Application Note: IPAN1001

Using B-TRAN™ in Solid-State Circuit Breaker (SSCB) Design

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Introduction

The world is rapidly advancing towards a more sustainable and green energy infrastructure to address climate change. Electric vehicles, renewable energy and grid modernization are key drivers of reducing greenhouse gas emissions. 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. 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, especially in DC voltage applications. 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 which can open the circuit orders of magnitude faster thereby eliminating electrical arcs and reducing contact wear with no moving parts subject to mechanical wear. SSCBs have not seen widespread deployment due to the comparatively high conduction losses of currently available Insulated-Gate Bipolar Transistor (IGBT) devices. Recently, wide bandgap devices (GaN and SiC) have been proposed for lower losses, but the cost of these devices is high. It should be noted that all contactors switching AC power must inherently have bidirectional current flow capability. B-TRAN™ overcomes this problem by combining fast switching, low conduction losses, and bidirectional capability using a monolithic silicon die.

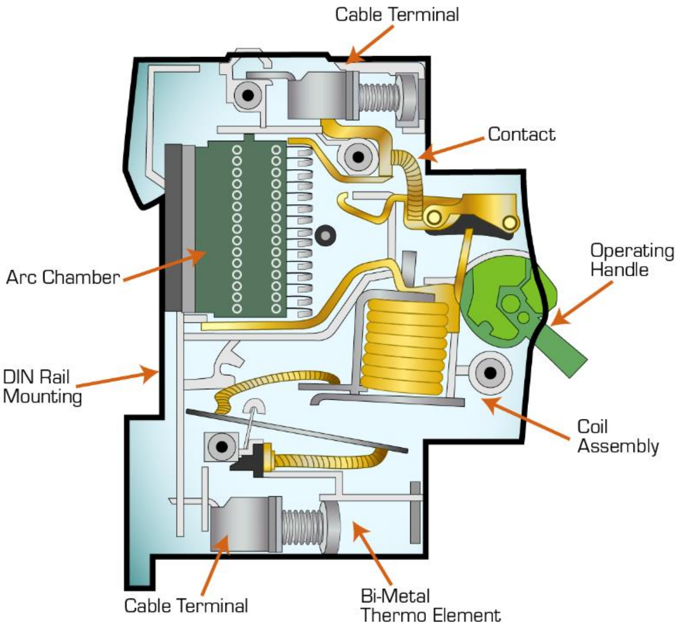


Figure 1. Internal diagram of a mechanical circuit breaker.

SSCB Overview and Application Requirements

SSCBs represent a modern alternative to traditional mechanical circuit breakers, offering enhanced capabilities, flexibility, and safety. SSCBs are electronic devices designed to interrupt or break an electrical circuit when abnormal conditions such as overcurrent, short circuits, or faults occur. Unlike mechanical circuit breakers that use physical mechanisms like springs and levers to trip, SSCBs utilize semiconductor devices to achieve rapid and precise circuit interruption. The advantage of SSCBs is fast response as it can break fault currents up to 100 times faster compared to mechanical breakers and they are also more reliable due to fewer moving components.

The main challenge with SSCBs is increased conduction losses due to higher resistance of power semiconductor devices, especially high voltage (>650V) power semiconductor devices. Compared to other power semiconductor technologies for SSCBs, the Si-based B-TRAN™ offers >3x reduction in conduction losses while offering fast response at the same time.

A typical block diagram of a solid-state circuit breaker is shown in the *Figure 2* below. The major components include a power semiconductor device, in this case B-TRAN™, a driver to drive this device, overvoltage protection and an overcurrent detection method which is fast and reliable. The delay between the overcurrent detection and opening of the fault current is an important design parameter for SSCBs. Some of the key challenges to address in a SSCB design are summarized below:

