

A Solid-State Switch for 13.8kV Power Distribution

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Abstract

Power switching technology in low and high power applications has followed a progression from mechanical switches to vacuum/arc switches, and finally, to solid state switches. At low voltages and power, virtually every electronic system uses solid state switching for power control. The utility industry has followed this same progression in its switchgear and power converters. Mechanical switches and vacuum breakers are common throughout the industry, and represent the vast majority of 13.8 kV-class switchgear installations. Simple solid state switches (SCRs / GTOs, etc.) have been introduced for medium voltage commutated applications, and at very high voltage levels, such as HVDC links. At medium voltage (>> 1 kV), high power (1-20 MVA), and high speed (>>60 Hz), however, no solid state technology has previously been demonstrated which allows the final step to universal, practical, and inexpensive solid state switching for power conversion.

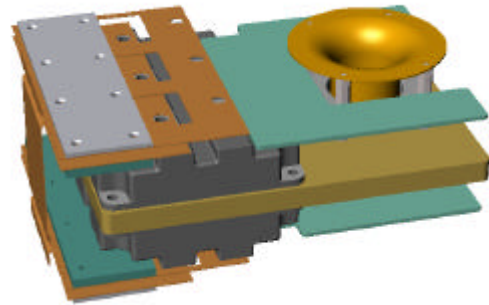


Figure 1. Back to back 4.5kV, 800A IGBT series pair module with bus connection, over voltage protection, control power, fast fiber optic control, and diagnostics.

Diversified Technologies, Inc. of Bedford MA has developed a high voltage solid-state switch that allows high frequency power conversion at voltages 13.8kV and above. The switch design permits AC-DC, AC-AC, DC-AC and DC-DC power conversion at low cost and high efficiency. This paper summarizes the concept of solid-state, medium voltage, high power conversion, discusses the relevant converter topologies, and presents the structure and benefits of the proposed switch and system designs for utility and facility distributed power systems.

Introduction

In recent months, the power shortages and subsequent high pricing of electricity in California have highlighted the fragility of the existing U.S. power grid. Demand for electric power has increased in virtually every industry and home.

In response to the economic threat from power grid disruptions, many companies are investing in supplemental power for critical loads. The rationale behind these investments is simple: the potential for power disruptions is growing, and even the high cost of low voltage supplemental systems is lower than the cost of the disruptions themselves. Typically, supplemental power consists of a second, independent utility grid feed (for major installations) and/or an Un-interruptible Power Supply (UPS) or energy storage system that can be switched in-line when needed. Multiple technologies, from batteries to diesel generators, to fuel cells, to superconducting magnetic storage systems, have been introduced to serve these supplemental power requirements at 480VAC and below.

Sandia National Laboratories, in its report titled "*Summary of State of the Art Power Conversion Systems for Energy Storage Applications*," dated 01 Sep 98, has compiled a number of potential topologies for integrating the elements of a distributed, reliable power system. These topologies rely on solid state devices, in a variety of configurations, to switch power from line to loads (matrix converters), or convert power from AC to DC (rectifiers), DC to DC (buck/boost regulators) and DC to AC (bridge inverters). Similar configurations are used for VAR, power factor, and/or voltage sag compensation. These topologies have been proven at low voltage (e.g., <480 VAC) to provide significant advantages in response, power quality (power factor and harmonics), voltage sags, peak shaving, and integration of local power sources.

However, the majority of high power (1 – 30 MVA) facilities operate at 13.8 kV AC. They cannot easily adopt these low voltage solid state converter topologies without significant modifications to their power distribution systems. The answer to this problem is a simple, reliable, and fast medium voltage switch that permits the use of high-speed converter topologies at medium (13.8 kV) voltage. The high voltage, bi-directional IGBT switch shown in Figure 2 is an example of such a switch. This switch is built out of a number of low-voltage solid state devices, connected in series using DTI's patented technology. DTI's solid state switching technology can be scaled to a range of medium voltage, 13.8 kV, 1 – 20 MVA class, high speed/high power converter designs for distributed power generation and control applications.

