Hitachi's Adjustable-speed Pumped-storage System Contributing to Prevention of Global Warming

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OVERVIEW: To help prevent global warming, it is anticipated that renewable sources of electric power will provide an increasing proportion of energy needs. Because energy sources such as wind and solar power are dependent on weather conditions, their output can vary widely. Usually, balancing supply and demand for power has been performed by adjusting the generation output in response to varying load, but there is a need to improve the supply and demand balancing functions of existing generation systems to allow the addition of generation capacity produced from renewable energy sources. Hitachi has developed a world-first adjustable-speed pumped-storage generation system that incorporates active-power-based control to provide a power supply and demand balancing function that can operate on time scales from the order of seconds to the order of hours, something that is not possible with conventional systems. It is anticipated that the addition of a large number of adjustable-speed pumped-storage generation systems to the electricity grid will help prevent global warming.

INTRODUCTION

PUMPED-storage power plants were first constructed and operated in the early 1900s as a supply and demand balancing mechanism that worked on a time scale of hours by storing excess power during the night so that it could be supplied back during the daytime demand peak.

The "adjustable-speed pumped-storage generation system" developed by The Kansai Electric Power Co., Inc. and Hitachi incorporates a function (active-power-based control) that can control the power level in both pumping and generation modes with a faster response time than existing pumped-storage power plant systems.

This feature allows the adjustable-speed pumped-storage generation system to share the burden of balancing supply and demand during the night when demand is low that is normally handled mainly by thermal power generation, and this in turn helps shorten the operating time for thermal power generation and reduce CO_2 (carbon dioxide) emissions. The Okawachi Power Plant of The Kansai Electric Power has two adjustable-speed pumped-storage generation systems which were manufactured by Hitachi, have the largest capacity of any such systems in the world, and have been operating reliably for over 15 years.

It is also anticipated that the proportion of the power supply provided by renewable energy sources such as wind and solar power will increase significantly in the future. Incorporating energy sources such as wind and solar power from which it is difficult to obtain a steady power output into the electricity grid will reduce the relative proportion of thermal, hydro, and other conventional power sources and this is likely to make balancing supply and demand even more difficult. This has the potential to become a major impediment to providing a stable electricity supply.

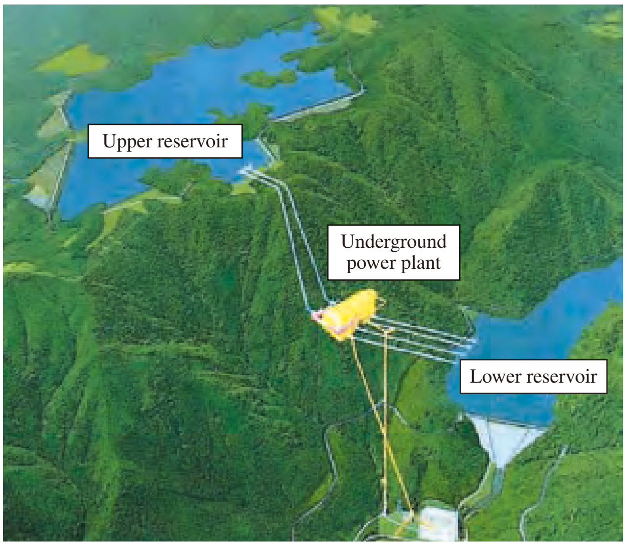

Fig. 1—Bird's-eye View of Okawachi Power Plant of The Kansai Electric Power Co., Inc.
The site consists of upper and lower reservoirs along with a power plant that was constructed underground to minimize the environmental impact.

The power level of adjustable-speed pumped-storage generation systems can change rapidly and this high-speed adjustment capability can help provide a stable supply of electricity even in electricity grids that incorporate a significant proportion of wind, solar, and other variable power sources.

Pumped-storage power plants require upper and lower reservoirs (dams) and are subject to severe site restrictions to prevent damage to the environment. The issues facing pumped-storage power plants in Japan include a shortage of sites suitable for new construction and that the construction, including earthworks, of a new plant requires a dozen or more years. In response, Hitachi has also been working on developing technology for retrofitting an adjustable-speed capability to existing pumped-storage power plants that are already in operation.

Overseas, because the construction of large hydro power plants involves building large dams, close attention is paid to the impact on the environment. In contrast, because pumped-storage generation systems do not need large dams that obstruct the flow of major rivers because they reuse the water they collect over and over again, and because the power plant can be built underground, the burden on the environment is small and the momentum behind the introduction of adjustable-speed pumped-storage generation systems is growing, particularly in Europe and America where the proportion of renewable energy is continuing to increase. Hitachi has work ongoing on a range of different developments aimed at meeting these needs.

