ELECTRIC POWER RESEARCH INSTITUTE

Solid-State Transfer Switch Technology and Application Update

Review of State-of-the-Art Technologies and Potential Applications

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ABSTRACT

Static transfer switches are used to switch between multiple voltage sources. Most legacy transfer switches typically use electromechanical devices, and some use thyristors. The advent of advanced high-voltage power semiconductors has allowed the realization of solid-state transfer switches (SSTS) that can seamlessly transfer between switches to provide high-quality uninterrupted power. Although a few legacy applications have been reported, SSTS could have an important role to play in alternating-current (ac) and direct-current (dc) microgrids. For example, they could be used in adaptable microgrid architectures to split microgrids into subgrids; dc transfer switches could be similarly employed in dc microgrids. Discussions with utilities are underway to understand the roles of these transfer switches in microgrid applications.

Keywords
AC and DC microgrids
Automated systems
Grid reliability
Solid-state transfer switches

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INTRODUCTION

Introduction

There are many issues that are increasing utilities' emphasis on improving overall system efficiency and asset utilization. These include, but are not limited to, CO2 reduction, tighter financial markets, and increased generation costs. Maintaining proper load balance on distribution circuits can reduce system losses as well as allow greater utilization of existing distribution assets.

The objective is to investigate the possibility of using an automated system to maintain optimal distribution circuit load balance. The practice used by many utilities is to use a line crew and engineering personnel to measure load balance at key points in each circuit and manually move single-phase lateral taps to different phases to obtain the desired load balance among the phases. This practice has many shortcomings: the load balance is only achieved for a single point in time, requires the use of both physical and engineering personnel, requires short outages for all customers on the laterals, and must often be repeated due to seasonal load changes. An automated system could be applied to key laterals, maintaining better load balance over a wide range of system loading conditions.

Today's Switching Technologies

Maintaining high reliability in today's power grid relies increasingly on solid-state switching technologies and their applications. Switching is a basic but necessary function to control the flow of power. The ideal switch would have the following characteristics: 1.) zero resistance or forward voltage drop in the on-state, 2.) infinite resistance in the off-state, 3.) zero switching time, and 4.) would not use any input power to make it switch.

Existing solid-state switch technologies strive to approach the idea switch, however real world designs have their limits. Therefore, the switch characteristics must be optimized for the application with minimal loss and efficiency. The switch design involves considerations of parameters such as voltage, current, switching speed, applicable circuitry, load and temperature effects. There are a number of solid state switch technologies available today to perform switching functions; they all come with advantages and short comings. The following is a brief description of existing switching technologies.

This section focuses on switching technologies available to utilities, specifically the static source transfer switch. In addition, traditional automatic transfer switches, high-speed vacuum-switched transfer systems, and hybrid (both solid-state and electromechanical) systems.

The following is a brief description of these switching technologies.

Source transfer switches have been used throughout the industry for many decades for protecting critical loads from power system disturbances. Transfer switches enable seamless transfer of energy from a primary source to an alternate source in order to avoid service interruption upon a deficiency in power quality. A Source Transfer Switch (STS) is designed to protect critical loads from power system disturbances. This is accomplished by transferring the critical load from a preferred feeder (e.g. faulted) to an alternate feeder (e.g. un-faulted). The STS contains two or more "switches" that allow a transfer from one source to another. Using ideal switches, a simple diagram of an STS is shown in Figure 1-1. Under normal operation, S1 is closed and S2 is open. When a disturbance is detected on Source 1, S1 opens and S2 closes, thus supplying the load through Source 2.

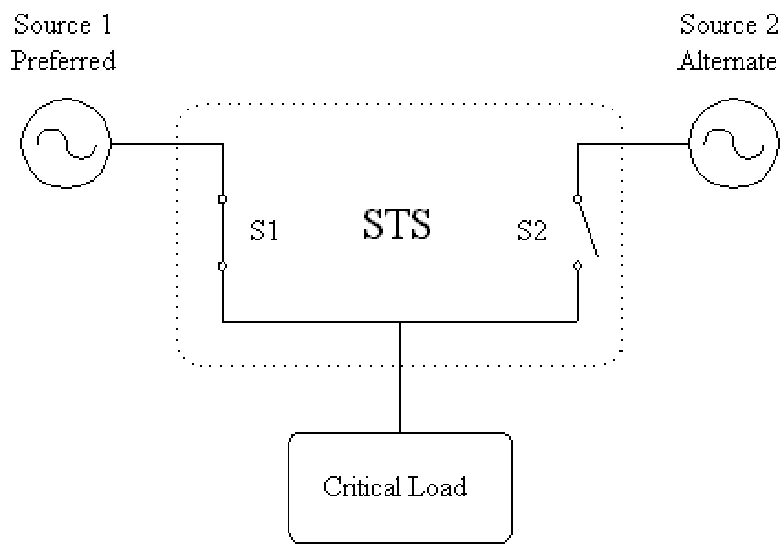

Figure 1-1
Basic Diagram of a Static Transfer Switch

Legacy STS have used electromechanical devices as "switches". Unfortunately, due to the nature of the electromechanical switches used in the ATS, a "seamless" transfer is not obtainable. Typical transfer times can range from a few seconds up to approximately ten seconds. Some work is currently being done that involves incorporating vacuum switches in this type of application to obtain approximate transfer times between 1½ and 2 cycles. Within the last decade, advances in new switch technologies have broadened the possibilities for applying such devices. Solid-state power semiconductor switches can now be used for the switching operation, thus decreasing the switching time, and allowing for a more seamless transfer of load from one source to the next.

The Solid State Transfer switch (SSTS) can provide added functionality beyond mere current interrupting and. Key functions include rapid load transfer capabilities, circuit sectionalizing and reconfiguration and the ability to monitor electrical and environment parameters at the switch location as a component of a larger ADA™ monitoring system.

As a result, power quality problems become transparent to the critical or sensitive customer loads that the SSTS protects. Solid-state switches can now be used for the switching operation, thus decreasing the switching time, and allowing for a more seamless transfer of load from one source to the next.