Table 1. Desired Power Converter Characteristics

<ul style="list-style-type: none"> • Highly Reliable and fault tolerant • Very fast – capable of controlled opening and closing in microseconds, and continuous operation at high frequency ($\gg 60$ Hz) • Bi-directional (switching both positive and negative polarities for AC) 	<ul style="list-style-type: none"> • Grid and Load Compatible (e.g., 13.8 kV class) • Highly efficient ($>98\%$) • Capable of switching high power (1 – 20 MVA) • Low Cost ($< \\$500/\text{kW}$)
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Technical Background

DTI's patented technology is based on series-strings of high power IGBTs or field effect transistors (FETs), all of which open or close simultaneously. When utilized in this manner, the entire switch operates as a single component, although it may be constructed from hundreds of discrete semiconductor switches. Unlike a Silicon Controlled Rectifier (SCR), an insulated gate bipolar transistors (IGBT) can be turned on and off arbitrarily at high speed. SCRs have long been used at very high power for HVDC links and large power supplies where the turn-on time is controlled, but the turn-off time is produced by a reverse voltage of the line or load. During faults on an AC line, the SCR often has to endure enormous peak currents until the next zero-voltage crossing.

DTI's PowerMod™ systems use up to 200 IGBTs, connected in series-parallel combinations, to switch high power at high voltage. DTI's solid state modulators do not use resonant circuits. Each pulse can be arbitrarily sized by closing and opening the IGBT switch stack, allowing complete pulse width and separation flexibility - from under 1 μ S to DC - on a pulse to pulse basis. This pulse control flexibility is the key to very fast, highly controlled, universal power conversion. DTI has already built high voltage power supplies using PWM switching at up to 160 kV and 3 MW average power that are in operation in national laboratories, semiconductor manufacturers, and other industrial locations. This technology has now progressed to the point where it is extensible to high average current applications, such as distributed power generation and control at 13.8 kV AC and above.

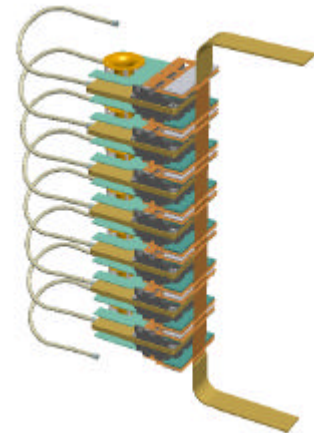


Figure 2. Proposed eight IGBT-pair, 20kV, 600A fluid cooled switch. Approximately 7" w x 40" h x 20" d

Solid State Switch Design

DTI's has developed a high-average current, 15kVAC, 600A RMS switch that can interrupt very high fault currents in less than one microsecond, and operate at switching frequencies up to 10kHz. This makes this switch technology ideal for PWM control and power converter circuits.

The 4.5kV, 800A dual-IGBT pair module shown in Figure 1 can be used to build 20 kV, 600 A, high-speed solid-state switches as shown in Figure 2. Figure 3 shows a simplified view of an air insulated, three-phase, bi-directional design having a stack of eight of the IGBT series pairs per phase. The overall size is just 36" w x 40" h x 20" d - smaller than a 15kV fused disconnect assembly.

