SOLID-STATE HIGH FREQUENCY POWER CONVERTERS

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Abstract

In a recently completed Small Business Innovation Research (SBIR) grant, DTI demonstrated the electronics and controls for an extremely low-distortion, quiet, and reliable 60 Hz to 400 Hz power converter (Figure 1). Its features include three-phase output power of 2 kW at 208 V, harmonic distortion at the switching frequency of less than 0.1%, and THD of less than 7% into a complex, non-linear load. The power switching transistors (IGBTs) operate at 50 kHz. The complete Power Converter will also include auxiliary DC-DC power supplies, and operational controls.

The next phase of this effort will qualify this design for Navy shipboard installation, and transition the converter into production for use in Navy submarines and ships. When combined with DTI's proprietary method of directly switching high voltages, this level of control will become a reality at multi-MW power levels for facility and utility power control. In this paper, we will describe the converter architecture, test results, and the scalability of this approach to multi-MW power levels.

Keywords

power converter, solid-state, power distribution, FACTS

1. Frequency Converter

Since the adoption of Commercial Off the Shelf (COTS) electronics in military systems, new ship electronics use 60 Hz to maintain commonality with commercial, land-based equipment. However, legacy electronics for submarine and other weapon systems still require input power at 400 Hz. To operate from ship power at 60 Hz, these legacy systems need a clean, reliable, and very stable frequency converter.

Frequency converters, at their simplest, operate by rapidly switching input power on and off to produce output power at the desired frequency. This switching, however, produces switching harmonics, as well as the output at the desired frequency. The major requirements of the Power Converter, as they affect the frequency converter design, are:

- The switching is at much higher frequency than either the input or output frequencies. This allows the harmonies to be highly filtered, without affecting power at the main frequency of either the input or output. The demonstrated unit operates at 50 kHz on both the active rectifier, and the inverter.
- The switching controls require high-gain feedback and adequate phase margin for accurate regulation and stability into transient and non-linear loads.
- The power converter must continue operation during the brief power interruption caused by changing power between the port and starboard generators. This requirement is met by the energy storage capacitors located between the 60-Hz-to- DC active rectifier and the DC-to-400-Hz inverter.

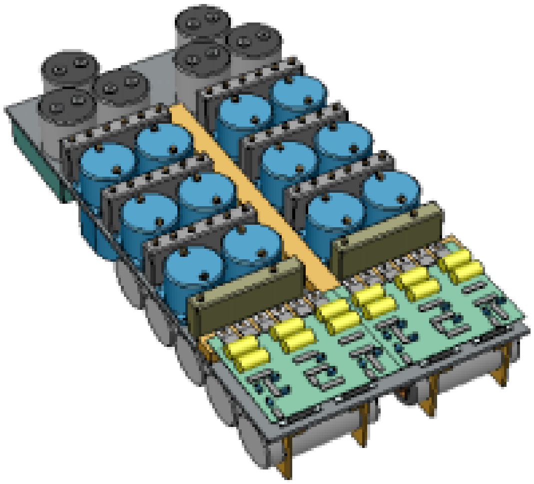

Figure 1. Artist's rendition of power converter. Size is approximately 29"l x 15"w x 7"h. From front to back are the control circuit boards, filter inductors, and transformer isolation capacitors. The DC-DC converters are under the circuit boards.

The basic frequency converter circuit is illustrated in Figure 2. The 60-Hz input power passes through a soft start, and filters (both differential and common mode) that keep switching harmonics and noise transients from the input power line. The input power is rectified by an active bridge circuit, which acts as a sine-wave-tracking boost converter.

