Power System Technologies for Reliable Supply of Electric Power and Wide-area Grids

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OVERVIEW: A renewable energy feed-in tariff took effect in Japan in July 2012, and is expected to accelerate the adoption of photovoltaic power generation and other forms of renewable energy. Due to restrictions in the building of photovoltaic and wind power plants, there are expected to be increasing numbers of cases where such plants are built in remote locations far from the places where large amounts of energy are consumed, both in Japan and internationally. For this reason, problems related to the stabilization of power grids between energy production and consumption locations may grow serious. To deal with this situation, Hitachi is working towards the realization of power supply stabilization and wide-area interconnection by pursuing efforts in power system stabilizers, SVCs, energy storage systems, high voltage DC transmission systems, and other power grid technologies.

INTRODUCTION

AS electric power systems are reinvented around the world, the use of renewable energy is expanding at a rapid pace. Although the objectives of energy policies differ from country to country, the presence of renewable energy grows on a daily basis, with approximately half of the power generation capacity added in 2011 being from power generation equipment for use in generating renewable energy(1). Photovoltaic power generation, wind power generation, and other forms of renewable energy are gaining traction in Japan as well, with measures such as a renewable energy feed-in tariff being implemented with the goal of realizing a low-carbon society.

Photovoltaic and wind power generation is affected by weather-induced changes in output, lightning strikes, and other disturbances that can trip the entire system. In order to secure high-quality electric power, it is necessary to be able to adjust voltage and frequency and take measures to maintain the stability of the power grid. Furthermore, if the power generation equipment for photovoltaic or wind power generation is built offshore or in a vast isolated area far from cities and other energy load centers, power system stabilization measures will be necessary for the transmission, distribution, and power grid systems used to transmit electricity to the energy load centers.

By integrating transmission and distribution systems and information and communication technology (ICT), Hitachi aims to achieve strong grids that offer optimized control and strength in a power grid, as well as smart grids that offer expanded consumer services (see Fig. 1).

This article describes Hitachi's efforts in contributing to power grid stabilization through the use of strong grid technology and smart grid technology.

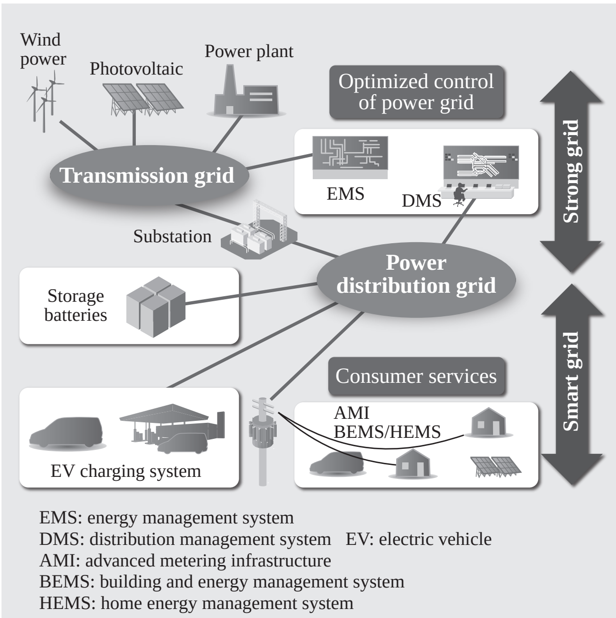


Fig. 1—Overview of Strong and Smart Grids.
An overview of a strong grid, which provides optimized control and strengthening of a power grid using renewable energy, and a smart grid, which provides expanded consumer services.

SYSTEM TECHNOLOGIES FOR IMPLEMENTING STRONG AND SMART GRIDS

Power System Stabilization Systems

When a transmission line is hit by lightning, or when some other fault occurs in a power grid, a loss of voltage can cause a momentary reduction in the amount of electric power transmitted, and a power swing will occur after the fault is eliminated. This phenomenon is called "power grid transient stability." If there is a large swing, the disturbance can spread throughout the entire grid, resulting in a major power outage. The transmission lines of a power grid are required to operate within the operational limitations, and the operational limitations caused by transient stability are particularly dominant when it comes to large, long-distance electric power transmission grids. To deal with this problem, power system stabilizers can rapidly and optimally shed (isolate) generators from the grid, thereby removing the operational limitations caused by transient stability and drastically improving the total tranasfer capability (TTC).

