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FACTS and Custom Power Equipment for the Enhancement of Power Transmission System Performance and Power Quality

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Summary: In a deregulated utility environment, financial and market forces will demand a more optimal and profitable operation of the power system with respect to generation, transmission, and distribution. Power electronic based equipment, such as Flexible AC Transmission Systems (FACTS), High-Voltage DC (HVDC), and Custom Power technologies constitute some of the most-promising technical advancements to address the new operating challenges being presented today. This paper describes four power electronic based technologies to help meet the needs of today's power systems. System needs, equipment characteristics, and application examples are provided for: (1) a static compensator (STATCOM); (2) a voltage sourced converter based back-to-back dc tie; (3) a distribution STATCOM; and (4) a solid-state transfer switch (SSTS).

Keywords: FACTS, Voltage Sourced Converter, STATCOM, Solid-State Transfer Switch (SSTS), D-STATCOM, Power Quality, Custom Power

1. INTRODUCTION

With the ongoing deregulation of the electric utility industry, numerous changes are continuously being introduced to a once predictable business. With electricity increasingly being considered as a commodity, transmission systems are being pushed closer to their stability and thermal limits, while the focus on the quality of power delivered is greater than ever. In the evolving deregulated utility environment, financial and market forces are, and will continue to, demand a more optimal and profitable operation of the power system with respect to generation, transmission, and distribution. Now, more than ever, advanced technologies are paramount for the reliable and secure operation of power systems. Power electronic based equipment, such as Flexible AC Transmission Systems (FACTS), High-Voltage DC (HVDC), and Custom Power technologies constitute some of the most-promising technical advancements to address the new operating challenges being presented today. These advancements are based on the high-performance capability of power electronic equipment to rapidly respond to system events, increase power transfer limits, and improve the quality of power delivered.

The potential benefits of FACTS equipment are now widely recognized by the power system engineering community [1,2,3,4,5]. As an advancement within the FACTS arena, voltage sourced converter based technology has been successfully applied in a number of projects [6,7,8,9,10,11,12,13]. In addition to the applications described in the these references, there are several other recently announced voltage sourced converter based FACTS installations planned for operation in 2000 and 2001 in the USA, in the states of Texas and Vermont (no technical references are yet available for citation). All of these voltage sourced converter based applications are in addition to the established FACTS technologies of Static Var Compensation (SVC) [14] and Thyristor Controlled Series Compensation (TCSC) [15,16,17,18].

As for the Custom Power requirements [19], utility distribution networks, sensitive industrial loads, and

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critical commercial operations can potentially suffer from various types of outages and service interruptions. These can cost significant financial losses per incident based on process down-time, lost production, idle work forces, and other measurable and non-measurable factors. The types of interruptions that are experienced are classified as power quality problems and are most-often caused by voltage sags and swells, lightning strikes, and other distribution system related disturbances. In many instances the use of Custom Power equipment, such as Dynamic Voltage Restorers (DVR), Solid-State Transfer Switches (SSTS), or Distribution level Static Compensators (D-STATCOM), can be some of the most cost-effective solutions to mitigate these types of power quality problems. There have been numerous applications of Custom Power technologies [20,21,22, 23,24,25,26].

This paper focuses on identifying system needs, equipment design and performance characteristics, and system applications of power electronic based equipment for FACTS, dc ties for back-to-back power transfer, and Custom Power.

2. STATIC COMPENSATOR (STATCOM) FOR TRANSMISSION SYSTEM APPLICATIONS

2.1 Equipment Description and Performance Characteristics

Figure 2-1 shows a one-line diagram of a static compensator (STATCOM). The STATCOM shown in this figure consists of self-commutated converters using Gate Turn-Off (GTO) thyristors, a dc voltage source, a converter transformer, a step-up transformer, and a controller. Note that the step-up transformer is not normally necessary for the lower system voltage applications.

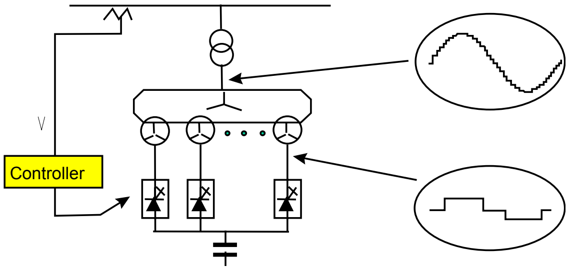


Figure 2-1. One-line diagram of a STATCOM

Each GTO converter generates a voltage that is stepped-up by a line-side-series-connected multi-stage converter transformer. The converter transformer enables the build-up of a sine-wave voltage in both magnitude and phase. Because STATCOMs with multi-stage converter transformers do not generate significant internal harmonics, they generally require minimal, or no, harmonic filtering. If the number of firing pulses for the GTOs is increased (i.e., pulse-width modulation (PWM) order), the harmonics are further decreased. High-side voltage is generally used as a controller input, as indicated in Figure 2-1.

Figure 2-2 shows the equivalent circuit of a STATCOM system. The GTO converter with a dc voltage source and the power system are illustrated as variable ac voltages in this figure. These two voltages are connected by a reactance representing the transformer leakage inductance. Figure 2-3 shows the basic principles of operation for a STATCOM. The output voltage of the GTO converter (Vi) is controlled in phase with the system voltage (Vs), as shown in this figure, and the output current of the STATCOM (I) varies depending on Vi. If Vi is equal to Vs, then no reactive power is delivered to the power system. If Vi is higher than Vs, the phase angle of I is leading with respect to the phase angle of Vs by 90 degrees. As a result, leading reactive power flows from the STATCOM (capacitive mode). If Vi is lower than Vs, the phase angle of I is lagging with respect to Vs by 90 degrees. As a result, lagging reactive power flows into the STATCOM (inductive mode). The amount of the reactive power is proportional to the voltage difference between Vs and Vi. Note that this is the same basic operating principal as a rotating synchronous condenser.