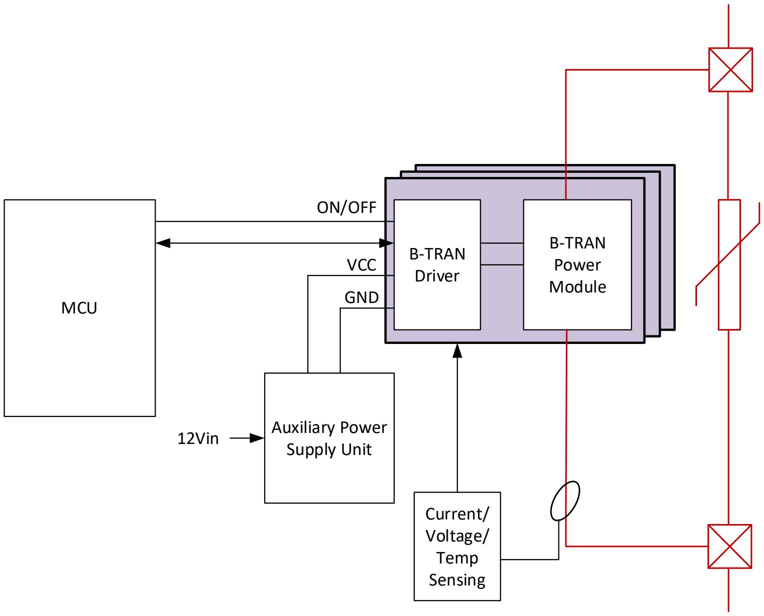


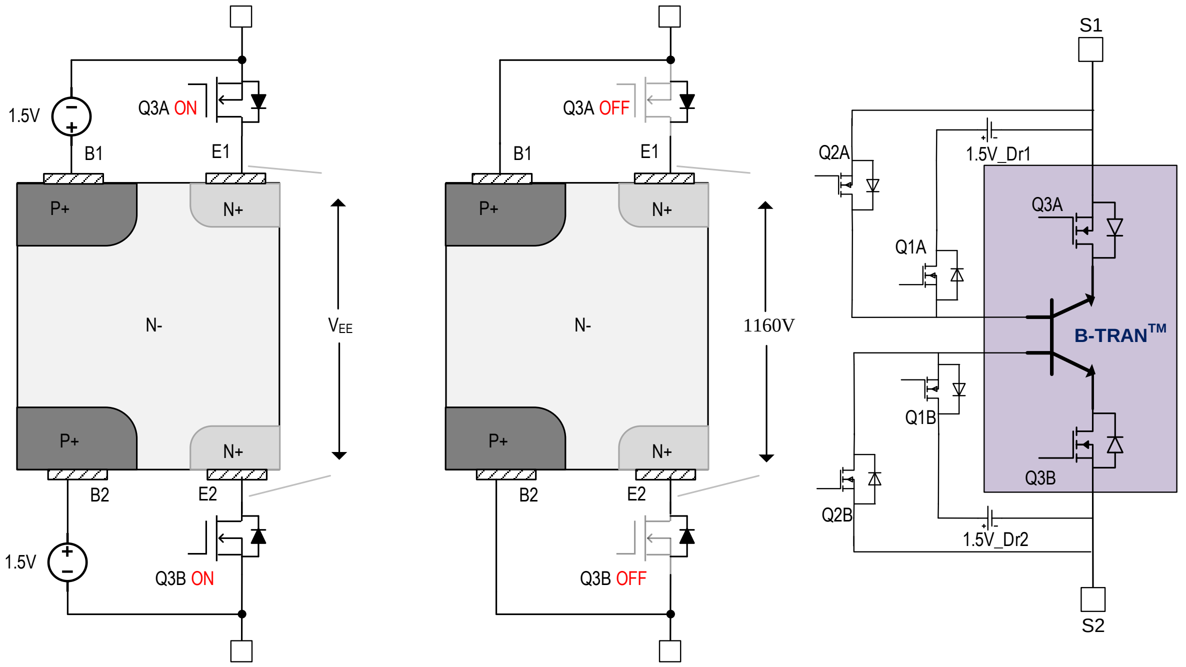
Figure 2. Solid State Circuit Breaker Block Diagram with B-TRAN™ as the power semiconductor switch.