An "online transient stability control" (online TSC) system has been put into practical use as a typical power system stabilizer. This online TSC system is a grid stability system that combines ICT with advanced reliability evaluation that is made possible with calculations based on information such as the power flow and bus voltage(2) derived from the power system. The online TSC consists of a central-TSC and several remote-TSCs. The central-TSC system incorporates power grid data, calculating detailed transient stability in advance by envisioning large numbers of grid faults (contingency cases) such as lightning strikes. For the contingency cases that would cause the grid to become unstable, the system determines which stabilization countermeasures to take (generator shedding, etc.), and communicates this information to the remote-TSCs installed at the substation. If a grid fault actually occurs, the stabilization control is quickly applied by the remote-TSC. The system performs the optimized measures for various network faults autonomously. Also, since the TTC can be boosted during ordinary operation as well, this provides greater flexibility in running generators, making highly economical operation possible.

Another problem facing large, long-distance electric power transmission grids is that when a fault occurs in the power grid, countermeasures must be taken at the same time to deal with both voltage and frequency, while also dealing with the transient stability issue. The integrated stability control system (ISC) integrated power system stabilizer was developed to solve this problem by adding the ability to simultaneously deal with transient stability, voltage, and frequency to an online TSC system(3).

The ISC system uses the following functions to carry out transient stability and voltage fluctuation countermeasures when a fault occurs that causes no network splitting:

(1) Generator shedding to maintain transient stability when a grid fault occurs

(2) Additional generator shedding to prevent a reduction in transient voltage

(3) Reactive power control with shunt compensators to prevent voltage fluctuations after generator shedding

Transient stability countermeasures are performed using these functions after a fault occurs, making it possible to stabilize the voltage within the target range.

What follows is a description of the processing that occurs in a master station system using an ISC system to implement the aforementioned functions (see Fig. 2).

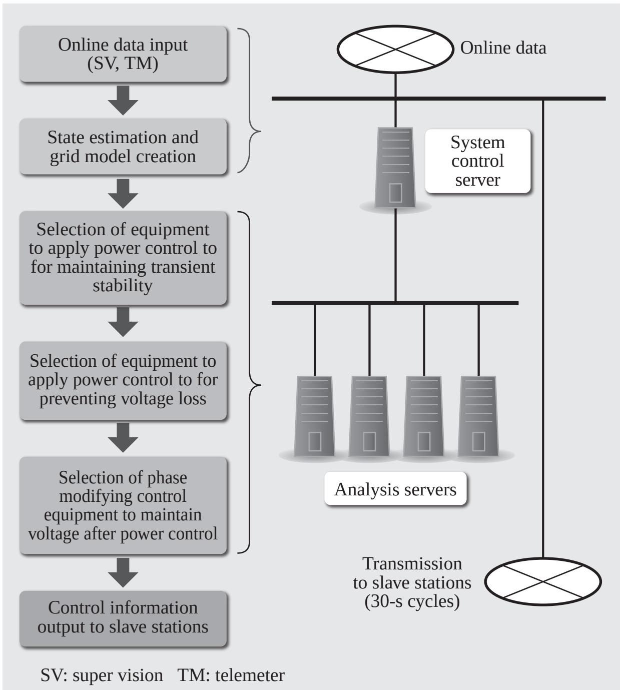


Fig. 2—System Configuration and Processing Flow of ISC Master Station System Delivered to Chubu Electric Power Co., Inc.
At the integrated stability control (ISC) system's master station, online data is loaded and approximately 100 grid failure scenarios are considered in order to calculate stability as well as to execute stabilization countermeasures in areas such as transient stability and voltage. The results of these countermeasures are sent to the slave stations in 30-s cycles. The stability calculations and countermeasure processing require the capabilities of multiple high-speed blade servers computing in parallel.

The system control server performs state estimation using the online data derived from the power grid to obtain a consistent grid model. Next, the analysis server runs detailed stability simulations concerning around 100 different possible grid fault scenarios, in order to select the optimal equipment to use for applying stabilization control. Finally, stabilization control information for each envisioned fault is sent to the slave stations. Power system stabilization is performed based on this information when an actual fault occurs.