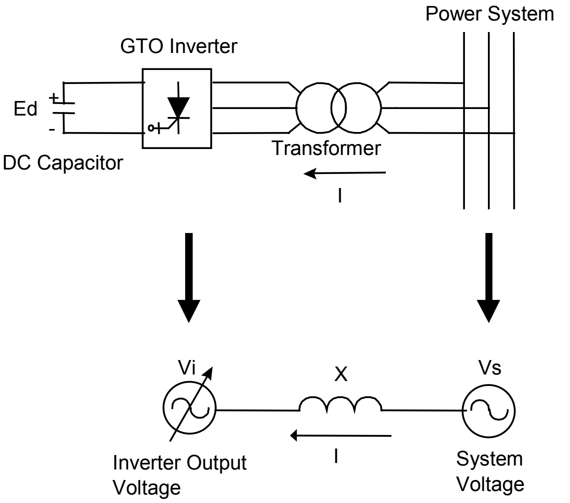


Figure 2-2. Equivalent circuit of a STATCOM

Figure 2-4 shows the V-I characteristic of the STATCOM. The STATCOM smoothly and continuously controls voltage from V_1 to V_2, as shown in Figure 2-4. However, if the system voltage exceeds a low-voltage (V_1) or high-voltage limit (V_2), the STATCOM acts as a constant current source by controlling the converter voltage (Vi) appropriately. Thus, when operating at its voltage limits, the amount of reactive power compensation provided by the STATCOM is more than the most-common competing FACTS controller, namely the Static Var Compensator (SVC). This is because at a low voltage limit, the reactive power drops off as the square of the voltage for the SVC, where Mvar=f(BV^2), but drops off linearly with the STATCOM, where Mvar=f(VI). This makes the reactive power controllability of the STATCOM superior to that of the SVC, particularly during times of system distress. In addition the STATCOM has other advantages compared to an SVC, such as:

- Quicker response time (A STATCOM has a step response of 8 ms to 30 ms). This helps with compensation of negative phase current and with the reduction of voltage flicker.
- Active power control is possible with a STATCOM (with optional energy storage on dc circuit). This could further help with system stability control.
- No potential for creating a resonance point. This is because no capacitor banks or reactors are required to generate the reactive power for a STATCOM.
- The STATCOM has a smaller installation space due to no capacitors or reactors required to generate Mvar, minimal or no filtering, and the availability of high capacity power semiconductor devices. Designs of systems of equal dynamic ranges have shown the STATCOM to be as much as 1/3 the area and 1/5 the volume of an SVC.
- A modular design of the STATCOM allows for high availability (i.e., one or more modules of the STATCOM can be out-of-service without the loss of the entire compensation system).

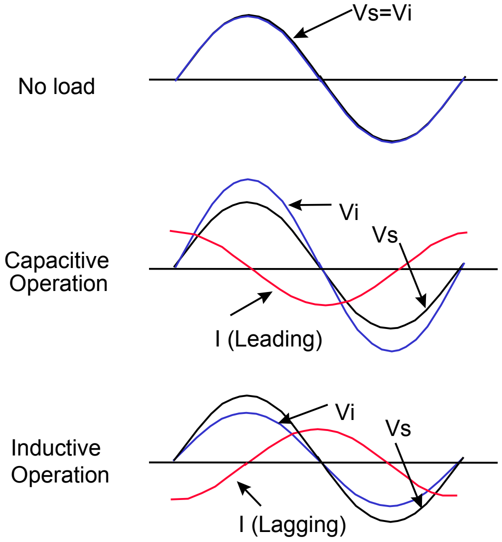


Figure 2-3. Principle of operation of a STATCOM

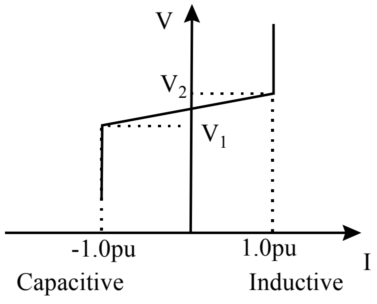


Figure 2-4. V-I characteristic of a STATCOM

2.2 Application Example

In 1991, the world's first commercial transmission system STATCOM (at the time known as SVG for Static Var Generator) was installed at the Inuyama substation of The Kansai Electric Power Company in Japan, for the objective of improving power system and voltage stabilization [6]. It has been successfully operating for nearly 9 years.

Figure 2-5 shows an aerial view illustration of the Inuyama STATCOM installation. Table 2-1 shows the equipment specifications. Figure 2-6 shows the one-line diagram of this 80 MVA STATCOM. Shown in this figure are the eight 10 MVA voltage sourced converter stages connected via a line-side-series-connected multi-stage converter transformer to a 34.24 kV bus, and then through a main transformer up to the 154 kV transmission system. Each of the eight stages has the same output voltage, but shifted by 7.5 degrees from one to the other. With this 48-pulse system, minimal harmonics are generated.

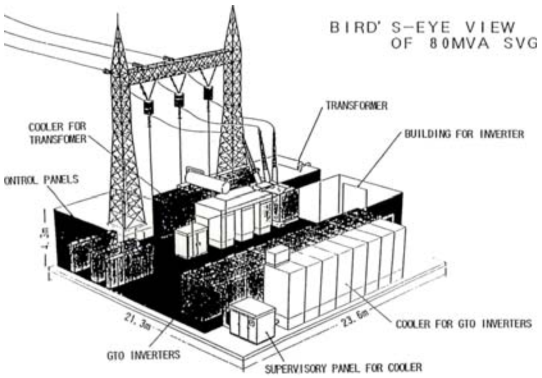


Figure 2-5. Ariel view of the Inuyama STATCOM

Table 2-1. Equipment Specifications

Capacity	80 MVA
Number of Pulses	48
Number of Converters	8
Type of Converter	1 pulse PWM
Semiconductors	GTO: 4.5 kV 3000 A Diode: 4.5 kV 1000 A
Arm Configuration	3-Series,1-Parallel 4-Arms
Cooling System	Pure Water
DC Voltage	4150 V
Converter Current	1110 A
Converter Voltage	3000 V

The basic control of the Inuyama STATCOM consists of a voltage regulator (AVR) and a supplemental power system damping control (PSS). The input signals to the control system are the high-side voltage (for the AVR and PSS) and line current (for the PSS), as indicated in Figure 2-6.