- **Low Conduction Losses**: Compared to mechanical breakers which just offer a small contact resistance, power semiconductors can offer significantly higher resistance increasing system losses. B-TRAN™ devices offer state-of-the-art conduction loss performance by providing >300% improvement over conventional semiconductors such as IGBTs.
- **Fast & Reliable Overcurrent Detection**: There are several methods which are being studied to implement overcurrent detection such as DESAT protection, rate of change of current protection (ROCOC), shunt resistor method, etc. Multiple methods may be used at the same time to provide protection against different kinds of faults.
- **Power Semiconductor Short Circuit Capability**: It is critical that the semiconductor can handle short circuit currents for desired time and operate reliably for the lifetime of the product. Power semiconductors are sensitive to overcurrents and overvoltages, especially SiC devices, and hence proper system design and protection mechanisms must be designed.
- **Remote Control and Monitoring**: Use of advanced diagnostics and communication is also a great feature of SSCBs. The intelligent driver design of B-TRAN™ provides protection and diagnostics of the device and, at the same time, can provide system diagnostics and CAN bus support for communication interfaces.
- **Compact Size: B-TRAN™** offers ultra-low Vceon and, hence, the losses and corresponding waste heat are much lower than an IGBT-based SSCB solution. As a result, the heat sink and corresponding thermal management size can be much smaller as well.

Summary of B-TRAN™ Device Operation

B-TRAN™ is a normally-on device; however, it can be easily used in normally-off applications using a cascode structure as shown in *Figure 3* below. The two MOSFETs (Q3A and Q3B) are low voltage (<60V) MOSFETs which have low on-state resistance to keep the total conduction losses low. Both Q3A and Q3B are needed for bidirectional applications. The circuit implementation of this design is shown as well.

To turn-on the device, both Q1A and Q1B are turned on which allows driving current to flow in the drift region and lowers the resistivity of the device. Q3A and Q3B are then turned on to allow load current to flow between S1 and S2. When turning off, Q1A and Q1B are first turned off and Q2A and Q2B are turned on. After a small dead time, Q3A and Q3B are turned off, to create pinch-off voltage between B1-E1 and B2-E2 and block current and voltage in both directions.



(a) On State (b) OFF State (c) Circuit Implementation of B-TRAN

Figure 3. (a), (b) show B-TRAN™ device operation in ON and OFF states. (c) shows the circuit implementation of the driving FETs to achieve four quadrant operation.

B-TRAN™ Device Selection

Ideal Power offers multiple products which cater to a wide range of applications. SymCool™ power module is a multi-chip power module with integrated cascode FETs making it a normally-off 1200V, 160A bidirectional switch.

Part Number	Description	Current Rating
IPAD01205A04	Discrete, normally-on B-TRAN™ in a double side cooled TO-264 package	50A
IPAM01210C10	SymCool™ Power Module, bidirectional normally-off device	160A
IPAI01216DFx	SymCool™ IQ Intelligent Power Module with integrated driver, bidirectional, normally-off device	160A

For this application, since the maximum load current is less than 100A, a single discrete device is chosen. To operate it as a normally-off device, two discrete cascode MOSFETs (Q3A and Q3B) are added to the driver board.

B-TRAN™ Driver Design

The proposed device operation enables bidirectional conduction and blocking without the need for sensing the voltage/current direction. Being a current driven device, the bases B1/B2 are driven by a low voltage high current supply. This is typically implemented by a buck converter. Q3A and Q3B are low voltage silicon MOSFETs of 60V maximum breakdown voltage or less. Hence, a very low resistance (1-2mΩ) MOSFET can be chosen without a significant size and cost impact to keep the overall conduction losses low. Q1A, Q2A, Q1B and Q2B are also low voltage MOSFETs of 20V or less maximum breakdown voltage. Appropriate gate drivers and digital isolators for required isolation can be chosen based on the application.