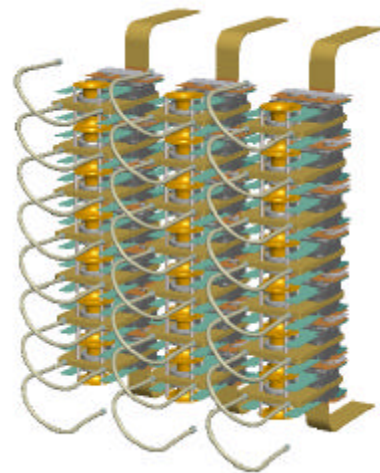


Figure 3. 13.8 kVAC, 20 MVA Water Cooled, High Frequency Solid State Switch Design (approx 36" w x 40" h x 20" d)

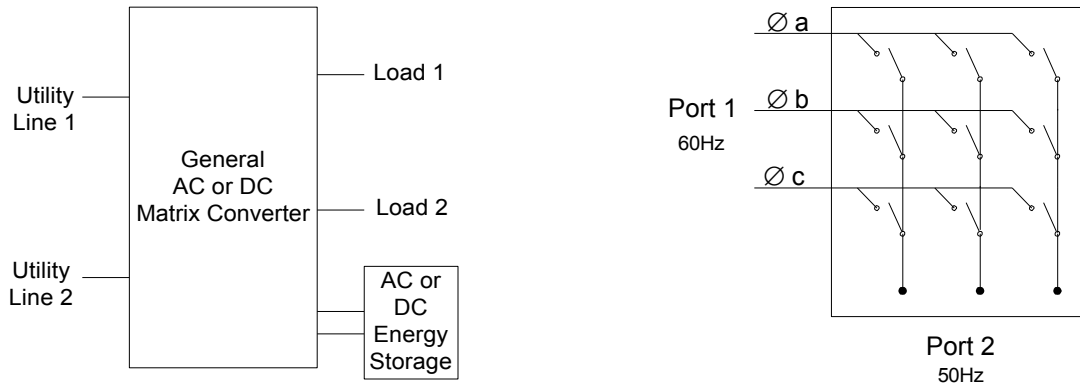


Figure 4. Matrix converter (AC to AC, AC to DC, DC to DC, or DC to AC)

A key reliability factor in DTI Powermod™ systems is the use of extra IGBTs for redundancy. Redundancy is achieved because IGBTs always fail shorted, and as many as three devices (out of twenty in a medium voltage switch) can fail without adversely impairing the operation of the series stack.

Power Converters

Two basic topologies, matrix converters and bridge converters, use multiple switches and can be used for medium voltage power conversion.

Matix Converters

A matrix converter simply switches between one or more sets of inputs and outputs as shown in Figure 4. In this type of converter, the inputs and outputs are simply interconnected in pre-programmed configurations depending upon the application. Conventional static transfer switches, using mechanical or vacuum switches, allow power to be connected from multiple input feeds to one or more loads. When high frequency switching ($\gg 60$ Hz) is used in a matrix converter, it can perform a variety of functions beyond simple power transfer, such as soft-start; frequency conversion (cyclo-converter); power factor, VAR and harmonic correction; and compensation for voltage sags. Even advanced concepts such as line phase imbalance and dynamic dual-line current sharing equilibrium are possible with a properly controlled matrix converter.

Bridge Converters

A bridge converter (Figure 5) is a simplified form of converter that uses unipolar switches to transfer power from AC to DC (active rectifiers) or DC-AC (inverters). With high-speed switches, these converters can provide highly regulated and flexible DC and AC output. Multi-level converters (Ref. 5) are a special subset of bridge converters, and represent a complex and expensive method of circumventing the previous unavailability of high voltage switching devices.

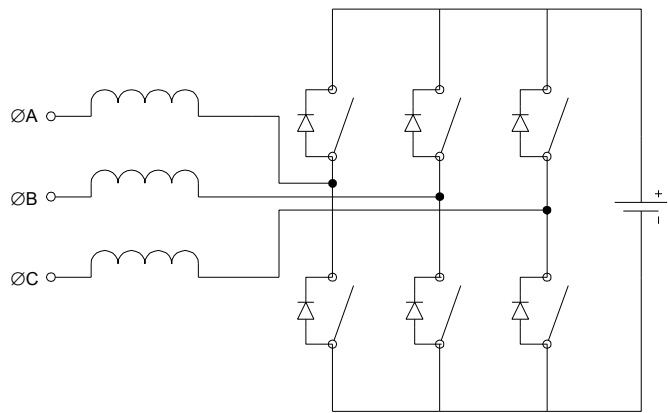


Figure 5. 3-Phase Bridge Converter (AC to DC or DC to AC)

Distributed Power Generation Systems

DC Link

A simple system for distributed power generation and control applications using these switches configured in a multi-converter topology, is shown in Figure 6. In this DC-link configuration, three different bridge converter configurations can provide a seamless, controlled means to integrate distributed generation and storage technologies for a single, large facility.