2
SOLID STATE TRANSFER SWITCH: REVIEW OF THE STATE-OF-THE-ART

Solid-State Transfer Switch

Recently new designs of solid-state breakers ("***all solid-state***" as well as "***hybrid***" designs), transfer switches, and fault current limiters using modern power electronics have captured the attention of utilities as well as equipment producers. New designs for an intelligent "all solid-state" as well as "hybrid" distribution and transmission switchgears have resulted from the marriage of advanced power electronics and conventional switchgear technology. The operating characteristic of solid-state switchgear is primarily dictated by the capabilities of the semiconductor devices used. Voltage and current ratings of the breaker define the number of power semiconductors required and, consequently, the cost and the operating losses of the breaker.

Motivations for possible market transformation using next-generation family of universal power electronics based switchgear designs, include:

- *Rapid Load Transfer Capabilities* – Solid-state transfer switches are the primary application for distribution solid state switchgear at the present time. These designs are used to transfer the power supply of sensitive loads, from a "normal" supply system to "alternate" supply system when a failure is detected in the "normal" supply. This transfer needs to be performed in a very fast way (1/4 cycle) so that the load does not experience any power quality problem

- *Circuit sectionalizing and reconfiguration* – Solid state switches have the potential to eliminate momentary interruptions for the great majority of customers on distribution systems when a fault occurs. Solid state switches for reconfiguring systems can also allow for optimizing performance through reconfiguration without imposing momentary interruptions on customers

- *Rapid Fault Current Solution Deployment* – Solid state switchgear designs will enable transmission and distribution entities to effectively deal with pressures to add new transmission capacity, provide open access for distributed and aggregate generation and deal with the challenges presented by new fault current sources.

- *Rapid Fault Isolation and* A*id Power Quality Improvements* – With the flexibility of power electronic switching, the solid state switchgear will achieve fault isolation and provide better network protection and take care of most of the distribution system situations that result in voltage sags, swells, and power outages

- *Instantaneous Current Limiting* – Solid state switchgear designs will provide instantaneous (sub-cycle) current limiting. Solid State switchgear will alleviate the short circuit condition in both downstream and upstream devices by limiting fault currents coming from the sources of high short circuit capacity.

- *Faster Fault Clearing and Shorten Recloser Interval* - Utilities may wish to clear faults more quickly than current circuit breakers allow

- *Mitigating the Effects of New Generation Within Distribution System* – New generation will increase the available fault current of the network and may result in existing equipment not being adequately rated to handle the new ratings. Upgrading the system to accommodate the new fault current ratings may be expensive and create excessively high prices and barriers to new generation. The solid state switchgear designs with current limiting capabilities can be used to mitigate this situation.

- *Interfaces with distributed generators* **–** Solid state switches can facilitate implementation of local islanding schemes for distributed generators and allow connection and disconnection without concern for transients

- *Repeated Operations With High Reliability and Without Wear-Out* – High fault currents are known to be a factor in reducing transformer life, so it is expected that an advantage from the use of a current limiting breaker will be longer life with higher reliability for nearby transformers

- *Curtail Mechanical Wear and Tear in Equipment* – Equipment in the fault current path will not experience the high asymmetrical and symmetrical fault currents that would be possible without the solid state switchgear

- *Soft Start Capability* – Limit the inrush current for capacitive loads, by gradually phasing in the switching device rather than making an abrupt transition from an open to a closed position

- *Reduce Switching Surge*s – Solid state switches can prevent transient voltages during capacitor switching and will allow capacitors to be switched in and out as often as needed. The result is better control of VAR flows, voltage, and flicker on the distribution system without causing unacceptable transient voltages

High Voltage Power Semiconductor Devices

There are three major semiconductor device technologies: (1) silicon-controlled rectifier (SCR) with a forced commutation circuit, (2) current-driven gating devices such as gate-turn-off (GTO) and GTO derived thyristor devices, and (3) voltage-driven gating devices such as insulated-gate-bipolar-junction-transistor (IGBT). These devices have been all developed at high-voltage levels and can be all used for solid-state circuit breakers. The latter two options offer the advantage of using a simple power circuit and very high speed operation. The current can be switched into an energy absorber in a few micro-seconds. However, these devices have both a lower voltage rating then SCRs have (6500 V vs. 8500 V) and a lower current carrying capability, the result of a more complex structure.

There has been tremendous advancement in HV power electronics devices in the past several years primarily led by high-power application for traction and FACTS devices. Currently, HV power electronic devices high power (gate turn-off thyristors (GTOs)[1], IGBTs[2], integrated gate commuted thyristors (IGCTs)[3], emitter turn-off thyristors (ETOs)[4]) are available at 6-kV level and R&D work is being conducted for achieving the holy grail of higher switching speed, lower losses, and increased reliability using either IGBT, GTO, ETO, IGCT, or other technologies. Moreover, industry and other consortium in the field of SiC and Diamond are also conducting considerable research work.

Recently, numerous power devices made using SiC material have exceeded the fundamental capability of Si, leading to an acceleration in the research and development of high voltage SiC devices. The DARPA High Power Electronics Program was also recently established with the goal to revolutionize high power electrical energy control, conversion, and distribution by establishing a new class of solid state power switching transistors employing wide bandgap semiconductor materials. This program as well as other research efforts has demonstrated many of the power device structures previously made in Silicon but with much higher voltage capability. These devices include: SiC BJT, SiC JFET, SiC MOSFET and SiC IGBTs.

The highest voltage level achieved with silicon is a 12-kV SCR. The highest voltage rating for all gate-driven devices is 6.5kV. The technology for silicon (Si) devices is nearly matured, and the rooms for further improvement are limited to packaging and the compromise between switching and conducting characteristics. The emerging wide-bandgap semiconductor devices have been reported at higher than 10kV in its early development stage. The field-effect-transistor (FET) in traditional Si technology has been limited to low-voltage (<600V) applications, but the silicon carbide (SiC) JFET has been reported at 5kV level [49], and MOSFET has been report at 10kV level[5]. The major limitation with SiC device is its material defect, and thus their current rating is always limited to very low level. Recent DARPA high-power electronics (HPE) program has pushed the SiC wafer size from 2” to 3” and continued improving the material defect problem. It is expected in a near future, the SiC devices will have a significant presence in high-voltage applications.