In the future, many renewable energy sources such as photovoltaic and wind power generation will be connected to the grid. However, stability control systems with predefined parameters will have difficulty handling such a grid because of its many unpredictable factors. Online TSC systems and ISC systems, in contrast, can minimize these factors because these systems analyze the network stability with realtime data derived from the power network. Also, the power grid must be stabilized in an even smarter fashion based on the installation to the power grid of static var compensators (SVCs), storage batteries, and other such equipment.

SVCs

An SVC is a system that uses power electronics equipment to control reactive power at high speed. Although there are a number of different types of SVCs, thyristor controlled reactors (TCR) and static synchronous compensators (STATCOM) are typical.

A TCR controls the on and off periods of thyristors connected in an reverse-parallel fashion, and changes the average strength of the flowing current in order to control phase lagging reactive power (see Fig. 3).

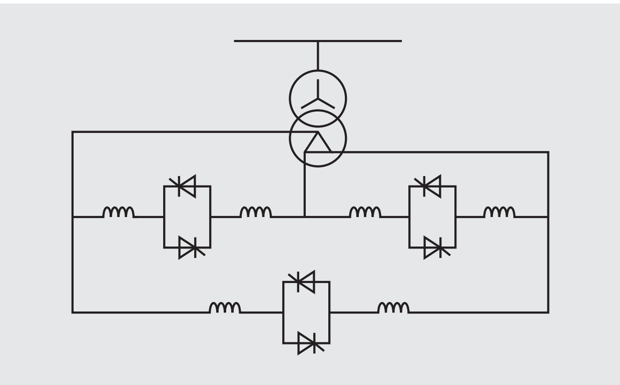


Fig. 3—Schematic of TCR Circuit.
By controlling thyristors, a thyristor controlled reactor (TCR) changes the average strength of current flowing in a reactor, thereby controlling phase lagging reactive power.

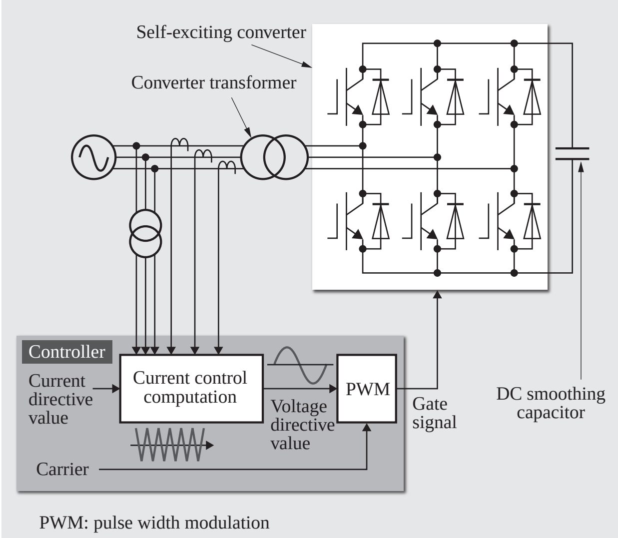


Fig. 4—Schematic of STATCOM Circuit.
A static synchronous compensator (STATCOM) is a system that uses self-commutated conversion equipment comprised of insulated-gate bipolar transistors (IGBTs) and other semiconductor devices to control reactive power at high speed.

Phase advanced reactive power is also controllable by combining with electric power capacitors.

A STATCOM is a device that controls phase advanced and phase lagging reactive power at high speed through the amplitude and phase of voltage outputted by a self-commutated converter that is comprised of insulated-gate bipolar transistors (IGBT) and other self-turn-off semiconductor devices (see Fig. 4).