This article describes the background to the development of adjustable-speed pumped-storage generation systems, their technical characteristics, and other related topics.

BACKGROUND TO DEVELOPMENT OF ADJUSTABLE-SPEED PUMPED-STORAGE GENERATION SYSTEMS

The load (demand) on an electricity grid varies continuously depending on a wide range of factors and the adjustments to keep supply and demand in balance are made on the generation (supply) side. If supply and demand get out of balance, variations occur in the frequency, voltage, and other parameters and this may impede the reliable delivery of electricity. Accordingly, the generation output is continuously adjusted in response to the varying load. Power plants can be broadly divided into nuclear, thermal, and hydro power, but only thermal and some hydro power plants can adjust their power output. Most thermal and hydro power plants shut down during the night when electricity demand is low. The higher proportion of nuclear power during this time creates a potential for problems with insufficient supply and demand balancing capacity.

Pumped-storage power plants which work by using excess power at night to pump water to an upper reservoir and then using this to generate electricity when the demand increases during the daytime have been constructed in Japan since the 1930s as a way of balancing supply and demand over time between day and night. However, the characteristics of the pump-turbines and the fact that the synchronous machines used as motor-generators have a constant speed meant that adjustment of the input power during pumping operation was almost never performed.

With the aim of using pumping-mode operation to perform supply and demand balancing during the night, The Kansai Electric Power and Hitachi commenced the development of an adjustable-speed pumped-storage generation system in 1981. Following the commissioning in 1987 of a 17.5-MW demonstration plant that used adjustable-speed generation system at The Kansai Electric Power's Narude Power Plant, two separate adjustable-speed pumped-storage generation systems with a world-largest capacity of 400 MW were commissioned in 1993 and 1995 respectively at The Kansai Electric Power's Okawachi Power Plant, and these have been operating reliably since then (see Fig. 1).

Fig. 2—Assembly of Motor-generator for Omarugawa Power Plant of Kyushu Electric Power Co., Inc.
Scene from the assembly of the rotor for the motor-generator which features the world's highest rated speed of 576 to 624 min^{-1}. The rotor with a weight exceeding 400 t is to be installed inside the stator.

In 2007, a 340-MW adjustable-speed pumped-storage generation system with the world's highest speed was commissioned at the Omarugawa Power Plant of the Kyushu Electric Power Co., Inc. (see Fig. 2).

PRINCIPLES OF OPERATION OF ADJUSTABLE-SPEED PUMPED-STORAGE GENERATION SYSTEM

Speed Control of AC Electric Motors

Although techniques for controlling the speed of AC (alternating current) electric motors include a frequency control method called VVVF (variable voltage, variable frequency) and the Scherbius system used for wound-rotor induction motors, the doubly-fed system for wound-rotor induction motors was adopted because it satisfies the requirement to duplicate the functions of the synchronous machine and for reasons of economics.

The doubly-fed system controls the speed of a wound-rotor induction motor by varying the active power in the secondary circuit (rotor winding or field winding). When the primary circuit of the wound-rotor induction motor (stator winding or armature winding) is connected to the power grid, a voltage is induced in the field winding at the slip frequency. By applying an appropriate voltage from the exciter based on this induced voltage, the active power in the secondary circuit can be manipulated to control the speed.

The thyristor-based cycloconverter that is used as the exciter can cause the secondary circuit to operate in torque-producing or regenerative mode and this allows generation to be performed below the synchronous speed and pumping to be performed above the synchronous speed. Also, by having the exciter supply a current component corresponding to the air-gap flux, what is known as the field current in a synchronous machine, an internal induced voltage can be produced to control the reactive power (see Fig. 3).

Active-power-based Control

Development of speed control for AC electric motors has been ongoing aimed at applications such as railways and elevators. In these fields, quality is determined by the ability to control speed in such a way that ride comfort can be maintained while accelerating and decelerating. For an adjustable-speed pumped-storage generation system, in contrast, the main objective is to adjust the level of electric power and therefore speed control as such does not determine quality. Accordingly, Hitachi developed and adopted active-power-based control which controls the active power to be at the specified reference level.