Sample test results are shown in Figure 2-7, where the plot shows a case without STATCOM (top) and with STATCOM (bottom). In the top half of the figure, the system is at its oscillatory stability (i.e., damping) limit, as is evidenced by the oscillations in the plot. In the early part of this plot, there are oscillations seen in the waveforms of transmission system power and voltage. The power flow is increased only slightly from about

510 MW to 530 MW and the oscillations continually grow in magnitude (i.e., they are undamped). In the bottom half of Figure 2-7, the STATCOM is on-line with its AVR and PSS enabled, with a power flow of nearly 621 MW. Here, the absence of any oscillations is observed, clearly showing the effectiveness of the STATCOM. Note that the 621 MW transfer level was based on the thermal limit of the lines at the time of the tests. The results shown in Figure 2-7 imply that the actual oscillatory stability (damping) limit is much higher with the addition of the STATCOM.

References [6,7] contains some other test results for line faults, further indicating the STATCOM's effectiveness for damping oscillations, overall system stabilization, and the achievement of maximum permissible transmission power.

As for the operating experience of the Inuyama STATCOM, it has been successfully operating since May 1991.

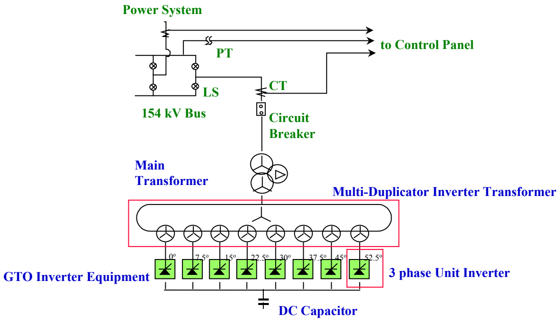


Figure 2-6. 80 MVA STATCOM configuration

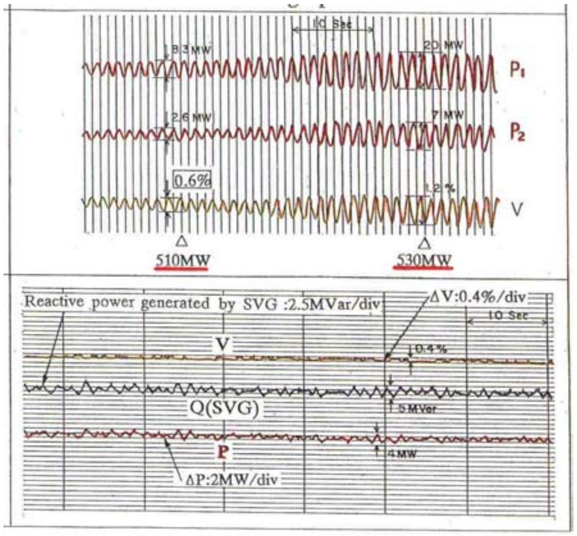


Figure 2-7. Test result showing power system oscillatory stability (i.e., damping) without STATCOM (top) for transfer levels of 510-530 MW and with STATCOM (bottom) for transfer levels of 621 MW

3. VOLTAGE SOURCED CONVERTER BASED BACK-TO-BACK DC POWER TRANSFER

3.1 Development

In recent years, voltage sourced converter technology has made significant progress through the development and advancement of high power controlled turn-off type semiconductor devices, such as GTOs, IGBTs, and GCTs. Because of the advantages over the line commutated type of converters in performance characteristics and compactness, various applications of the voltage sourced converter based technology have been commissioned. The wide-spread availability of this technology at practical MVA levels was illustrated by numerous references of actual applications given in the introduction to this paper.

As one major example of recent developments, over the past few years the power utilities and the Central Research Institute of Electric Power Industry (CRIEPI) in Japan have been jointly promoting a long-range R&D program subsidized by the Agency of Natural Resources and Energy, a national government organization. One part of this program is to develop a high-power voltage sourced converter system with high reliability and efficiency for dc interconnections between asynchronous ac networks. Three major Japanese manufacturers have also been involved in the project, which encompasses, among other development areas, the main circuit configuration (both electronic and magnetic), the constituent components of the system (such as the semiconductors and the converter transformer), and the control and protection schemes. Three 53 MVA voltage sourced converters have been installed as a three-terminal back-to-back (BTB) system, and are undergoing extensive field testing at the 50/60 Hz Shin-Shinano substation of Tokyo Electric Power Company's (TEPCO) power system [8].

In this section, a description is given on the voltage sourced converter for BTB applications with details of both the 53 MVA prototype converter system and the development of a planned 300 MW converter.

3.2 Equipment Description

3.2.1 300 MW BTB

The ultimate goal at the time of the initiation of this Japan Research Project, executed jointly by research organizations, manufacturers, and utilities, is the commercial application of a 300 MW voltage sourced converter based BTB tie. Figure 3-1 and Table 3-1 show the circuit configuration and basic equipment specifications of the 300 MW BTB, respectively. Active power and reactive power are independently controlled and the rated outputs are 300 MW active power and 100 Mvar reactive power. The converter consists of four 75 MW voltage sourced three-phase bridges (i.e., stages). The GTOs applied are 6 inch wafers rated at 6 kV and 6 kA. The four windings on the ac side of the converter transformer are series-connected so that the converter output can be directly linked to the transmission system, and the delta-connected dc windings are tied to the unit converter of each stage.