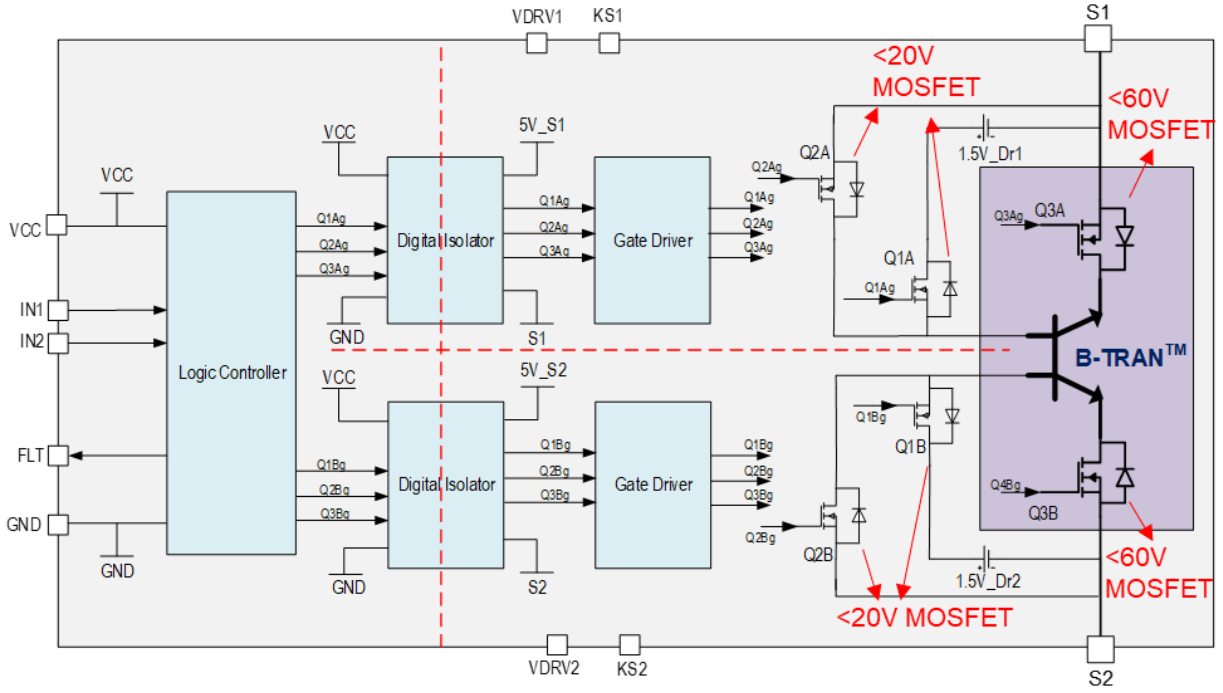


Figure 4. Internal block diagram of B-TRAN™ driver for bidirectional applications. B-TRAN™+Low Voltage cascode MOSFETs shown in the purple box can be integrated in a module/package for a normally-off device.

Design of Low Voltage High Current Base Power Supply

Select a buck converter IC depending on the maximum load current requirement in the application. The buck converter provides base current to the B-TRAN™ device which is proportional to the load current between E1 and E2. Typical β of B-TRAN™ is 5 with worse-case value being 4 high current and high temperature. Hence, maximum base current needed is:

$$I_{base} = \frac{ILoad_{max}}{4}$$

Since, in this case, we are using a symmetrical dual base drive, the total base current can be divided equally between the two buck converters. Hence, the max load current rating of the buck converter should be higher than Ibase/2. The voltage input to buck IC is the floating 12V w.r.t S1/S2 and hence a widely available 16V/18V buck IC can be used for this application.

$$I_{buck} = {}^{I_{base}}/_{2}$$

A typical circuit diagram of the buck converter with inductor and capacitor is shown below. Select inductor, output cap and switching frequency to optimize losses, AC response and solution size for the given application.

The output voltage regulation of the buck converter can be done in CV and/or CC/CV mode. In the CV mode, the buck will regulate the output voltage to the desired value which will dictate the base current depending on the forward voltage drop of the B-E diode of B-TRAN™. The output voltage set point can be adjusted to change the base current. In CC mode, the buck output current will be regulated to the set value and the buck voltage will be adjusted as needed. This scheme can offer advantages in some applications as the max load current through B-TRAN™ will depend on the base current. Controlling the base current will directly control the max load current and hence can provide overcurrent protection. On the other hand, part-to-part variation in the VBxEx voltage will not impact the drive current.