A second high-frequency bridge circuit then inverts the DC power to give the three-phase 400-Hz output. This bridge circuit is nearly identical to the bridge used as an input rectifier. In this instance, however, it acts as a buck converter instead of a boost converter, giving a regulated

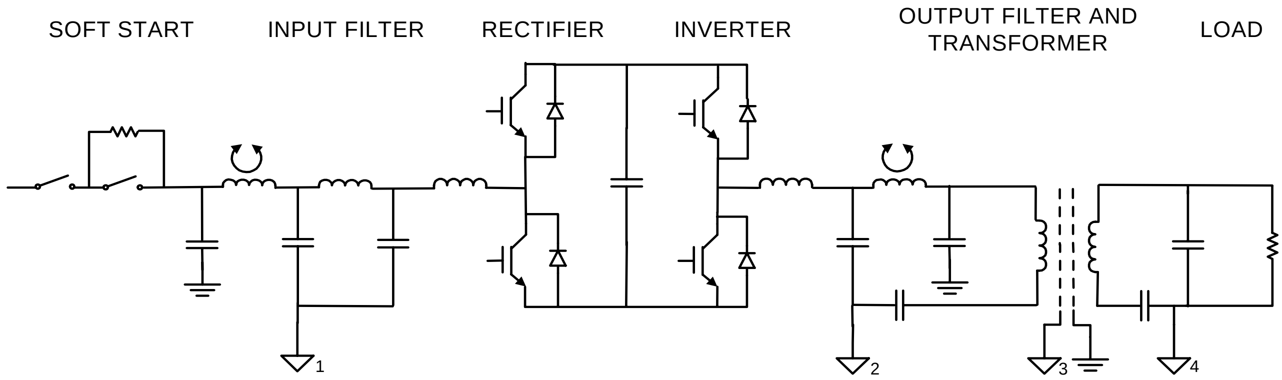

Figure 2. Simplified circuit schematic of the frequency converter, showing a single phase of the rectifier and inverter.

AC output with a peak voltage that is less than the DC input.

The 400-Hz power passes through filters, which strip off the switching harmonics and noise transients, and a Y-Y transformer, which isolates the output from the input. The clean 400-Hz power then passes to the load. An example of the currents flowing into the active rectifier is shown in Figure 3.

2. Design

There are three key elements in the design that allowed us to meet the critical specifications:

- *Operation of power switching transistors (IGBTs) at 50 kHz.* High switching frequency directly lowers the harmonic distortion, and provides the ability to precisely control the converter's performance into non-linear loads. The choice of a low-loss IGBT was critical to this step.
- *Sufficiently large filter inductance* to minimize switching harmonics, with most of the total inductance in the first stage, required for the feedback design.
- *Robust controls for the switching,* with feedback for the inverter from both output filter stages. The lead and lag were appropriately chosen to give high feedback gain, minimizing the output distortion.

This technology demonstrates the practicality of a cost-effective and 'clean' solution for other military and commercial power control and conditioning needs, such as active power factor correction and harmonics control for complex loads, VAR compensation, and Flexible AC Transmission Systems. Furthermore, this approach can be readily combined with DTI's high-voltage switching technology, allowing active, direct power control at voltages over 100 kV.

3. Solid State Switching

DTI's switching 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 Silicon Controlled Rectifiers (SCR), insulated gate bipolar transistors (IGBTs) can be turned on and off arbitrarily at high speed, typically, at multi-kHz frequencies. The ability to switch at high power eliminates the need to wait for zero- crossing of each phase, a severe limitation on typical SCR systems.