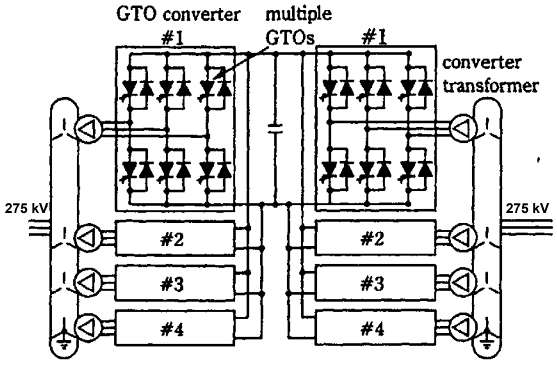


Figure 3-1. System configuration of a 300 MW BTB

Table 3-1. Basic Specification of a 300 MW BTB

Apparent power rating	316 MVA
Active power rating	300 MW
Reactive power rating	100 Mvar
AC output voltage	275 kV
Main circuit configuration	Voltage sourced 3-phase bridge 4-stage connection
Insulation	Air insulated
Semiconductor device	6 kV/6 kA 6-inch GTO
Device connection	4-in-series *x* 1-in-parallel *x* 6-arm *x* 4-stage
Cooling	De-ionized water circulated
Control	9-pulse PWM
Switching frequency	450 Hz (50 Hz system)
Voltage distortion at connection point	Total Below 1%, Each Order Below 0.5%
Transformer Connection	Primary star, Secondary delta *x* 4

3.2.2 53 MVA BTB Prototype

Based on the design criteria confirmed through a significant amount of development and factory testing [27,28,29,30], three 53 MVA GTO based voltage sourced converters and transformers were installed at the Shin-Shinano substation in TEPCO's power system as a prototype BTB link between a 50 Hz/66 kV and a 60 Hz/275 kV system, for verifying the practicability of a high-performance converter. The rating of each converter is 53 MVA (37.5 MW active power and 37.5 Mvar reactive power) so that a 300 MW level BTB can be tested on a 1/8 scale.

The following new technologies were developed for the converter in this effort so that the issues of the higher-power rating of 300 MW level could be solved through both design and tests. These developments, and others, are described in detail in [28,29,30].

1. Series connection of GTO thyristors
2. Gate power supply from main circuit
3. Low loss snubber circuit with regeneration of snubber energy

Figure 3-2 shows the overall configuration of the 53 MVA BTB system. It consists of three-terminals, with one converter on the 60 Hz side and two converters on the 50 Hz side. Therefore, the system can be tested as a two-terminal or three-terminal BTB. The dc circuits of the converters are connected to each other and active power is sent or received via this dc link.

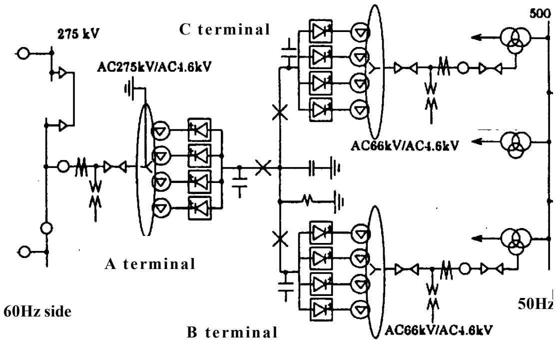


Figure 3-2. System configuration of a three-terminal 53 MVA BTB

The basic electric and magnetic circuit configuration of the voltage sourced converter used at each BTB terminal is illustrated in Figure 3-3, with the key equipment specifications given in Table 3-2. The converter consists of dc circuit components where dc reactors and dc capacitors are mounted; main circuit components where GTO modules are installed; and ac circuit components where ac bus bars are fitted. The main circuit components are aligned vertically with phase-W, phase-V and phase-U modules from bottom to top, and the regenerative snubber circuit is placed on the phase-U module. The arrangement of these modules is done in very close proximity to minimize the stray inductance.

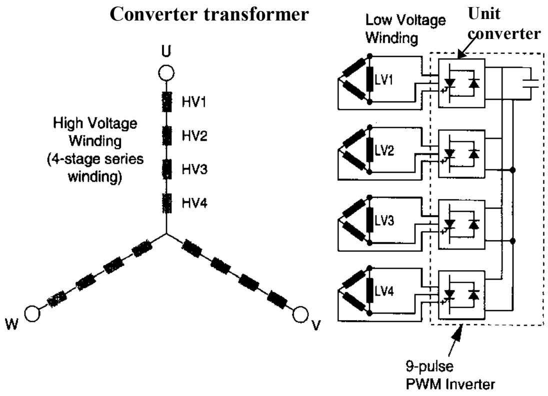


Figure 3-3. Electronic and magnetic circuit configuration of the 53 MVA converter

Table 3-2. Specifications of 53 MVA BTB

Apparent power rating	53 MVA
Active power rating	37.5 MW
Reactive power rating	37.5 Mvar
AC output voltage	4.623 kV
Rated dc voltage	10.6 kV
Main circuit configuration	Voltage sourced 3-phase bridge 4-stage connection
Insulation	Air insulated
Semiconductor device	6 kV/6 kA 6-inch GTO
Device connection	4-in-series *x* 1-in-parallel *x* 6-arm *x* 4-stage
Cooling	De-ionized water circulated
Control	9-pulse PWM
Switching frequency	450 Hz (50 Hz system) 540 Hz (60 Hz system)

The converter consists of four three-phase bridge unit converters (i.e., stages) and are connected through a line-side-series-connected multi-stage converter transformer for proper build-up of the magnitude and phase of the voltage. The arm circuit configuration is shown in Figure 3-4. The GTO thyristors are 6-inch, 6 kV, and 6 kA. Four GTOs are connected in series in one arm of the three-phase bridge. The unit converter is pulse-width modulated (PWM) using a 9-pulse order. This has an advantage that for close-in transmission line faults, the converter can continue operation even during the fault period.

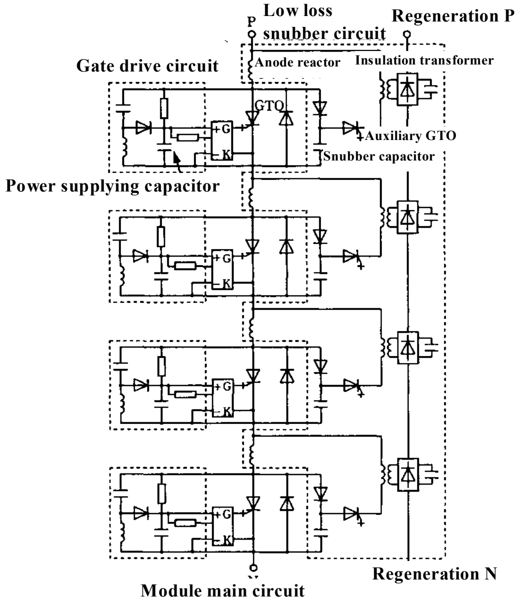


Figure 3-4. Arm circuit configuration

Table 3-3 gives the principal specifications of the converter transformer. The transformer has been designed as a test version of a future 300 MW converter transformer [29]. To make the excitation characteristic of the transformer identical on each stage, the main core is designed as common to all the unit transformers, and gap cores are inserted to withhold circulating currents among the low voltage windings. The winding configuration and the core structure are illustrated in Figure 3-5.