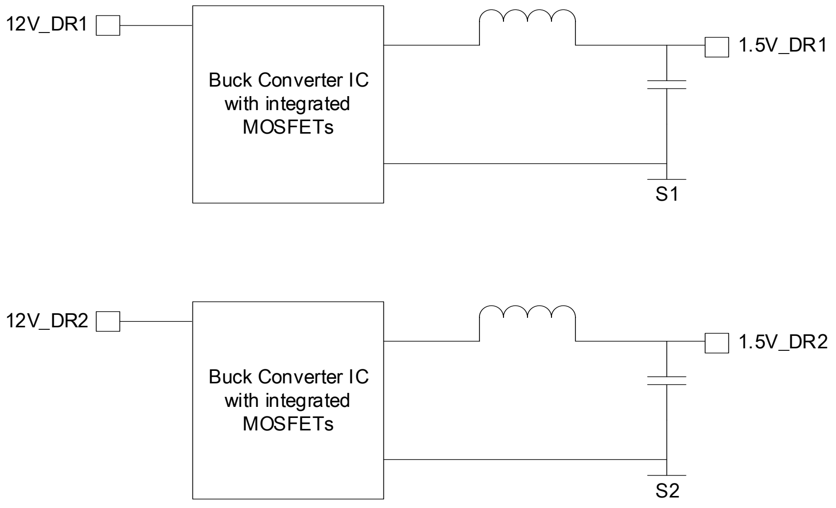


Figure 5. Simple buck converter block diagram for a B-TRAN™ driver bias supply. Additional functionality of the buck converter, if needed for an application, is not shown.

Design of Isolated Power Supply

The isolated power supply is designed to provide floating power to buck converters w.r.t S1 and S2 high voltage terminals and other housekeeping supplies such as gate drive voltage, digital isolator supply, etc. In the reference design, this is implemented using an LLC converter running in open-loop. Other isolated topologies such as flyback can also be implemented based on the power levels. Since total driving power is supplied by the isolated power supply, care must be taken for proper isolation and reducing parasitic capacitance to avoid any high dv/dt noise coupling between primary and secondary domains.

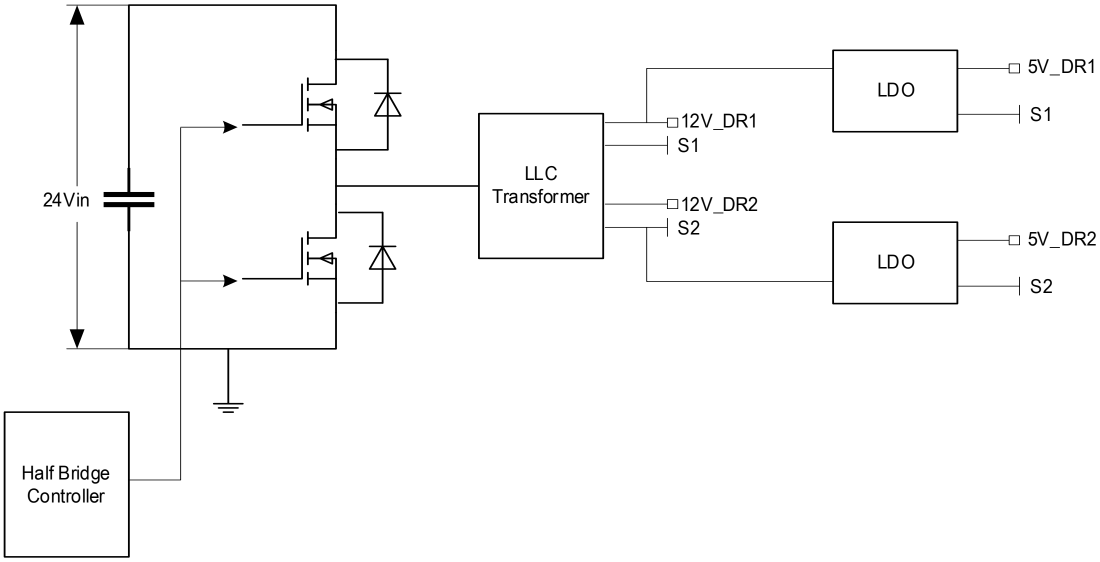


Figure 6. Isolated power supply for B-TRAN™ driver. This is an open-loop LLC design which offers high efficiency operation at high frequencies.