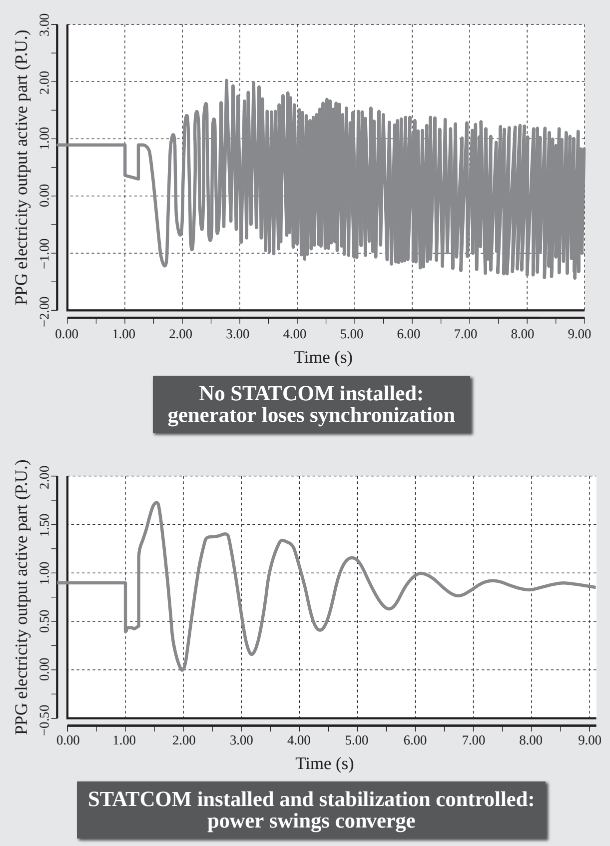
Since voltage can also be controlled by controlling reactive power, SVCs play an active role in suppressing the voltage fluctuations that occur when the output of renewable energy fluctuates due to changes in the amount of sunshine or wind conditions, or when load changes rapidly in an electric furnace. The degree to which the power grid can operate in a stable manner without large voltage drops in response to tripped generators or transmission lines, or sudden increases in load, is referred to as “voltage stability.” An SVC is a device that can contribute to improvements in voltage stability.

In addition to voltage stability, a power grid is also characterized in terms of “synchronization stability.” Synchronization stability refers to the degree to which the power grid can continue to operate by recovering to a stable state without loss of synchronization in a running synchronous generator after transmission line failures or other disturbances occur in the power grid. Since synchronization stability is mainly related to active power, and SVCs only control reactive power, one might assume that an SVC would be unnecessary. However, active power between two points is related to voltage amplitude, and so by controlling voltage with an SVC, it is also possible to control active power. Therefore, SVCs also provide an effective means of improving synchronization stability. Fig. 5 shows waveforms in an example simulation of the use of a STATCOM to improve synchronization stability. In this example, a generator loses synchronization due to a grid failure with no STATCOM installed. A STATCOM is then installed on the grid and provides suitable control, enabling stable operation.

Hitachi has an extensive track record in manufacturing SVCs. Typical examples are shown in Table 1. The TCRs delivered to the Noshiro Thermal Power Station owned by Tohoku Electric Power Co., Inc. are mainly aimed at providing both voltage fluctuation, suppression and power swing suppression, but also contribute to improvements in synchronization stability[4].

The STATCOM delivered to the Hokuriku Electric Power Company's Fushiki Substation features flicker countermeasures. When there is massive load fluctuation, as can occur with an arc furnace, electric lamps and other devices can flicker due to voltage fluctuation. The main purpose of the Fushiki Substation's STATCOM is to suppress this flicker[5].

Overseas, Hitachi delivered a power distribution grid STATCOM in 2011 to the major British power distribution companies Western Power Distribution (South West) plc and Western Power Distribution (South Wales) plc (WPD). This STATCOM is being used by the smart grid demonstration experiment carried out by WPD as a part of the low-carbon network projects promoted by the UK's energy regulator. The main purpose of this STATCOM is to suppress the voltage changes caused by renewable energy, which is known for its instability, thereby continuously providing the power grid with stable electric power. As a future step, there are plans to add three similar STATCOMs in a test of a distribution grid voltage control system.



PPG: pulse pattern generator

Fig. 5—Improving Synchronization Stability with STATCOM.
This simulation example shows how grid operations can be made stable by installing a STATCOM for appropriate control.

TABLE 1. Examples of Major SVCs Manufactured by Hitachi
This table shows the rated capacity and major purpose behind the TCR delivered to the Noshiro Thermal Power Station owned by Tohoku Electric Power Co., Inc. and the STATCOM delivered to the Fushiki Substation owned by the Hokuriku Electric Power Company.