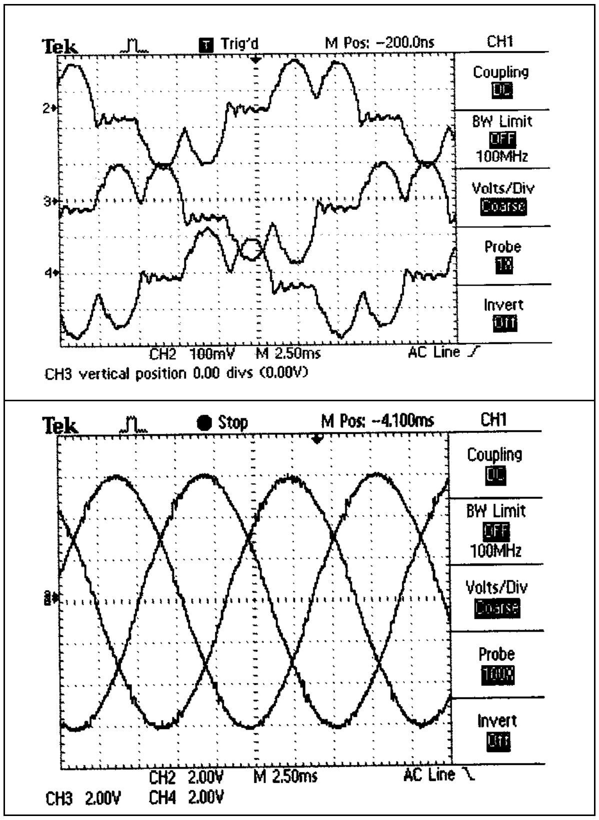

Figure 3. Top:Three phase currents without *the active rectifier. The sweep speed is 2.5 ms/div. The currents are typical of a six-pulse three-phase capacitor-input rectifier. Bottom: Three phase currents* with *the active rectifier. The current sensitivity is 2 A / division; sweep speed is 2.5 ms/division. The power factor is near unity, and the harmonic distortion is very small.*

DTI's PowerMod™ systems use up to 200 IGBTs connected in series-parallel combinations to switch high power at high voltage. They 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, on a pulse to pulse basis, from under 1 µs to DC. This precise pulse control is the key to very fast, highly controlled, universal power conversion.

DTI has supplied high voltage power supplies using PWM switching at up to 160 kV and 3 MW average power to 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.

The 4.5 kV, 800A dual-IGBT pair module shown in Figure 4 can be used to build large high-speed solid-state switches that can interrupt very high fault currents in less than one microsecond, and operate at switching frequencies up to 10 kHz. This technology is ideal for PWM control and power converter circuits.

Figure 5 shows a high voltage solid-state switch array that allows high frequency power conversion at 13.8 kV. The switch design permits AC-DC, AC-AC, DC-AC and DC-DC power conversion at low cost and high efficiency. It is an air insulated, three-phase, bi-directional design having a stack of eight IGBT series pairs per phase. The overall size is just 36"w x 40"h x 20"d, smaller than a 15 kV fused disconnect assembly.

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

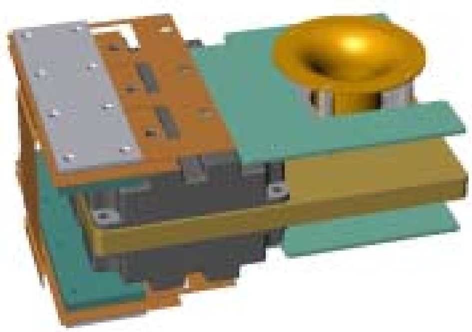

Figure 4. Back to back 4.5 kV, 800A IGBT series pair module with bus connection, over voltage protection, control power, fast fiber optic control, and diagnostics.

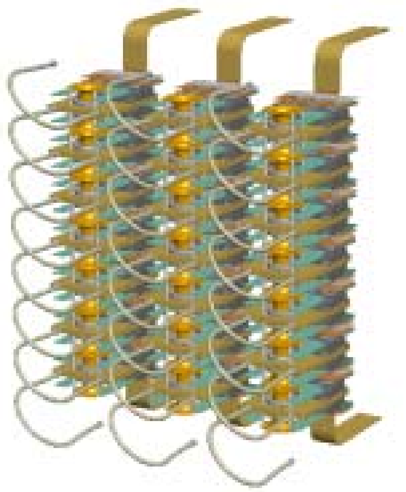

Figure 5. 13.8 kVAC, 20 MVA water cooled, high frequency 3-Phase, bi-directional solid state switch design (approx 36"W x 40"H x 20"D).

4. 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.

The DC-link is a highly flexible means of integrating multiple power sources for a facility load. The frequency converter discussed earlier in this paper uses this DC link configuration at low voltage, and with only a single power source. The basic switching controls are *identical* for a low voltage system and a medium voltage system, but the switches themselves must be capable of directly switching the 13.8 kVAC of a medium voltage system. To implement this configuration in a medium voltage facility, each of the converters requires six, fast, unidirectional switches as shown in Figure 5.