Logic Controller Design

The logic signals for each FET in the circuit are shown below. Q1A/Q2A and Q1B/Q2B are operated as a typical half bridge with a programmed dead time to avoid any shoot-through condition. Q3A and Q3B are turned on/off based on the input signal and an appropriate delay. A simple DSP/microcontroller can be used to generate such logic signals. Or it may also be implemented in analog by simple AND/NAND gate ICs. With microcontroller/DSP, other functionalities such as current sensing, fault diagnostics and communication such as CAN/LIN can be implemented to optimize the overall system cost.

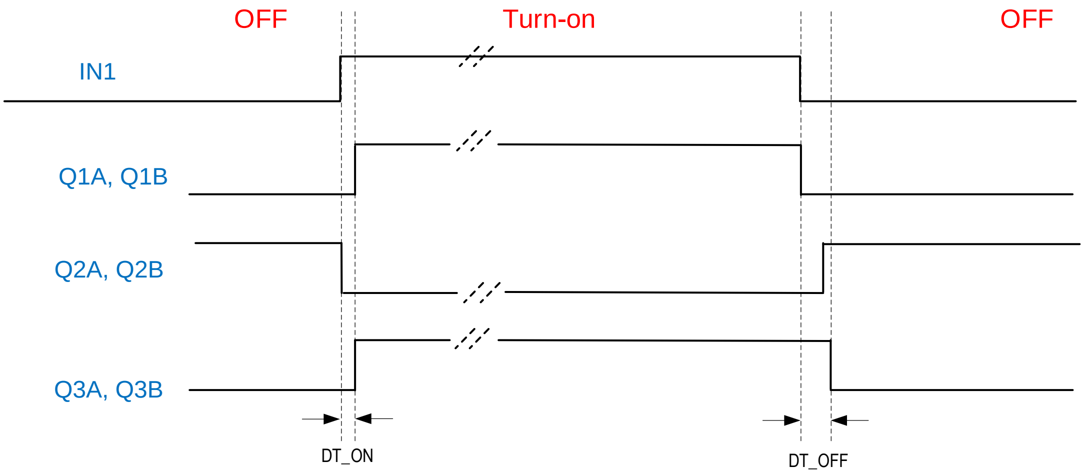


Figure 7. Logic signal internally generated in the driver to drive six FETs.

Test Setup and Results

For verifying the operation of B-TRAN™ in a breaker application, circuit shown in *Figure 8* is implemented. Application requirements for the system are shown in the Table 1.

Table 1. Application Requirements

Parameter	**Value**
Input Voltage	400V
Nominal Load Current	NA
Short Circuit Detection + Delay Time	5µs