This section provides a detailed review of the state-of-the-art high-power commercial and research power semiconductor device technology (Si and SiC) and their ability to build up solid-state switchgear products of multiple ratings in a family which will have low cost in volume production. Key considerations includes: 1) Technology availability (thyristors, GCT, IGBT, SiC, etc.) 2) Current handling and current interrupting 3) Communication and control considerations 4) Cooling requirements 5) Snubber requirements 6) Space requirements. It also documents the current status of wide-band-gap semiconductor technology and its application areas. Comparisons of the Si technology with wide band-gap technologies in the context of

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[1] Gate turn-off thyristors. The capacity of the state-of-the-art GTO device has reached 6 kV and 6000 A.
[2] Insulated gate bipolar transistors. Today, 1.2-kV, 1.7-kV, 2.5-kV, 3.3-kV, and 6.5-kV, 600-A IGBTs are commercially available.
[3] Integrated gate commuted thyristors. These have reached the same power level as that of the GTOs.
[4] Emitter turn-off thyristors. These have reached the same power level as that of the GTOs.
[5] S.-H. Ryu, S. Krishnaswami, M. O'Loughlin, J. Richmond, A. Agarwal, J. Palmour, A.R. Hefner, “10-kV, 123-m/spl Omega//spl middot/cm/sup 2/ 4H-SiC power DMOSFETs,” ,” IEEE Electron Device Letters, vol. 25, no. 8, Aug. 2004, pp. 556 – 558.

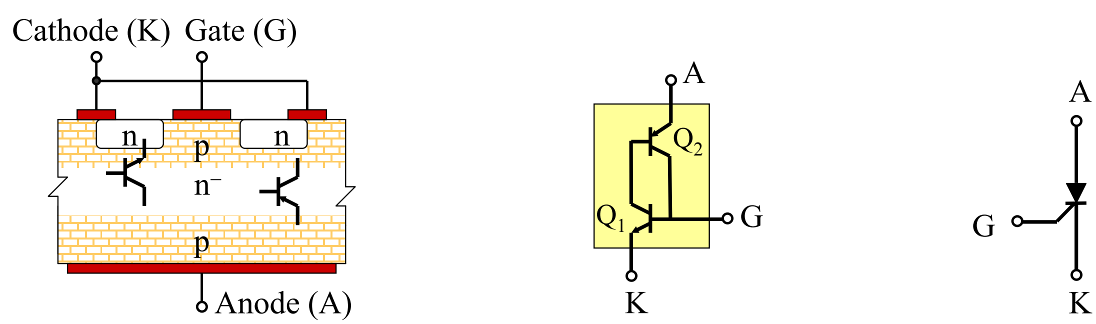
switchgear application area are documented. This chapter also provides a consolidated summary of the key technology metrics, based on DARPA's R&D program, that are required to realize the development of high-voltage semiconductor devices.

SCR (Silicon-Controlled Rectifier or Semiconductor-controlled Rectifier)

Silicon-Controlled Rectifier (SCR) is the oldest conventional power device. **Most exisiting STS use SCRs.** The SCR has a simple structure that allows the device to be easily fabricated, and thus the cost is lowest among all high power devices. Shown in Figure 2-1(a), the SCR consists of four alternate P and N layers, i.e., PNPN structure, between anode (A) and cathode (K). Its equivalent circuit is shown in Figure 2-1(b).

The operation of SCR can be considered in terms of a pair of tightly coupled transistors, NPN transistor Q_1 and PNP transistor Q_2. The NPN transistor Q_1 can be turned on by a positive current applied to the gate (G). Once Q_1 is turned on, Q_2 is supplied with a based current that allows Q_2 to be turned on. The collector current of Q_2 then in turn supplies a current to Q_1 base. Thus even if the gate current is removed, Q_1 and Q_2 remain conducting by mutually supplying the base current to each other with the collector current. This is a well-known "latch" mechanism. After device is latched on, it cannot be turned off except by applying a negative current to the anode or a negative voltage against anode-to-cathode. Thus SCR is mostly used in line commutation type circuit that it has to wait for the negative voltage through next zero crossing to naturally turn off the device.

The voltage drop during turned off is equivalent to a PN-junction diode under forward biased condition. Under reverse biased condition, the SCR is also similar to diode that it can block the reverse voltage.



(a) (b) (c)

Figure 2-1
Thyristor: (a) Internal Sturcture; (b) Equivalent Circuit; (c) Schematic Symbol

Figure 2-2 shows the SCR schematic circuit symbol with symbols (A, K, G) representing a three-terminal device. Figure 5.5 shows the photograph of the world's highest voltage rated semiconductor device – a 12kV SCR made by Mitsubishi. The package is a popular "hockey puck" type that allows heat sinks applied to both sides for effective cooling.

Figure 2-2
Photograph of the World's Highest Voltage Semiconductor Device – Mitsubishi FT1500AU-240[6,7]

Key features of SCR related to circuit breaker operation can be summarized as follows.

1. Highest blocking voltage level: 12kV is available commercially
2. Lowest voltage drop: less than 2V for 6.5kV device and less than 4V for 12kV device
3. High surge current capability: half-cycle surge current is typically 20 times the average current
4. Reverse blocking: an inherent capability similar to diodes
5. Slow turn-off speed: typically larger than 500μs for large device, not suitable for high-frequency pulse-width-modulation (PWM)
6. Lack of gate turn-off capability: it relies on the negative voltage with line commutation or an external commutation circuit to force the controlled turn-off
7. Low dv/dt capability: typically less than 2kV/μs, thus requires voltage snubber if the device is not turned off at zero crossing
8. Low di/dt capability: typically less than 200A/μs, thus requires current snubber if the device is used in voltage source converters

Table 1-1 compares three commercially available high-voltage high-power SCRs made by three different companies. The Mitsubishi FT1500AU-240 is rated at 12kV blocking voltage, 1.5kA continuous current capability and 34kA surge current capability. The ABB 5STB18U 6500 has a unique design that contains two anti-paralleled thyristors in one wafer and allows reverse

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[6] Feasibility Study for the Development of High-Voltage, Low-Current Power Semiconductor Devices: 2003 Strategic Science and Technology Project (EPRI report 2004 1009516)
[7] IUT EHV Patent Disclosure and IUT Power Semiconductor Evaluation: 2005 Strategic Science and Technology Project (EPRI report 2005)

conducting. Thus one single device can be used as a standalone circuit breaker. Its current rating is also high enough for typical circuit breaker rated at 600A and 1200A. The SPCO SPT401 has a diameter size of 125mm and a current rating of 5kA, high enough for most circuit breakers.

