Medium Voltage DC power," 2011 IEEE Electric Ship Technologies Symposium, 2011, pp. 254-257, doi: 10.1109/ESTS.2011.5770877.

[3] https://www.idealpower.com/