	Rated capacity	System	Year delivered	Major purpose
Noshiro Thermal Power Station	100 MVA	TCR	1994	Power swing suppression
Fushiki Substation	20 MVA	STATCOM	2006	Flicker suppression

Energy Storage Systems

Hitachi provides energy storage systems as energy storage solutions for a wide range of purposes, such as peak-shifting of electric power, and power system stabilization for when wind or photovoltaic power generation is introduced. Electric power utilities stipulate grid interconnection requirements for power fluctuation levels separately in order to stabilize the power system when large amounts of renewable energy are introduced. Energy storage systems are provided as power fluctuation alleviation solutions to meet these requirements, and are comprised of lead-acid batteries with an expected life of 17 years (LL1500-W model), power conditioning systems (PCS), and the control equipment necessary to operate the systems in an optimal fashion. This control equipment monitors the state of power fluctuation of renewable energy, as well as the charging state of storage batteries, and directs storage batteries to charge or discharge in order to alleviate power fluctuations. The PCS converts the DC electric power to AC, and AC to DC. For wind farm projects, it is important to choose an adequate battery capacity in terms of cost. In one example, Hitachi developed an energy storage system for the Shiura Wind Farm owned by Kuroshio Wind Power Plant Inc., which began operations in February 2010 (commercialized by Hitachi Engineering & Services Co., Ltd., Goshogawara City, Aomori Prefecture). For this project Hitachi determined the minimum battery capacity needed to satisfy the grid code requirements by analyzing the fluctuation characteristics of the total generation output of the wind farm[6](see Fig. 6).

As an example of Hitachi's power system stabilization solutions including energy storage systems being deployed overseas, the New Energy and Industrial Technology Development Organization (NEDO) has commissioned the Japan-U.S. Collaborative Smart Grid Project in Los Alamos, New Mexico, USA, which includes a LL1500-W model lead-acid battery system, a 500-kVA PCS for storage batteries, a 500-kVA PCS for photovoltaic power generation, and amorphous transformers. The PCS is a hybrid type that includes two circuits of DC/DC converters that can be connected to storage batteries and photovoltaic cells. This demonstration project involves the construction

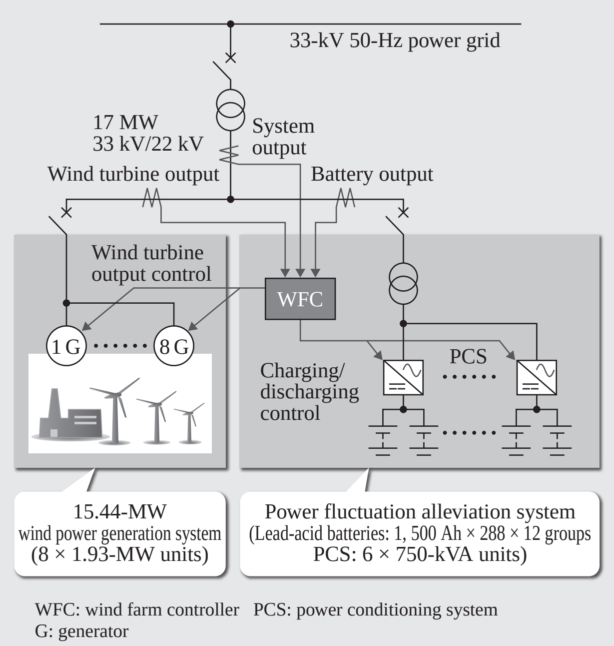


Fig. 6—Shiura Wind Farm System Configuration.
The Shiura plant is a large wind power plant comprised of long-lived lead-acid batteries, PCS, and control equipment as a solution to alleviate power fluctuations.

Fig. 7—Lead-acid Battery System Installed in Los Alamos County, New Mexico, USA.
The lead-acid battery system installed in a Japan-U.S. Smart Grid Collaborative Demonstration Project in Los Alamos County, New Mexico.

of a system that is interconnected with the distribution line, and is currently engaging in a demonstration study into the effectiveness of suppressing short-term output fluctuations in photovoltaic power generation through the charging and discharging of lead-acid batteries (see Fig. 7).