Table 2-1. Comparison of three commercially available high-voltage high-power thyristors

Manufacturer	**Mitsubishi**	**ABB**	**SPCO**
Model	FT1500AU - 240	5STB18U 6500	SPT401 125mm
Reverse blocking	yes	yes	Yes
Reverse conducting	no	yes	No
Blocking voltage	12kV	6.5kV	5kV
Average current I_{av}	1.5kA	1.58kA	5kA
Surge current I_{pk}	34kA	31.8kA	70kA
Voltage drop	4V at 3kA	1.93V at 1.6kA	1.8V at 4kA
Turn-off speed	n.a.	800us	400µs
Critical di/dt	100A/µs	250A/µs	100A/µs
Critical dv/dt	2000V/µs	2000V/µs	1000V/µs

GTO (gate turn-off thyristor)

The general term for a PNPN latched semiconductor device is normally referred to as the "Thyristor." The gate-turn-off thyristor (GTO), shown in Figure 2-3, is an improvement over the SCR that it can be turned off by applying a negative current pulse to the gate, thus it does not need to wait for zero crossing condition. Shown in Figure 2-3(a), the GTO has n+ layer diffused into anode region to allow thinner wafer while maintaining low voltage drop. Its equivalent circuit is shown in Figure 2-3(b). With proper adjustment of current gains for the two transistors Q_1 and Q_2, the GTO can be turned off by a large negative current to the gate.

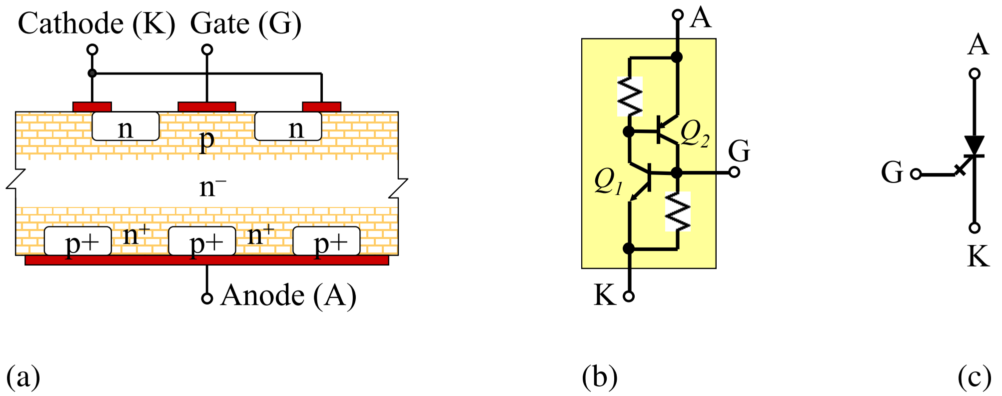
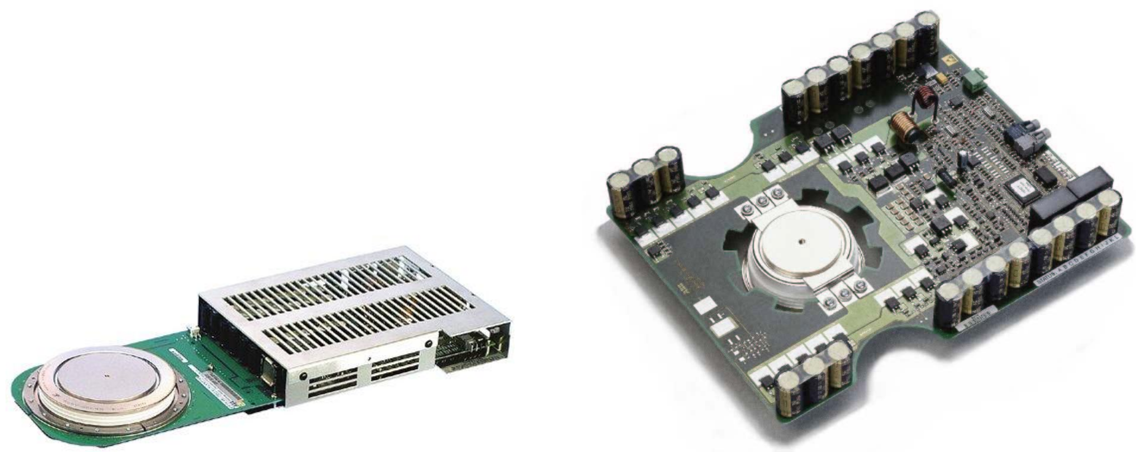


Figure 2-3
Gate-Turn-Off thyristor: (a) Internal Structure; (b) Equivalent Circuit; (c) Schematic Circuit Symbol

The gate current to turn off GTO needs to be excessively high, typically 20% to 100% of the device conducting current. For the device with thousands of amperes, the control becomes a major problem. Thus some GTO derived devices were developed recently. The most well-known one is the integrated-gate-commutated-thyristor (IGCT) made by ABB. The same technology is called GCT by Mitsubishi. The IGCT is to integrate the gate drive circuit and the device together with very low inductance between the gate drive and the device to accelerate the turn-off process. The cathode current has to be turned off in less than 1μs to avoid device going into instability. For a 5kA switching, this turn-off di_G/dt corresponds to 5kA/μs. The voltage needed for the gate circuit needs to be high, and the gate-circuit inductance needs to be sufficiently low. Thus the integrated package is necessary to achieve effective switching.