Table 3-3. Specifications of the Converter Transformer

Rated capacity	53 MVA
Rated primary voltage	66 kV (16.5 kV *x* 4 stages)
Rated secondary voltage	4.623 kV (4 stages in parallel)
Winding connection	Primary Star connection 4 stages in series Secondary Delta connection 4 stages in parallel
Short-circuit impedance	20%

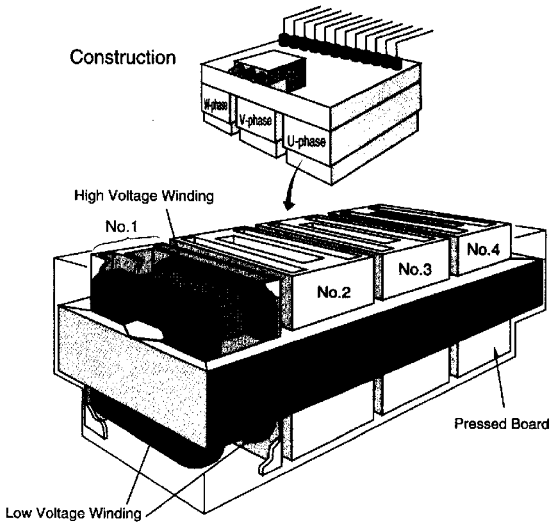


Figure 3-5. Structure of the converter transformer for a 53 MVA BTB

As for the control system, some very interesting development and test results showing the operational flexibility of the BTB described here are contained in [27,30].

3.3 Summary

A prototype of a 53 MVA voltage sourced converter system for a high performance dc (asynchronous) interconnection system was described. Three 53 MVA prototype designs of voltage sourced converters were installed as part of a three-terminal back-to-back system, and extensive field testing for this system has been undertaken. The test results indicate that the technology developed for a high-power voltage sourced converter has been successful and the system performance characteristics satisfy the development program expectations with respect to advancing the goal of achieving commercial viability for back-to-back voltage source converter based dc ties up to 300 MW.

4. DISTRIBUTION STATCOM FOR CUSTOM POWER APPLICATIONS

4.1 System Requirements

The development efforts of advanced static compensation technology at the power delivery level have resulted in a distribution STATCOM (D-STATCOM) that exhibits high speed control of reactive power to provide voltage stabilization, flicker suppression, and other types of system control. The D-STATCOM utilizes a design consisting of a GTO- or IGBT-based voltage sourced converter connected to the power system via a multi-stage converter transformer.

The compact design has resulted in a size ratio improvement to nearly 1/3 the area and 1/5 the volume of a conventional dynamic compensation device, namely, a distribution level SVC. This enables greater flexibility in terms of installation possibilities, and also provides a potential means to easily move the device to various locations around the power system.

The following sections describe some equipment and control aspects of the D-STATCOM, along with an application example.

4.2 Equipment and Control Description

The basic configuration and equivalent circuit of the D-STATCOM are similar to that for a transmission level STATCOM shown in Figure 2-2 and described in Section 2. The principal operation modes of the D-STATCOM output current, I, which varies depending upon the STATCOM internal voltage, Vi, are the same as illustrated in Figure 2-3.

Figure 4-1 shows the main circuit configuration of a 20 Mvar D-STATCOM, which consists of a GTO converter and multi-stage transformer [24].

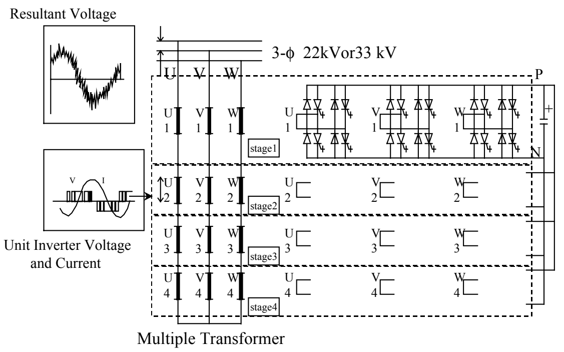


Figure 4-1. Main circuit configuration for a 20 Mvar D-STATCOM

A typical control circuit of the D-STATCOM is shown in Figure 4-2. The three-phase load currents to be compensated (iLa, iLb, and iLc shown in Figure 4-2) are measured from the system and transformed to two-phase orthogonal components (ip and iq) on rotating coordinates synchronized with the line voltage. The outputs of the filter circuit are inversely transformed to three-phase components (isa, isb, and isc shown in Figure 4-2). The output current of the D-STATCOM is controlled by three-phase current feedback control using isa, isb, and isc as reference signals for each phase. The output signals of the current control added by a sensed system voltage signal becomes the voltage reference signal of the PWM control. The PWM control circuit generates the firing signal of the GTO by comparing triangular wave carrier signals to the voltage reference signal.

The ratings of the GTO-based converter for a 20 Mvar unit are shown below in Table 4-1.

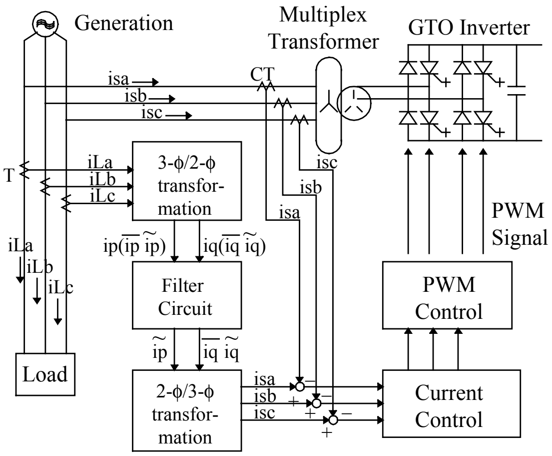


Figure 4-2. Control circuit configuration of a D-STATCOM

Table 4-1. Ratings of GTO Converter for 20 Mvar D-STATCOM

Rated Capacity	20 MVA
DC Voltage	2500 V
Output Voltage	1250 V
Output Current	1500 A
Switching Frequency	5 Pulse PWM 300 Hz (60 Hz System)

4.3 Application Example for Flicker Compensation

For weak distribution systems where the operation of arc furnaces causes significant power quality problems, a high performance flicker compensation device is necessary. As a solution to this particular power quality need, the D-STATCOM has been applied for a number of situations and has provided excellent performance for arc furnace flicker suppression [21,26]. Figure 4-3 shows the system configuration for a flicker compensation installation.