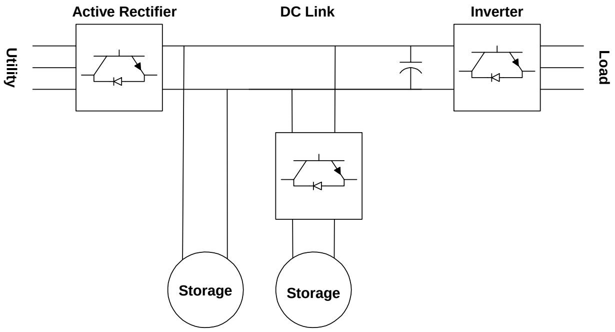

Figure 6. DC Link.

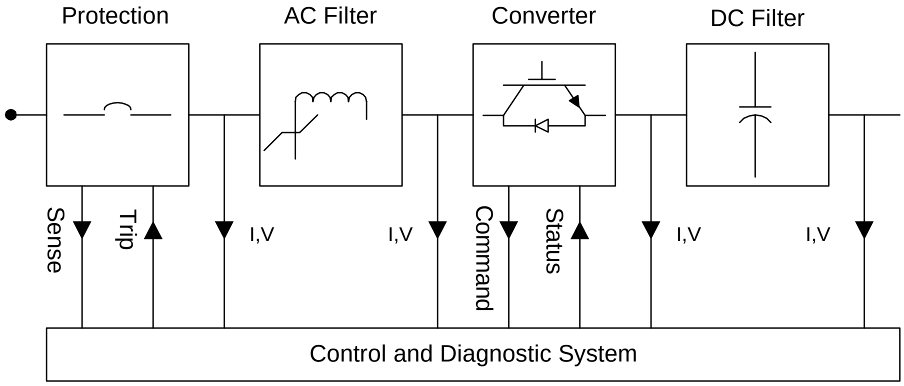

Figure 7. Simplified diagram of ancillary components of a converter system.

There are four basic elements to this system:

1. A high speed, 3-phase active rectifier converts 13.8 AC power to high voltage DC power. When this active rectifier switches at much higher frequency than the line frequency (e.g. 5-50 kHz), it provides highly regulated DC power in the central link. The rectifier 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.
2. The DC link itself contains energy storage elements (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. 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.
4. 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 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 are invisible. Even if the DC-link voltage varies, the active rectifiers 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.

5. 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, diagrammed in Figure 8, can be used in Flexible AC Transmission Systems (FACTS), as well as for direct medium voltage power conversion. Present controllers are less than ideal because they are comparatively slow, 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. 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.

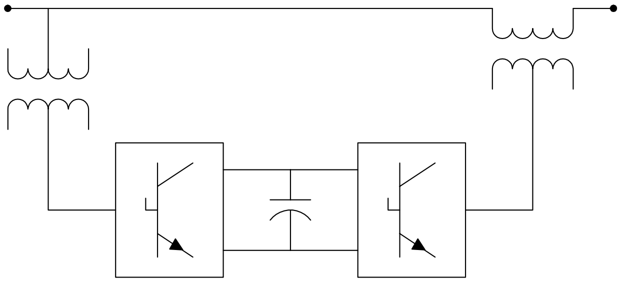

Figure 8. FACT unified power controller.

6. Benefits

The potential benefits of this converter technology are significant. 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
- Ease of integration of distributed generating sources at both the load and utility interfaces
- Instantaneous transition between power sources
- Reduced power control size
- Uninterrupted, highly reliable power
- High facility power quality independent of utility power quality

7. Conclusions

DTI has demonstrated a compact and efficient three-phase, 60 Hz to 400 HZ power converter and associated controls that can deliver clean 400 Hz power into a complex, non -linear load. When combined with DTI's high-voltage switching technology, active, direct power control at voltages over 100 kV is a reality.

One application is 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.

8. References

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