The GTO can be designed to have reverse-blocking capability, and the device is normally referred to as “symmetrical GTO.” Similarly, IGCT can adopt respective GTO to become symmetrical IGCT. Figure 2-4(a) shows the photograph of the ABB 5SHY30L6010 unidirectional IGCT. This IGCT is capable of operating at 1.3kA average current and 27.5kA surge current. It does not have reverse blocking capability, thus a series diode is needed for circuit breaker operation. The Mitsubishi GCU15CA-130 GCT, shown in Figure 2-4(b), has the reverse blocking capability, but its average current capability is only 500A.

Similar to thyristors, the GTO is also a latch on device that does not have linear operation region. In other words, it is either fully on or fully off. Varying gate voltage or current cannot change the conduction characteristic.



(a) (b)

Figure 2-4
(a) Photograph of ABB 5SHY30L6010 Unidirectional IGCT; (b) ABB 5SHZ08L6000 Reverse Blocking Type IGCT [12-13]

Table 1-2 compares five commercially available GTOs and IGCTs. The highest voltage rating is 6.5kV. The Mitsubishi FG6000AU-120D is rated 6kV, 6kA switching, but its average current rating is only 2kA. The rated current is based on the repetitive turn-off capability, but the average current is based on continuous conduction condition.

Table 2-2 Comparison of commercially available GTO and GTO derives devices

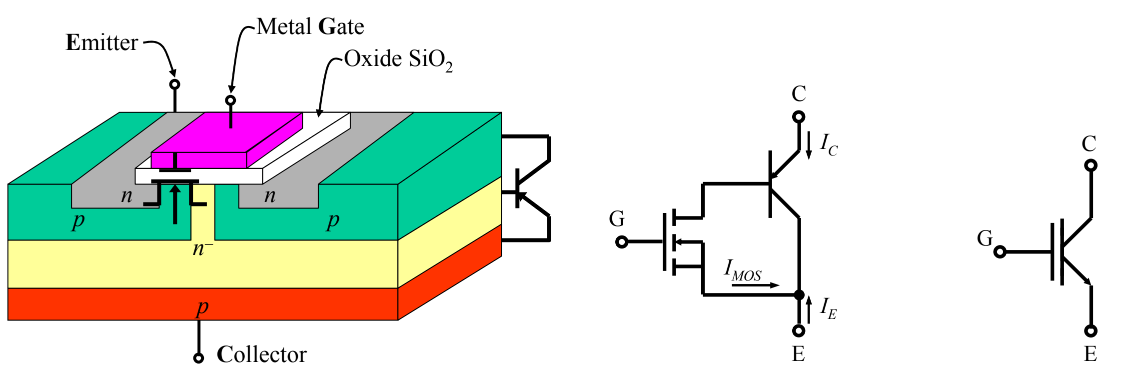
Device type	**GTO**	**GTO**	**GCT**	**IGCT**	**IGCT**
Manufacturer	Mitsubishi	ABB	Mitsubishi	ABB	ABB
Model	FG6000A U-120D	5SGT30J 6004	GCU15CA -130	5SHY30L 6010	5SHZ08F 6000
Rev. blocking	No	no	Yes	no	yes
Blocking voltage	6kV	6kV	6.5kV	6kV	6kV
Rated current	6kA	1.5kA	3kA	3kA	800A
Average I_{av}	2kA	1kA	500A	1.3kA	290A
Surge current I_{pk}	40kA	24kA	8kA	27.5kA	800A
Voltage drop	6V at 6kA	3.5V at 3kA	6V at 800A	3V at 3kA	8.4V at 800A

Turn-off speed	30µs	28µs	n.a.	14µs delay	n.a.
Critical di/dt	500A/µs	400A/µs	1kA/µs	1kA/µs	1kA/µs
Critical dv/dt	1kV/µs	1kV/µs	3kV/µs	1kV/µs	1kV/µs

IGBT (Insulated Gate Bipolar Transistor)

Figure 2-5 (a) shows the basic structure of an IGBT. Without the bottom p-layer, the structure is similar to a power MOSFET that has an n-channel to connect the current. When a positive voltage is applied in between the gate and the n-channel, the electric field will create a conduction channel between n^- and *n* layers. Adding a p-layer on the bottom allows the device to block a higher voltage. The equivalent circuit is shown in Figure 2-5(b). A PNP transistor is formed by the collector *p*-layer, the internal n^--layer, and the body *p*-layer form. The metal gate along with the insulated oxide layer and the emitter *n*-layer form a power MOSFET. With power MOSFET shorting the base and collector of the PNP transistor, the voltage drop of the IGBT is the sum of the PNP emitter-base voltage and the MOSFET resistive voltage. Larger silicon area allows smaller resistive drop, but the emitter-base voltage drop tends to be constant. The schematic circuit symbol shown in Figure 2-5(c) indicates that the IGBT is represented by three terminals: collector (C), emitter (E), and gate (G).

The punch-through (PT) technology was introduced to show that HV blocking could be achieved with the addition of an n+ buffer along with the local lifetime control, the optimization of p-collector layer and an improved wafer processing[8]. With the improved PT technology, high-voltage IGBT (HV-IGBT) is now available at 3.3 kV, 4.5 kV, and 6.5 kV levels.



(a) (b) (c)

Figure 2-5

[8] J. F. Donlon, E.R. Motto, K. Ishii, T. Iida, "Application advantages of high voltage high current IGBTs with punch through technology," in *Conf. Rec. of IEEE Industry Applications Annual Meeting*, Oct. 1997, pp. 955 – 960.

Insulated Gate Bipolar Transistor (IGBT) Structure and Symbol: (a) Basic IGBT Structure; (b) IGBT Equivalent Circuit and Symbol; (c) Schematic circuit symbol

IGBT typically has smaller silicon die size. Most commercial IGBTs are packaged in a plastic module with multiple dies in parallel internally. Figure 2-6 shows the photograph of ABB 5SNA0600G650100, 6.5kV, 600A IGBT. Three pairs of (C,E) terminals can be paralleled by external power bus bars.