Fault Inductance (L_{FLT})	4μH
Fault Resistance (R_{FLT})	4Ω

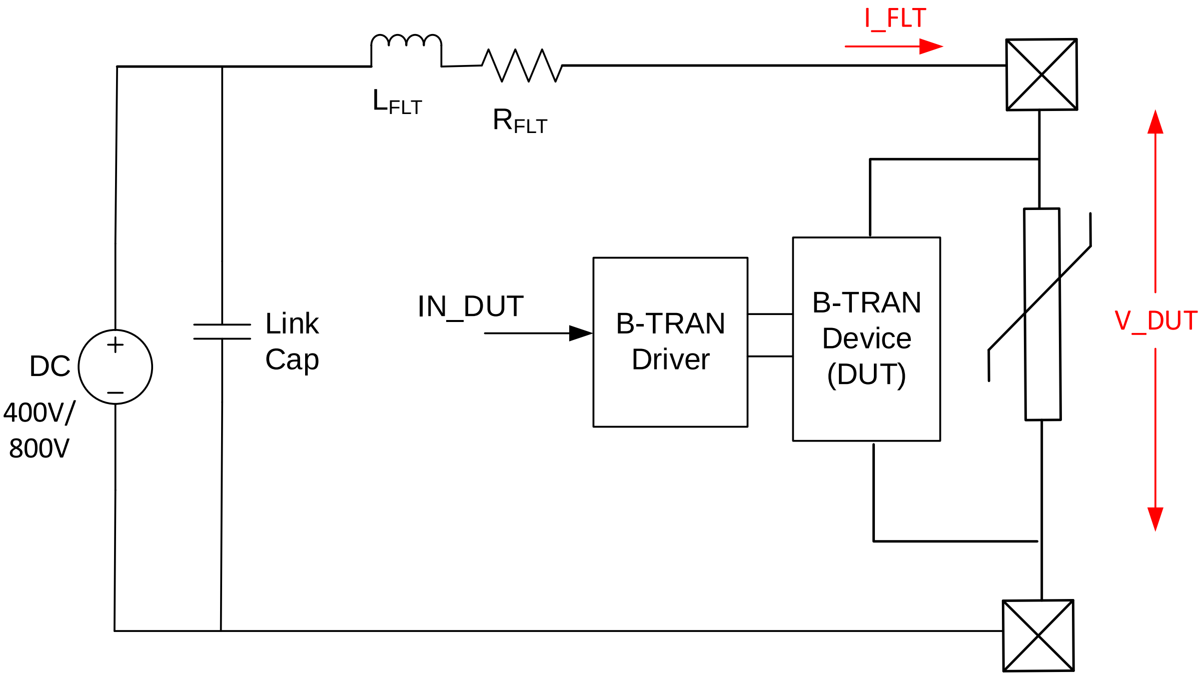


Figure 8. Test setup for solid-state breaker testing using B-TRAN™

The test results and setup are shown in *Figure 9* and *Figure 10*, respectively. CH1 shows the input signal which turns on the B-TRAN™ device into a short circuit with the fault resistance and inductance as specified in application requirements. The 5μs pulse simulates a typical short circuit detection and reaction time and, after that, the B-TRAN™ breaks 100A current at 400V. The extra energy stored in the fault inductance needs to be dissipated when the fault is broken and that results in the voltage spike across the B-TRAN™ device. Since the device is rated to 1200V, the device can absorb the fault energy without engaging the MOV device.