With the introduction of renewable energy to remote islands and other isolated grids, the importance of microgrids using energy storage systems is on the rise. The battery system for remote islands stores energy from renewable resources during times of light load, and performs frequency control to minimize the use of diesel engine generators and to reduce the fluctuations caused by use of renewable energy. The Okinawa Electric Power Co., Inc.'s Yonaguni wind power plant is comprised of wind generators (two 600-kW units), diesel generators (generating a total of 2,650 kW), and lead-acid batteries (200 cells at 1,000 Ah each) (commercialized by Hitachi Engineering & Services Co., Ltd.). The results of operation at the Yonaguni wind farm are shown in Fig. 8.

High Voltage DC Transmission System (HVDC)

Europe is considering a concept by which electric power is generated in the deserts of the Middle East and North Africa where natural conditions and installation conditions are ideal, using solar thermal, photovoltaic, and wind power generation and transmitting it to electric power load centers in Europe and elsewhere using a direct current transmission system called a "super grid". High-voltage direct current transmission systems (HVDC) are a key technology for building this super grid.

Japan currently has 2,000 MW of HVDC capacity, 1,200 MW of frequency conversion, and 300 MW of back-to-back (BTB) connections. Hitachi has

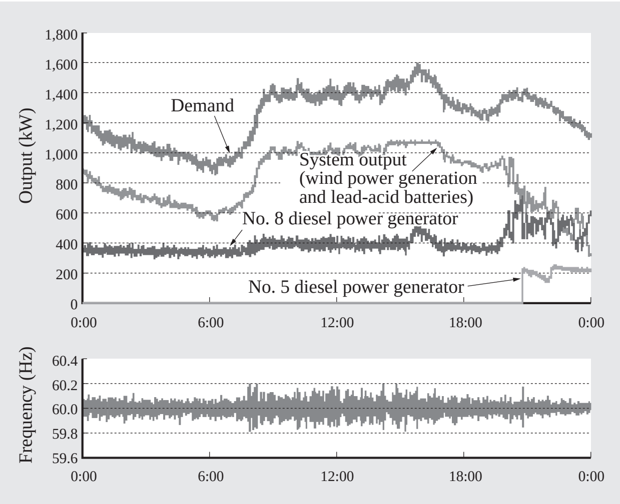


Fig. 8—Results of Yonaguni Wind Farm Operations.
Output and frequency are shown for wind generators, diesel generators, and lead-acid batteries. When wind power generation output decreases, the grid frequency is stabilized through control of system output (wind power generation and lead-acid batteries) based on the charging and discharging of lead-acid batteries, as well as the automatic startup of diesel generators.

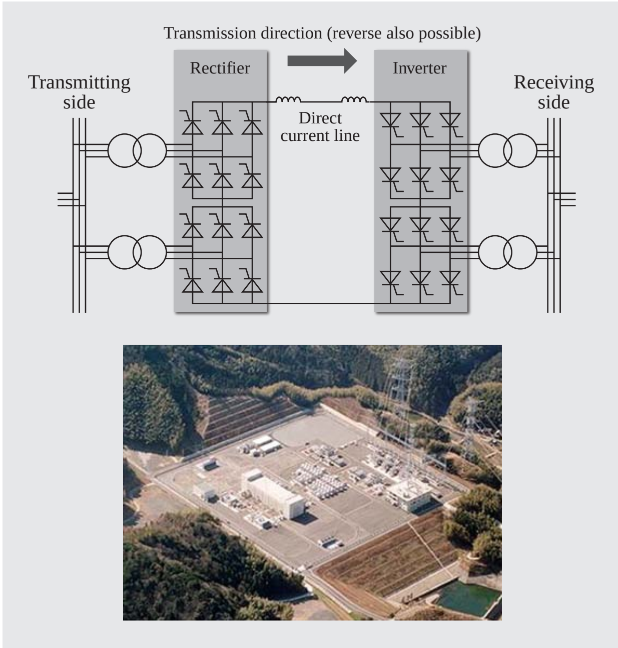


Fig. 9—HVDC Configuration Overview and Kii Channel HVDC Converter Station.
High voltage direct current (HVDC) operational values are DC ±250 kV and 1,400 MW, and some equipment is designed to operate at DC±500 kV and 2,800 MW with future expansion in mind. Note that the configuration overview omits circuit breakers, arresters, grounding switches, filters, and so on.

participated in all these direct current projects. HVDC offers the following three benefits:

(1) Advantageous for cable transmission because the charging current does not flow, and there is no dielectric loss

(2) Advantageous for long-distance transmission because there are no voltage drops due to inductance

(3) Power flow control is possible within the range of system capacity

HVDC is configured to operate with two AC/DC converters, one of which is a rectifier (AC power to DC power), and one of which is an inverter (DC power to AC power), with direct current used to transmit between the two. An overview of an HVDC configuration is shown in Fig. 9, along with the exterior of the Kii-Channel HVDC converter station. The converter is configured with a combination of power semiconductor devices (thyristors, IGBTs, and so on). A single combination unit is referred to as an “arm,” and electric power conversion is performed by moving current from one arm to another (commutation). There are two major types of converters, as described below:

(1) Converters configured with power semiconductor devices (thyristors) that require transit current to be set to zero when they are off (line-commutated)

(2) Converters configured with power semiconductor devices (such as IGBTs) that can be switched on or off at any time (self-commutated)

Recently, there has been growing demand for self-commutated converters. Self-commutated converters can contribute even further to power system stabilization, and development is heading in this direction at present.

As a concrete example of HVDC being used to achieve power system stabilization, Hitachi participated in the development of a Kii-Channel HVDC facility to interconnect Honshu (The Kansai Electric Power Co., Inc.’s Kihoku converter station) and Shikoku (the Shikoku Electric Power Co., Inc.’s Anan converter station). This system has power modulation (PM) functions for the purpose of controlling the suppression of power swings in the alternating current grid.

A brief explanation of the PM system follows[(7)].

When a grid failure or some other disturbance occurs, the power balance is lost between the engine and turbine input of the generators connected to the grid and the output, with power swings caused by fluctuations in the rotation of the generator. The PM correctly controls the HVDC when this happens in order to suppress power swings. An example of a two-unit parallel AC/DC system model is shown in Fig. 10. The DC power transmitted by the HVDC in this figure has had ΔP_{DC} transformed. This is equivalent to

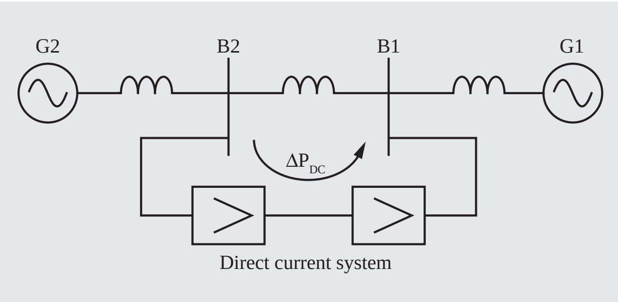


Fig. 10—AC/DC Parallel Two-unit System Model.
This figure shows an example of a two-unit parallel AC/DC system model. Power modulation (PM) suppresses power swings by controlling the HVDC.

sending active power ΔP_{DC} from bus B2 to bus B1. A component of this ΔP_{DC}, determined by the impedance ratio, is drawn from generator G2 and sent to G1. By matching the active power output fluctuation phase given to the generator here with the phase of the angular velocity fluctuation $\Delta\omega$ of the generator, it is possible to make the active power output fluctuations given to the generator act as a damping torque. This damping torque suppresses the generator's angular velocity fluctuation, which in turn suppresses the power swing. To apply this sort of control, it is necessary to detect the generator's $\Delta\omega$ and incorporate it into the HVDC's control system. Although various types of methods have been developed for detecting $\Delta\omega$, the Kii-Channel HVDC uses a method for detecting the grid frequency fluctuation Δf, which fluctuates in the same phase as $\Delta\omega$.

As described above, HVDC is a system that can greatly contribute to the strength of grid stability. In the future, Hitachi plans on taking the knowledge it has accumulated in successfully developing HVDC systems in Japan and participating in direct current transmission projects overseas as well, as the need for this sort of system increases due to the adoption of renewable energy sources.

CONCLUSIONS

This article described Hitachi's efforts in strong and smart grid technologies that can contribute to the stabilization of power grids.

In addition to the technologies described here, Hitachi also participates in a wide range of power grid stabilization projects both in Japan and internationally, and is promoting the development of technologies as well as the construction of systems. Hitachi will continue developing technologies that can contribute to the realization of strong and smart grids worldwide.

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