Figure 2-6
Photograph of ABB 5SNA0600G650100 High-Voltage IGBT

Figure 2-7 shows test results of a Mistubishi 2.5-kV, 1.2-kA HV-IGBT operating at 2-kV and 700-A conditions[9]. The turn-on process is less than 1.5µs, and the turn-off process is about 3µs. Measured turn-on and turn-off energies are 1.88 J and 0.86 J, respectively. The main reason for high turn-on loss is due to slow diode reverse recovery. If it were the low-voltage IGBT, the diode can be much faster, and the turn-on process can be one order magnitude faster.

It is worth of comparing the turn-on di/dt characteristic between HV-IGBT and GTO-derived devices here with the experimental waveforms. With limited FBSOA capability, the GTO-derived devices need to be limited to nearly 100 A/µs di/dt during turn-on by using external snubbers. Here the HV-IGBT operating without any snubber shows 1500 A/µs di/dt during turn-on. Such a number would have destroyed most GTO derived devices.

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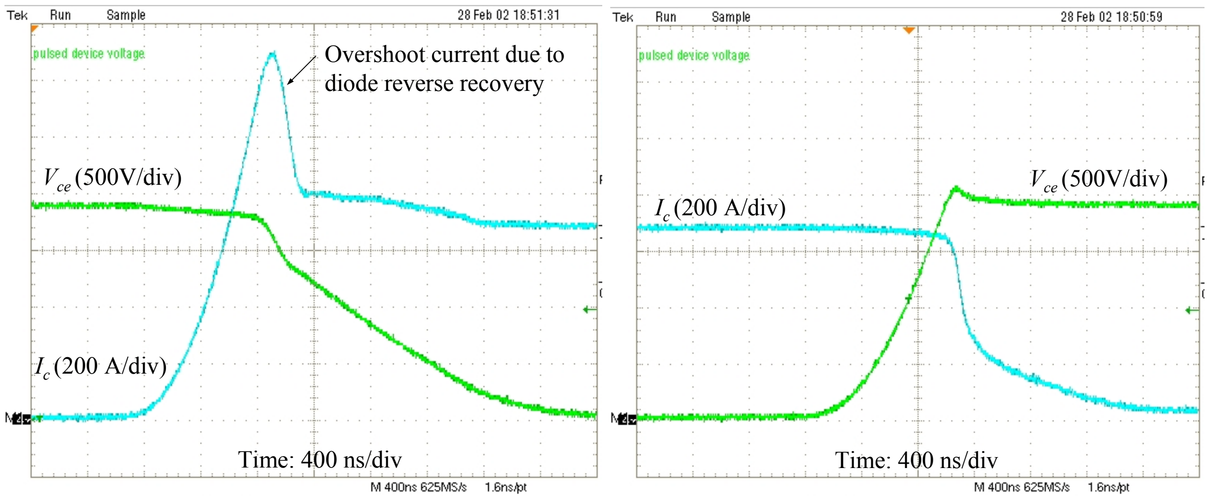
[9] J.-S. Lai, L. G. Leslie, J. F. Ferrell, T. Nergaard, "Characterization of HV-IGBT for High-Power Inverter Applications," to be appeared in *Conf. Rec. of IEEE Industry Applications Annual Meeting*, Oct. 2005.



(a) (b)

Figure 2-7
Voltage and Current Waveforms of a High-Voltage Insulated Gate Bipolar Transistor (HV-IGBT) Switching at 2-kV and 700-A Conditions: (a) turn-on and (b) turn-off

Table 1-3 compares four commercially available HV-IGBTs. The standard IGBT current rating is the continuous average current, which looks much smaller than what GTO is rated. Its peak current rating, however, can be much higher than its continuous current rating. Most IGBT modules limit its peak current rating to twice the continuous current rating. The ABB 5SNA0600G650100 provides half-pulse peak current rating, which is 10 times the continuous current rating.

The IGBTs tend to have higher voltage drop than that of thyristor devices. The 6kV devices typically have a voltage drop of 5V at 600A condition, and the 4.5kV devices have a voltage drop of 3.3V at 900A. The turn-off speed depends on the gated drive resistor value. Smaller gate resistance has less delay time, and the overall turn-off speed is faster. The ABB 5SNA0600G650100 shows 2.5μs turn-off time when the gate-drive resistance is 2.7Ω. Other HV-IGBTs using 10Ω or higher gate resistance have a much slower turn-off speed that is similar to GTO derived devices.

Table 2-3 Comparison of Four Commercially Available HV-IGBTs

Manufacturer	Mitsubishi	ABB	EUPEC	Powerex
Model	CM600HG - 130H	5SNA 0600 G650100	FZ600 R65KF1	CM900HG - 90H
Blocking voltage	6.5kV	6.5kV	6.5kV	4.5kV
Average current I_{av}	600A	600A	600A	900A

Peak current I_{pk}	1.2kA	6kA (8.3ms)	1.2kA	1.8kA
Voltage drop	5V at 600A	5.4V at 600A	5.3V at 600A	3.3V at 900A
Turn-off speed	10μs at R_g=10ohm	2.5μs at R_g=2.7ohm	6.5μs at R_g=25ohm	7.2μs at R_g=10ohm
Short ckt current	n.a.	2.7kA	3kA	n.a.
Short ckt period	n.a.	10μ	n.a.	n.a.

Key features of HV-IGBT related to circuit breaker operation can be summarized as follows.

9. High Blocking voltage level: 6.5kV is available commercially

10. Voltage drop: about 5V for 6kV devices and 3.3kV for 4.5kV devices

11. High surge current capability: The half-cycle surge current is typically 10 times the average current

12. Gate drive controllability: The gate resistance affects the turn-off speed significantly. In fact, the gate voltage can also be controlled to drive the device into or out of saturation.

13. No reverse blocking capability: Today's HV-IGBT does not have reverse blocking capability. Although it is possible to design with reverse blocking, the voltage drop may be compromised.