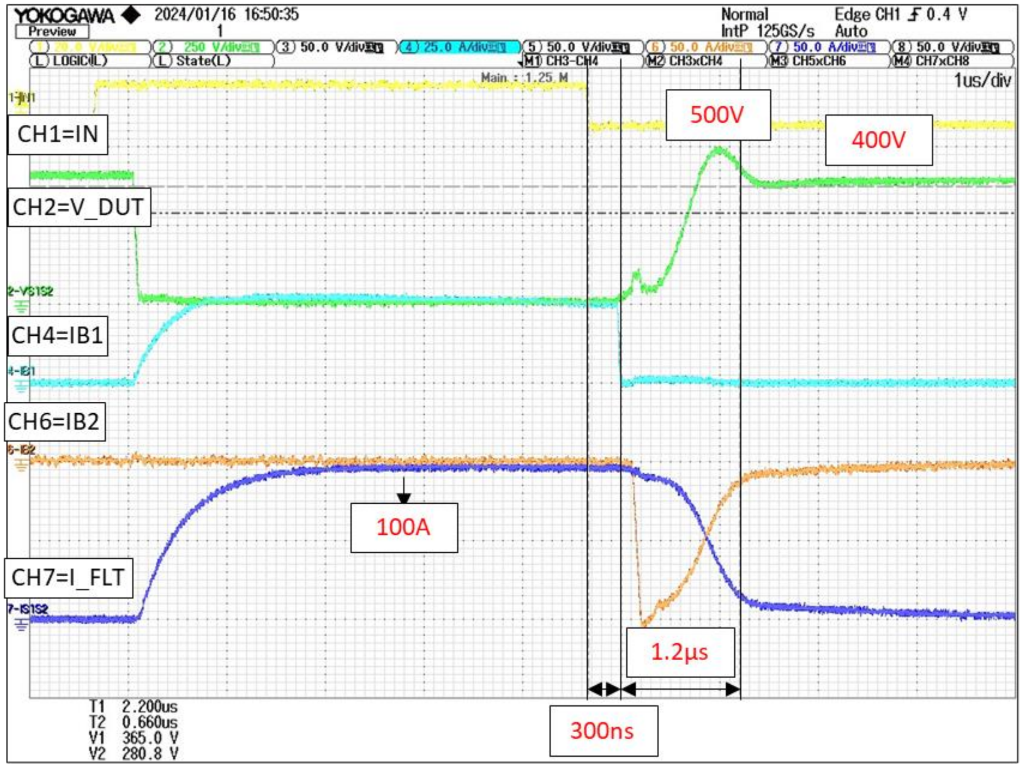


Figure 9. Test results from the breaker testing using B-TRAN™. 400V/100A breaker operation is achieved with a single discrete B-TRAN™ device.

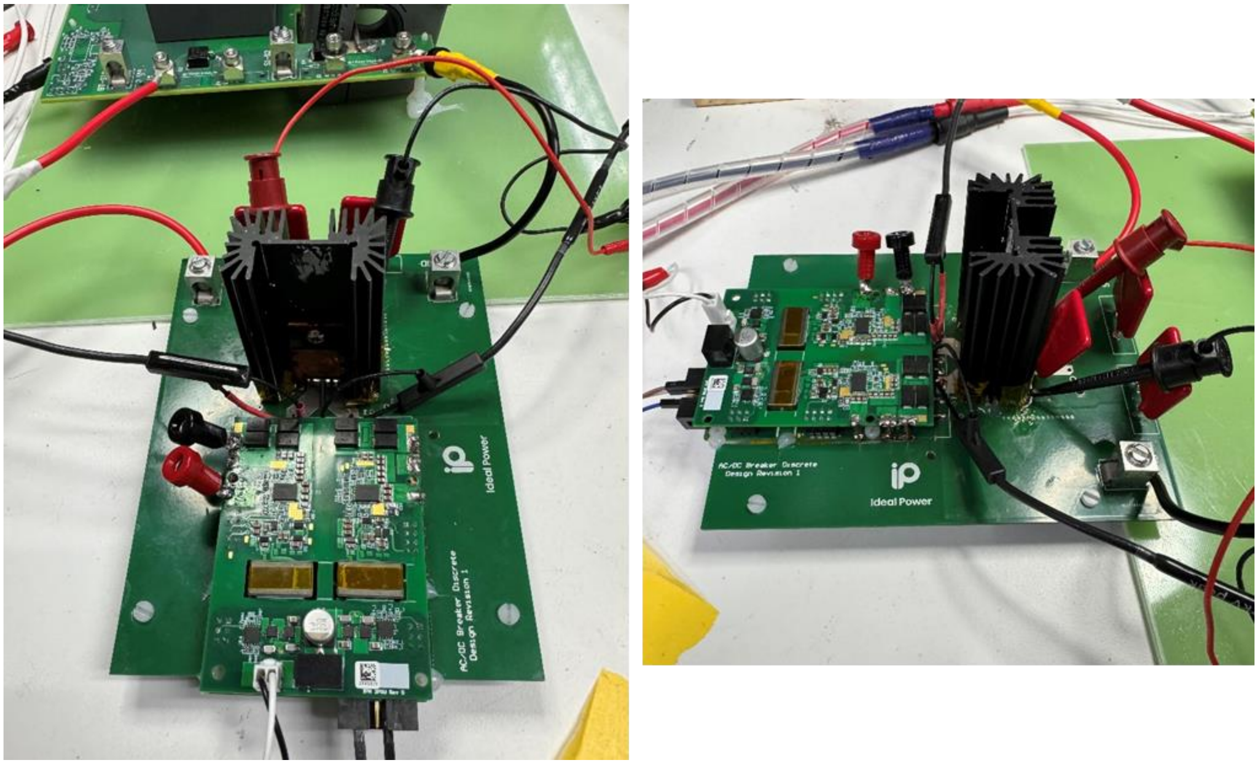


Figure 10. Test setup for breaker testing with B-TRAN™.

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