Changing the control target from speed to active power makes it possible to perform high-speed active power control regardless of the turbine characteristics and to achieve a level of rapid response for active power that is not possible using the conventional

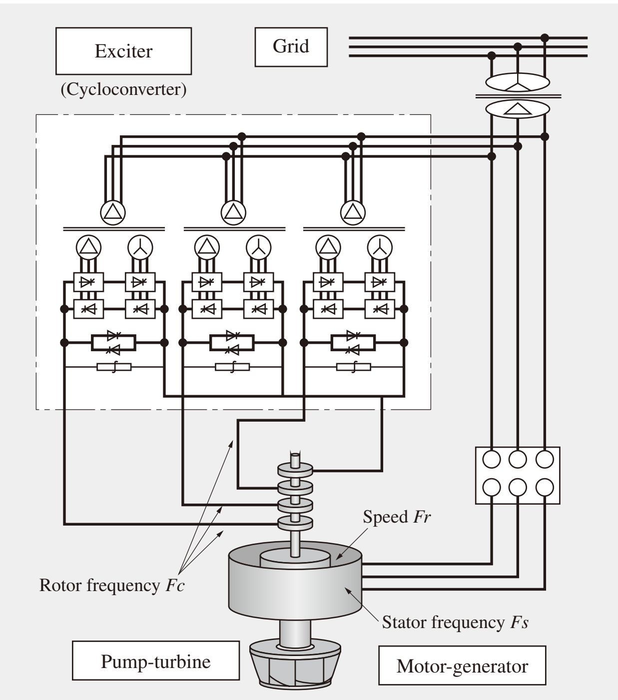

Fig. 3—Configuration of Adjustable-speed Pumped-storage Generation System Using Doubly-fed System.
The motor-generator has a configuration similar to a wound-rotor induction motor and uses AC excitation supplied from a cycloconverter via three-phase, four-wire collector rings.

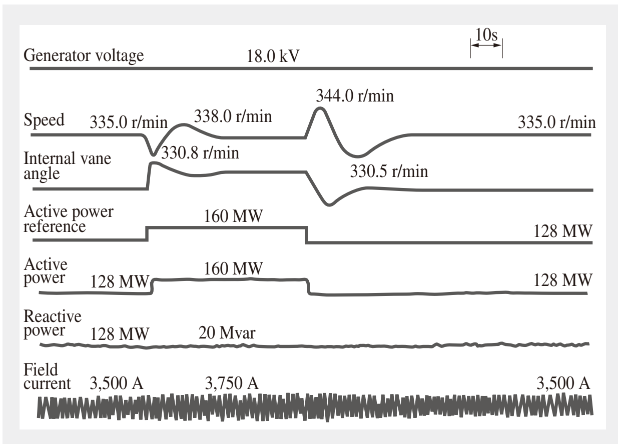

Fig. 4—Step Response for Active Power.
Because rapid control of the active power can be achieved regardless of the turbine characteristics, it is possible to perform step changes in the level of active power.

generation equipment connected to the electricity grid (see Fig. 4).

CHARACTERISTICS OF PLANT EQUIPMENT AND CONTROL METHODS

Pump-turbine

The speed of a constant-speed machine that uses a pump-turbine runner with fixed vanes (a "Francis turbine") is constant and the relationship between the head (determined by the dam water levels) and the motor input is a single fixed curve. In other words, the pump input for a given head is fixed. For a variable-speed machine that can vary its speed by a few percent either side of its rated speed, in contrast, the motor input for a given head can be changed (see Fig. 5 and Fig. 6).

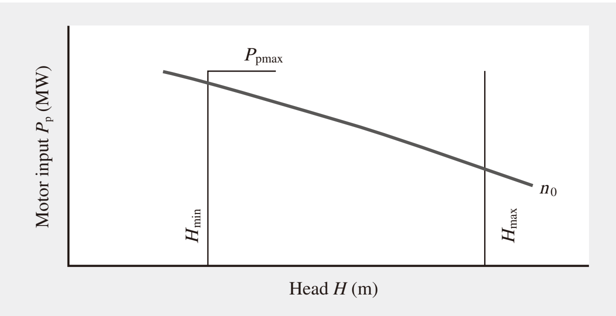

Fig. 5—Characteristics of Constant-speed Pump-turbine Runner.
Because the machine operates at the synchronous speed n_0, the relationship between the head H and the motor input P_p is fixed and cannot be adjusted.

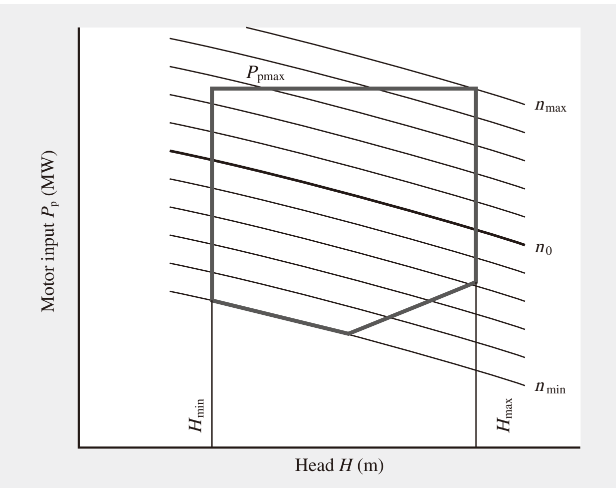

Fig. 6—Characteristics of Adjustable-speed Pump-turbine Runner.
Because the unit can operate anywhere between its minimum speed n_{min} and maximum speed n_{max}, the operating conditions can span a wide range.