14. Fast turn-off speed that can be controlled by the gate resistance: typically less than 10μs turn-off for large device; and the frequency switching can increased to as much as 10kHz.

15. High dv/dt capability: there is no need for the voltage snubber if the device is not turned off at zero crossing

16. High di/dt capability: there is no need for the current snubber if the device is used in voltage source converters.

Wide Band-gap Silicon Carbide Devices

Presently, almost all of the power electronics converter systems used silicon (Si)-based power semiconductor switches. However, SiC with superior properties compared to Si is a good candidate to be used in the next generation of power devices, especially for high-voltage applications. The emergence of SiC-based power semiconductor switches, with superior features compared with the Si-based switches, could bring in substantial improvement in the performance of power electronic converter systems.

SiC has a unique combination of a high critical electrical breakdown field, good majority carrier transport, long minority carrier lifetimes due to its indirect bandgap, and high thermal conductivity. These attributes combine to give SiC the potential to significantly exceed the current-carrying density, temperature and voltage-blocking capabilities of existing silicon power semiconductor devices (Figure 2-8)

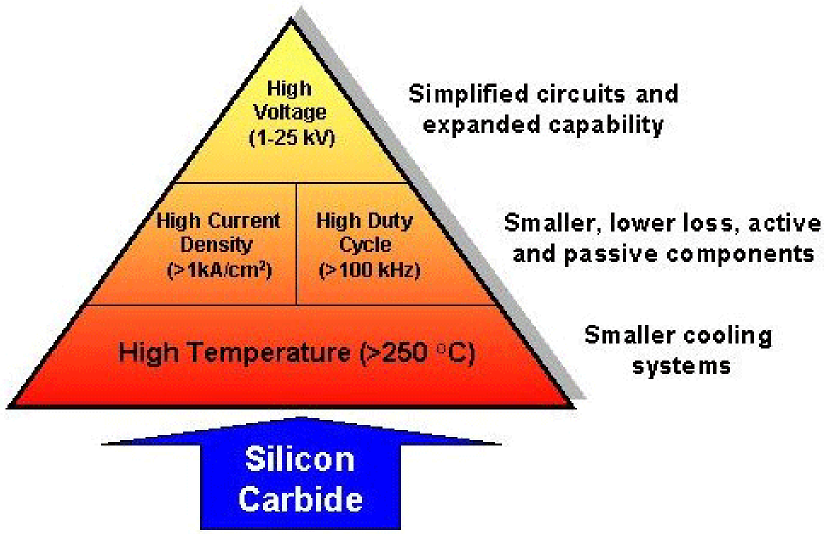


Figure 2-8
SiC Potential for Wide Bandgap High Power Electronics

Materials that have received the most interest for the development of power semiconductors include, but are not limited to gallium-arsenide (GaAs), gallium-nitride (GaN), aluminum-nitride (AlN), silicon carbide (SiC), and diamond. Three types of SiC polytypes have been studied: 3C, 4H, and 6H. The 3C-form has a cubic lattice structure while the others are hexagonal. The number indicates how many basic layers of 0.251 nm spacing from the elementary cell. The cubic form has isotropic properties, whereas the hexagonal forms have anisotropic properties. This means that material properties like carrier mobility and electrical permittivity take the form of tensors, and the carrier drift velocity and the dielectric polarization may take up directions that differ from that of the applied electric field. Table 1-4 compares physical properties of silicon and wide band-gap materials.

Table 2-4
Key Properties of Wide-Band Gap Semiconductor Materials

	Si	GaAs	GaN	3C-SiC	6H-SiC	4H-SiC	Diamond
Band Gap (eV)	1.12	1.42	3.4	2.2	2.9	3.2	5.5
Electron Saturation Velocity (10^7cm/s)	1	2	2.5	2.5	2	2.7	2.7

Dielectric Constant	11.8	12.9	10	9.7	10	9.7	5.5
Breakdown Field (MV/cm)	0.3	0.4	3.3	1.5	2.2	3.0	5.6
Thermal Conductivity (W/cm/K)	1.5	0.46	1.3	5	5.0	4.9	22
Electron Mobility μ_n ($cm^2/V{\cdot}s$)	1350	8500	900	100	460	800	1900
Electron Mobility μ_p ($cm^2/V{\cdot}s$)	470	90	150	50	50	120	1200

Some of these advantages compared with Si-based power devices are as follows:

- SiC unipolar devices are thinner and have lower “on” resistances. At low breakdown voltages (~50 V), these devices have specific on resistances of 1.12 μΩ, around 100 times less than those of their Si counterparts. At higher breakdown voltages (~5000 V), the on resistance goes up to 29.5 mΩ, which is still 300 times less than that of the comparable Si devices. With lower on resistance, SiC power devices have lower conduction losses; therefore, the converters have higher overall efficiency.

- SiC-based power devices have higher breakdown voltages because of their higher electric breakdown field; for example, Si Schottky diodes are commercially available at voltages lower than 300 V, but the first commercial SiC Schottky diodes are already rated at 600 V.

- SiC has a higher thermal conductivity (4.9 W/cm ·K for SiC and 1.5 W/cm ·K for Si), and SiC power devices have a lower junction-to-case thermal resistance, $R_{th\text{-}jc}$ (0.02K/W for SiC and 0.06 K/W for Si). Therefore, temperature increase of the device is slower.

- SiC devices can operate at high temperatures. SiC device operation at up to 600°C (1112°F) is mentioned in the literature [1]. Si devices, on the other hand, can operate at a maximum junction temperature of only 150°C (302°F).

- SiC is extremely radiation hard; that is, radiation does not degrade the electronic properties of SiC.

- Forward and reverse characteristics of SiC power devices vary only slightly with temperature and time; therefore, they are more reliable.

- SiC-based bipolar devices have excellent reverse-recovery characteristics. With less reverse-recovery current, the switching losses and EMI are reduced, and there is less or no need for snubbers.

Because of low switching losses, SiC-based devices can operate at higher frequencies (>20 kHz), which is not possible with Si-based devices in power levels of more than a few tens of kilowatts.