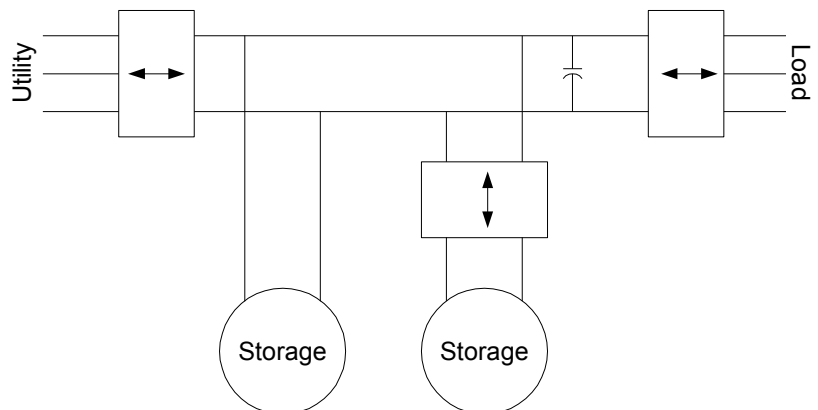


Figure 6. DC link

The DC-link is a highly flexible means of integrating multiple power sources for a facility load. To implement this configuration in a medium voltage facility, each of the converters requires six, fast, unidirectional switches as shown earlier in Figure 5.

There are four basic elements to this system:

1. A high speed, 3-phase active rectifier converts 13.8 kV AC power to high voltage DC power. When this active rectifier switches at much higher frequency than the line frequency (e.g. 5 –20 kHz), it provides highly regulated DC power in the central link. It also appears to the utility as a nearly ideal load. It appears resistive (unity power factor), and does not inject harmonics onto the utility grid. The converter may also be used as an inverter to re-inject the utility with real power (left over power from the load or storage system), reactive power, harmonic cancellation, or a combination of the above where needed.
2. The DC link itself contains energy storage elements (e.g., capacitors) to smooth disruptions on the link. Essentially, the DC link serves as a universal power medium, providing a ‘common format’ for power from a range of sources and to a range of loads.
3. Auxiliary power sources / storage systems provide power to the link when demand exceeds a nominal value, or store power from the link for use during peak demands. In this DC-linked configuration, virtually any power element can be connected to the DC link. If the auxiliary source is AC, such as a flywheel or motor-generator, it can be rectified (similar to the grid input). The frequency of the auxiliary AC source is irrelevant in this configuration – these sources do not need to operate at 60 Hz, or even at constant frequency. If the source is DC (batteries, superconducting storage), both high-speed inverters and small step-up transformers/rectifiers, or boost/buck regulators can provide the required high voltage DC power.

- Inverters take power from the DC link, and provide highly regulated power to the facility load power distribution system. By employing high frequency PWM switching of the power from the DC link, essentially perfect 60 Hz, 3-phase, 13.8 kV power can be provided to the facility.