The flicker caused by the arc furnace operation was measured by use of a flicker meter. The output of the meter was Δ10, and was used as an indicating factor of voltage flicker. The voltage deviation of the meter from the reference value is calculated for each cycle. It is then filtered by a human eye sensitivity curve and integrated for one minute to output a value for Δ10.

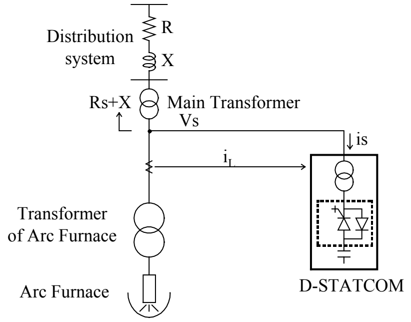
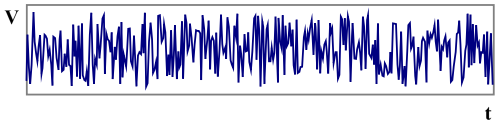


Figure 4-3. System configuration for arc furnace flicker compensation application

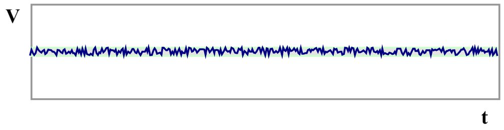
Table 4-2 shows the maximum values and the improvement ratio for operation of the D-STATCOM to compensate the flicker. In this application, the flicker suppression realized was 58% on average with utilization of the D-STATCOM. In this case, the capacity of the D-STATCOM was 21% of the maximum reactive power generated from the arc furnace. The measured results clearly indicate the high performance achieved by the D-STATCOM for flicker suppression. This improvement is also illustrated in Figure 4-4.

Table 4-2. Evaluation of D-STATCOM Arc Furnace Flicker Compensation Installation

No. of 4th Maximum	Δ10 (w/out D-STAT)	Δ10 (w/ D-STAT)	Improvement Ratio
1	1.30	0.58	55.1%
2	1.12	0.47	58.3%
3	1.09	0.42	61.7%



(a) Without D-STATCOM



(b) With D-STATCOM

Figure 4-4. Voltage flicker without (top) and with (bottom) a D-STATCOM on the same voltage scale

5. SOLID-STATE TRANSFER SWITCH FOR CUSTOM POWER APPLICATIONS

5.1 System Requirements

The successful operation of a solid-state transfer switch (SSTS) results in a seamless transfer of electrical energy from a primary supply to a secondary supply without service interruption to even the most critical and sensitive loads. As a result, system power quality problems become transparent to the critical or sensitive customer loads that the switch protects. However, a thyristor, which is the basis of the solid-state transfer switch, is not a pure conductor and this raises some issues in terms of losses and cooling. In a conventional solid-state transfer switch, line current flows in the thyristors continuously, causing a great deal of loss and element heating during normal operation. As a result, relatively large cooling equipment is required, which imposes additional operating costs on the user to maintain proper cooling. It also results in reduced efficiency and lower reliability in the device.

This section describes a unique approach to the design of a solid-state transfer switch using a combination of a thyristor switch in parallel with a vacuum switch. The equipment and operational aspects of this hybrid approach are discussed along with an application example.

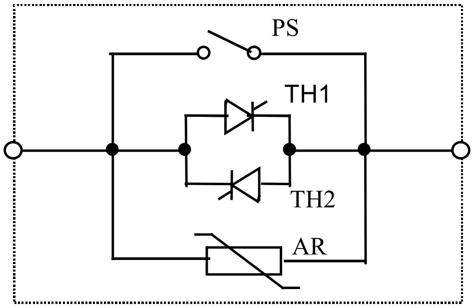
5.2 Equipment Description

During normal operation for a hybrid switch consisting of parallel thyristor and vacuum elements, the line current is carried by the parallel vacuum switch and the thyristor does not conduct any current. When an opening operation is required, the parallel vacuum switch is opened and the thyristor is turned on, simultaneously. Consequently, the current is commutated to the thyristor immediately and subsequently blocked by the thyristor at the first zero crossing of the current. Thus, the resultant operating losses of the device are negligible, since the thyristor conducts only during the few milliseconds of a transfer operation. The parallel vacuum switch opening time of less than 1 millisecond secures the same operational characteristics of a switching device consisting of thyristors alone. This characteristic enables the hybrid switch to be applied to a solid-state transfer switching scheme.

The following breakthroughs were made during the development of this device:

1. Development of a driving scheme for the parallel vacuum switch
2. Realization of fast current commutation from the parallel vacuum switch to the thyristors
3. Compact design using 12 kV, 1.5 kA thyristors

A circuit diagram of the hybrid switch is shown in Figure 5-1 and the ratings of the switch are given in Table 5-1. As noted in general above but now referring to Figure 5-1, during normal operation the line current is carried by the parallel vacuum switch (PS) and the thyristor (TH) does not conduct the current. When an opening operation is required, PS is opened and TH is turned on, simultaneously. Consequently, the current is commutated to TH immediately and blocked by TH at the first zero crossing of the current. Figure 5-2 further illustrates this basic scheme of the opening operation of the switch.