3
APPLICATIONS AND CONCLUSIONS

Legacy Applications

A few static transfer switches have been deployed for source transfer. Most of these STSs are legacy systems that use thyristors. The thyristor-based medium voltage STS (MVSTS) system consists of sets of solid-state switching elements, sense elements, and logic which enable the flow of electrical current to be controlled in both directions for each phase of each source. One set of switch elements is connected to Source 1, while the other set is connected to Source 2, as shown in Figure 3-1. The outputs of the two sets of switches are connected together and furnish power to AC loads.

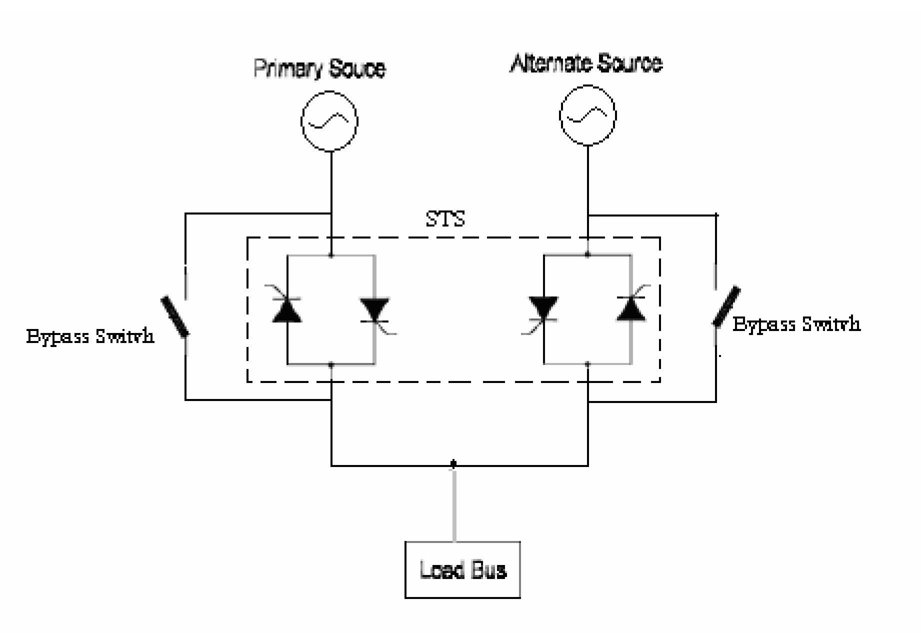


Figure 3-1 Single Line Diagram of STS

The MVSTS system includes a controller which performs the automated operational functions of the MVSTS. The controller shall also provide external status, control, and metering interfaces to external equipment including: Supervisory Control and Data Acquisition (SCADA), Remote Terminal Unit (RTU), external control and indication panel, and/or automated bypass and isolation switchgear which may be mounted in a separate location.

A bypass or isolation switch electrically isolates the MVSTS equipment. The bypass and isolation switches are intended to be used for safely performing electrical tests, maintenance, repairs, and emergency loading conditions without disturbance to the loads. While the MVSTS is bypassed, the bypass switchgear may be allowed to function as an electromechanical automatic changeover switch.

The following is a list of some thyristor-based STS applications over the past years:

- 15kV, 600A Mobile Application
- 15kV, 600A Outdoor Installation for Ford Motor, Detroit Michigan
- 38kV Installation at PECO, PA
- 15kV Installation at Applied Materials, CA
- Low-Voltage 600V and 100 – 4000A Class Sub-Cycle Transfer Switches

Figure 3-2 15kV, 600A Mobile Application

Figure 3-3 15kV, 600A Outdoor Installation for Ford Motor, Detroit Michigan

Figure 3-4 38kV Installation at PECO, PA

Figure 3-5 15kV Installation at Applied Materials, CA

Figure 3-6 Low Voltage Sub-cycle Transfer Switches

Conclusions

Besides the few legacy applications described above, not many applications have been reported in the recent years. However, with the growing popularity of AC as well as DC microgrids, solid-state transfer switches may find new application areas. Micro-grids offer improved system reliability and may use energy storage and renewable energy components. Advanced micro-grids may employ fuel cells, heat recovery, and energy storage. These microgrids provide the capability to operate in parallel with the utility system for grid support during normal conditions. In such applications, a static switch device is used that could isolate the system in about ½ cycle, performing essentially a seamless transfer during utility-system voltage sags.

Switches similar to static transfer switches also have an important role to play in adaptable micro-grids that can be broken into sub-grids. In such advanced architectures, sectionalizing switches are one of the most important components. These sectionalizing switches must have synchronizing capability (they only close when voltage magnitude, phase angle, and frequency differences on both sides are nearly equal). Static transfer switches could switch further down the feeder provides the ability to break the micro-grid apart into smaller micro-grids, which provides added reliability if one section of the campus becomes faulted or if one of the generation plants is unavailable. The sectionalizing switches would also need to be able to close into “dead” (de-energized) areas if generation is disabled in those areas and it is desirable for an adjacent sub-grid to attempt to carry a load on a dead sub-grid.

DC microgrids have their own advantages too. One of the advantages of DC is the ability to use *blocking diodes* at key points within the microgrid to isolate faulted sections and limit exposure to voltage sags. Blocking diodes may also be used with network architectures to provide the same isolating function, but more would be needed. Blocking diodes can be reversed by a mechanical switch to allow a change in power flow direction. An even more advanced solution is to use high-speed SCR devices (similar to AC static switches but operated with DC) that could be employed to allow instantaneous directional flow change when needed to reconfigure the DC micro-grid to support a new flow direction in the event of a loss of utility bulk supply or other problems. Another use of blocking diodes and SCR devices is the ability to simplify generator “zone” protection requirements on complex systems. Fault currents can be “steered” and controlled in a manner that helps identify which zone the fault is actually located in, so setting up the generator protection and control becomes much easier.

Presently, discussions are underway with a number of utilities to try and understand the role and potential applications for solid state transfer switches in microgrids.

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