The major benefits of this type of system are seen during either line or load disruptions. If the input line voltage sags, the active rectifier can compensate for this sag, and maintain the DC link voltage. The

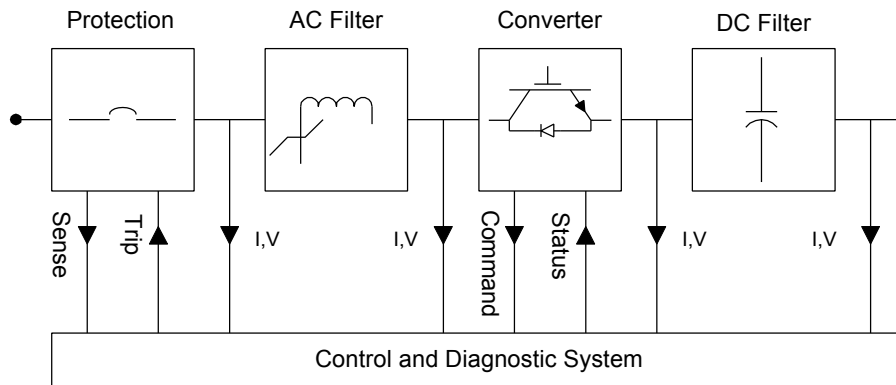


Figure 7. Simplified diagram of ancillary components of a converter system

auxiliary power generation / storage elements can provide additional power to the DC link, to prevent the utility power draw from peaking in response. In the extreme, if the utility power fails completely, an adequately sized auxiliary capability can replace the utility power altogether. At the facility (load) side, these disruptions and transitions are invisible. Even if the DC-link voltage varies, the active inverters can compensate, and maintain ideal power to the load. Figure 7 shows some details of the converter design and control architecture. This diagram illustrates the components required between the utility line and the DC-link

FACTS (Flexible AC Transmission System)

The same high speed switching technology can be utilized to compensate for VAR, line imbalances, and sags on 115 kVAC class distribution systems. A transformer-coupled, medium voltage converter, shown in Figure 8, can be used in Flexible AC Transmission Systems (FACTS), as well as for direct

medium voltage power conversion.

Present controllers are much less than ideal because they are comparatively slow and very complex and expensive.

DTI's ability to switch high power at high speed can significantly increase

the capabilities of these power-correction circuits at much lower cost.

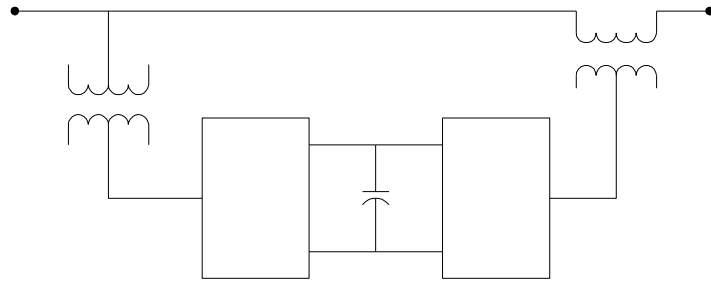


Figure 8. FACT unified power flow controller

Cost

We believe that medium voltage power converter systems, based on the technology described in this paper, can be built for \$100/kW or less in production quantities.

Conclusions

The delivery of high speed, high voltage power converters to support distributed power generation and control for the customer with medium voltage (13.8 kV) utility feeds at 10-20 MVA, and very high requirements for power stability, quality, and reliability is a near-term reality. We believe this represents both the largest, and fastest growing, and most demanding power customer population in the U.S.

Potential benefits are enormous. It is not an exaggeration to compare the availability of high voltage, high speed, solid state switches to the development of the integrated circuit (IC) – with the potential to revolutionize the power systems world. At a macro-scale, the benefits of this technology include:

- Elimination of grid disturbances / harmonics from major facility power systems
- Instantaneous transition between power sources
- Reduced power control size
- Ease of integration of distributed generating sources at both the load and utility interfaces
- Uninterrupted, highly reliable power
- High facility power quality independent of utility power quality

Users need more power, at higher quality and reliability for increasingly power sensitive loads. End users are increasingly taking responsibility for ensuring the reliability and quality of the power entering

their facilities. DTI has developed the technology required for fast, high voltage power converters at the facility level.

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