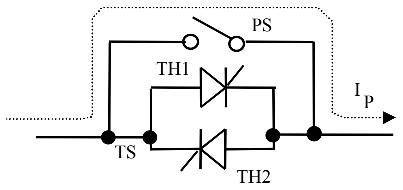
PS: Parallel vacuum switch
TH1, TH2: Thyristor Switch
AR: Zinc Oxide Surge Arrester

Figure 5-1. Circuit diagram of hybrid switch

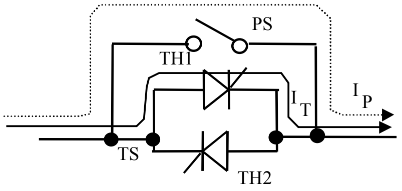
Table 5-1. Ratings of Hybrid Switch

Rated Voltage	15 kV
Rated Current	600 A / 1,200 A
Interrupting Current	12.5 kA / 25 kA
BIL	95 kV
Cooling Method	Natural Cooling

(a) Period A



(b) Period B



(c) Period C

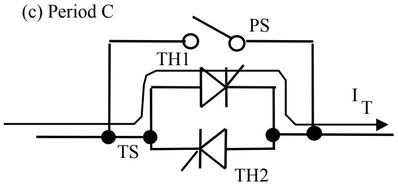


Figure 5-2. Current distribution between PS and TS

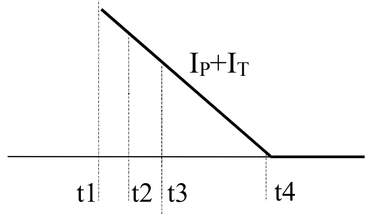
Referring to Figure 5-3, the overall opening time consists of the following parameters and timing sequences:

1. Detection time, t1, of a system disturbance
2. Opening time, t2, of the parallel vacuum switch
3. Commutation time, t3, from the parallel vacuum switch (PS) to the thyristor (TH1)
4. Thyristor blocking time, t4

In Figure 5-3, t2 and t3 are the key parameters associated with the hybrid switch. The times t2 and t3 are required to be as short as possible to achieve the high-speed opening characteristics. Time t2 depends on the opening characteristics of the parallel vacuum switch itself, and t3 is dependent upon the commutation circuit characteristics.

Figure 5-4 shows the basic structure of the parallel vacuum switch. The opening and closing drive mechanism consists of opening and closing coils, a repulsion plate, and a spring mechanism. For achieving high-speed opening operation, a pulse current is initially supplied to the opening coil, and the vacuum interrupter is driven by the magnetic repulsion force with the assistance of the spring mechanism. The difficult aspect in obtaining successful operation is to hold the contacts at the appropriate position. A newly developed spring mechanism provides the solution. This mechanism consists of two coned springs. The two-spring scheme generates the contact holding force and keeps the contact at an appropriate position without a latching mechanism. Figure 5-5 shows a characteristic of the opening operation of the parallel vacuum switch, showing that the opening time is 0.6 ms after the start of conduction of the pulse current.

(a) Total current (I_P+I_T)



(b) Individual current (I_P, I_T)

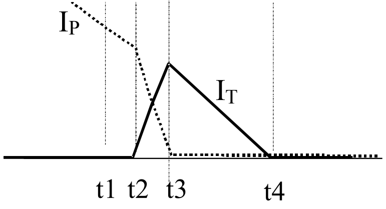


Figure 5-3. Current waveforms in PS and TS branches

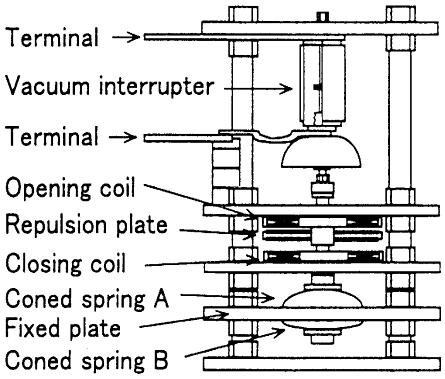


Figure 5-4. Basic structure of the parallel vacuum switch

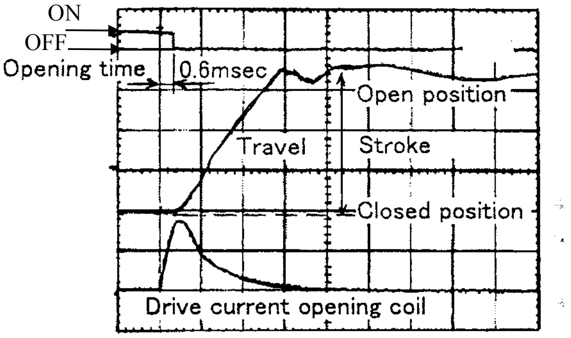
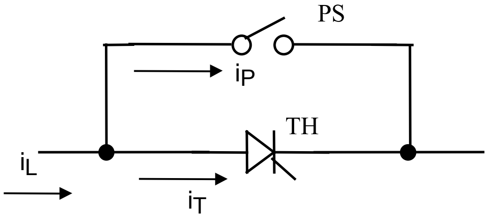


Figure 5-5. Opening characteristics of parallel vacuum switch

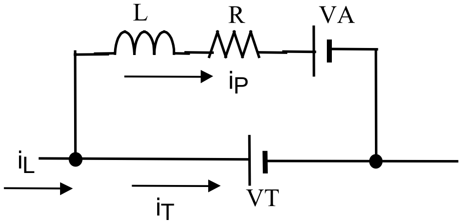
Figure 5-6 shows an equivalent circuit for analyzing the current commutation characteristics when opening the switch. Under normal conditions, the line current, i_L, flows in the parallel vacuum switch (PS). When the contact of the parallel vacuum switch is opened, an arc voltage (VA) is generated across the contacts, which initiates the commutation from PS to thyristor (TH). As shown in Figure 5-6, the commutation time significantly depends on the following parameters:

1. Inductance of the commutation circuit
2. Forward voltage drop characteristics of the thyristor

To reduce the commutation inductance and voltage drop in the thyristor string, the following considerations were taken into account for the hybrid switch design:



(a) Circuit diagram of commutation



(b) Equivalent circuit for analysis

i_L : Line Current
i_T : Thyristor Current
i_P : PS Current
V_A : Arc Voltage
V_T : Thyristor Forward Voltage Drop

Figure 5-6. Equivalent circuit of current commutation from parallel vacuum switch to thyristor

1. Thyristors: The rating of the thyristors are 12 kV, 1.5 kA using a 5-inch wafer. This results in the smallest number of series connected thyristors, which enables a smaller forward voltage drop in the string and a compact arrangement for the lower commutation inductance.
2. Switch hardware: The thyristors and the parallel vacuum switch are arranged very closely for the lower inductance. The switch hardware is contained in an air-sealed container immersed in SF6 gas, which results in a compact and contamination-free design.

Based on the incorporation of the hybrid switch and the elimination of cooling equipment, an extremely compact, lightweight, and highly reliable solid-state transfer switch is realized. This switch can be applied in situations such as the one described in the next section.

5.3 Application Example

Figure 5-7 shows a typical configuration for a SSTS application, in which the transferring of load between two separate sources is performed. In Figure 5-7, Feeder 1 is referred to as the primary or preferred source with associated switch AHTS1 supplying the sensitive load, and Feeder 2 is the alternate source with associated switch AHTS2.

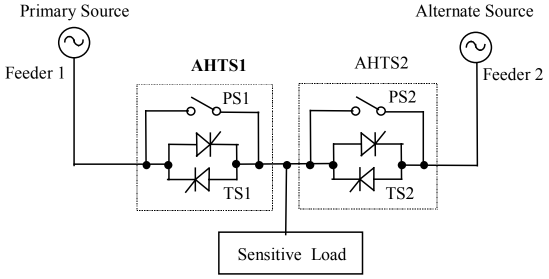


Figure 5-7. Application of an SSTS

During normal operation, AHTS1 is in the on-state, and AHTS2 is in the off-state. In AHTS1, the parallel vacuum switch PS1 is closed and the load current is conducted through PS1 by by-passing TS1, which results in an overall near lossless design.

Upon sensing a failure from the preferred source of Feeder 1, the control circuit signals the parallel vacuum switch PS1 to open, which simultaneously triggers thyristor switch TS1 to turn-on. Parallel vacuum switch PS1 then breaks the bypass circuit and transfers the load current into thyristor switch TS1. After completing the current commutation to TS1, the gate triggering signal is terminated and TS1 is turned off when the current in TS1 reaches the first zero-crossing. The thyristor switch AHTS2 (TS2) is then triggered, conducting the load current from the alternate source. Parallel vacuum switch PS2 is then closed to complete the transfer from the primary source to the alternate source. The entire transfer is completed in approximately 1/4 cycles (4 milliseconds).

Figure 5-8 shows the resulting waveforms of the two sources and the load voltages for the transfer switching operation test. The test was performed using an converter as a sensitive load, which is one of the most vulnerable loads with respect to voltage sag conditions. Without the SSTS, the converter operation comes to a halt 25 milliseconds after a 50% instantaneous voltage drop of approximately 6 cycles. However, with the SSTS, the preferred power source is transferred to the alternate source immediately, resulting in the continuous supply of quality power and maintaining operation of the sensitive converter load.

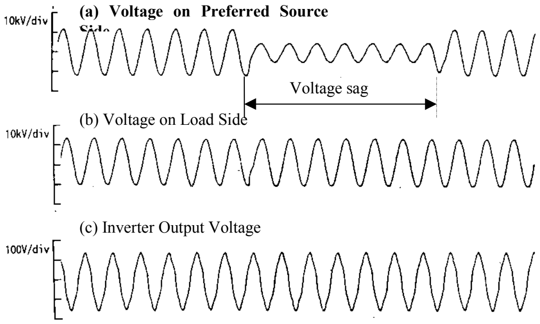


Figure 5-8. Voltage waveforms for SSTS operation

6. SUMMARY AND CONCLUSIONS

Power systems are being operated closer than ever to their operating limits. With the increased burden on the use of the transmission system and the heightened requirements on the quality of power delivered, the application of power electronic based equipment, such as FACTS, HVDC, and Custom Power is being increased. This paper described the details of four such applications, summarized as follows.

STATCOM For Transmission System Applications: For over three decades, conventional Static Var Compensators (SVC), have been successfully applied for various types of dynamic reactive power compensation. The rapid advancements of power semiconductor devices and enhanced control technologies have enabled the development of controllable shunt reactive compensation devices with a more rapid response capability and better performance characteristics than the conventional SVC. Specifically, the STATCOM, which is designed with self-commutated converter technology, has become widely accepted for reactive power compensation applications based on its performance and physical advantages over SVC technology. This paper described some of the system performance benefits available with the application of STATCOM technology.

Voltage Sourced Converter For Back-To-Back DC Power Transfer: A dc link using voltage sourced converter technology has been shown to provide an advanced dc interconnection system based on its wide ranging and flexible performance characteristics. A national technical project initiated in Japan to develop a high-power voltage sourced converter system for dc interconnections between ac systems was described. The development efforts required to solve numerous issues have been completed and verified. Three prototype designs of 53 MVA GTO-based converters were manufactured and applied to form a three-terminal BTB system at the Shin-Shinano substation of Tokyo Electric Power Company's power system. Field testing has been carried out and satisfactory test results have been obtained. The goal of this development work was to achieve commercial viability for voltage sourced converter based back-to-back dc (asynchronous) ties up to 300 MW. This overall project has achieved the necessary technical advancements.

D-STATCOM For Custom Power Applications: The D-STATCOM has been developed and incorporates a voltage sourced converter connected to the power system via a multi-stage converter transformer. The device is nearly 1/3 the area and 1/5 the volume of a conventional SVC. Operation of the D-STATCOM provides an advanced, high-speed control technology for reactive power compensation to provide flicker suppression, voltage stabilization, power factor control, and other power quality mitigation measures for distribution system improvement.

SSTS For Custom Power Applications: A novel switching device using a hybrid system of a parallel vacuum switch and a thyristor switch, and the application of this approach to the SSTS system were described. The operating characteristics of the device were exhibited in the test results presented. The advanced hybrid switching device is an effective means in solving power quality issues for power distribution networks.

In conclusion, in the new and evolving deregulated utility environment, financial and market forces will demand a more optimal and profitable operation of the power system with respect to generation, transmission, and distribution. Now, more than ever, advanced technologies are paramount for the reliable and secure operation of power systems. This paper has shown why power electronic based equipment, such as FACTS, dc ties for back-to-back power transfer, and Custom Power technologies constitute some of the most-promising technical advancements to address the new operating challenges being presented today.

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