For an adjustable-speed pumped-storage generation system, the operating conditions for the pump-turbine cover a wide range and a runner design that can achieve stable operation over the full adjustable speed range used in actual operation is needed because of the requirements to extend the adjustable input range when operating as a pump and to achieve high efficiency when operating as a generator.

The adjustable-speed pump-turbine runner supplied to the Okutataragi Power Plant of Kansai Electric Power uses intermediate vanes and is designed to be used over a wide operating range (see Fig. 7).

Fig. 7—Manufacture of Pump-turbine Runner with Intermediate Vanes for Okutataragi Power Plant of Kansai Electric Power.
A new design was adopted to facilitate adjustable-speed operation. The runner alternates long main vanes with short intermediate vanes to achieve improved efficiency and a wider stable operating range.

Motor-generator

The stator has the same configuration as in conventional synchronous machines and the armature winding consists of insulated three-phase distributed windings around an iron core made of layers of magnetic steel sheet. Like the stator, the rotor also has a field winding that consists of three-phase distributed windings around an iron core made of layers of magnetic steel sheet or thin steel sheet, and the rotor is coupled to the stationary part via collector rings. The collector rings have a three-phase, four-wire configuration which includes a coupling for the neutral phase. To generate a sinusoidal magnetomotive force distribution in the air gap, a balanced three-phase alternating current is passed through the field winding. This configuration maintains stable operation because any unbalanced component present in the field current flows to the neutral phase, thereby keeping a sinusoidal magnetomotive force distribution in the air gap.

A special insulation method with excellent insulation performance and mechanical strength was developed and adopted on the field winding to handle the high applied voltage and withstand the loads resulting from the strong centrifugal forces. The ability of the insulation to remain reliable over a long operating life was also verified during the development phase and this reliability has also been proven in actual operation.

The ends of the field winding are supported by binding wrapped around the outside of the winding. The binding is made of stainless steel strip or high-strength fiber material. Because a rotor for a 300-MW-class adjustable-speed motor-generator has a weight in excess of 400 t and a diameter greater than 4 m, it is assembled at the power plant to avoid transportation problems.

Exciter

The exciter is a cycloconverter that uses thyristors as its converter elements. The thyristors are separately-excited converter elements that do not themselves shut off the current flow but because they are better at withstanding over-current than self-excitation elements for which the capacity to withstand over-current is determined by the shut-off current, they are by their nature suited to large-capacity converters for power applications where over-current events caused by problems on the grid or other external factors can be anticipated.

On the other hand, because thyristors do not reverse-conduct, if current tries to flow in the reverse direction, the current path becomes open-circuit. On variable-speed machines, an alternating electromotive force is generated in the rotor current if an asynchronous current component flows in the stator of the generator due to a grid fault or other cause. While this current can flow through a conducting thyristor if it is in the forward direction, if it is in the reverse direction, the current path becomes open-circuit and an over-voltage occurs. The control required to eliminate this over-voltage and maintain operation is called "high-speed PN (positive-negative) switching." It works by detecting over-voltage independently in each phase and eliminates the over-voltage condition by temporarily reversing the cycloconverter's PN operation pairs in the over-voltage phase to allow the pulse current to flow. Use of high-speed PN switching improves the operational reliability of the system because it provides the same "function for maintaining operation in the event of a grid fault" as the damper winding in a conventional synchronous machine which acts as a shunt for the electromotive force generated by the asynchronous current component while still maintaining excitation. It has also become possible to shrink the size of the arrestors used for suppressing over-voltage. Also, the exciter circuit has a three-phase, four-wire configuration that includes the neutral phase as well as the three-phase circuits and keeps the currents of the other two phases correct during high-speed PN switching operation by allowing the unbalanced current component to flow to the neutral phase.

Also, because the thyristors are switched by an external power supply, it is possible if the voltage drops due to a grid fault or other reason that a commutation failure may occur resulting in an over-current condition due to the reduction in current control capacity. Accordingly, the protection concept used on the system identifies commutation failures by using a protection mechanism that can distinguish a commutation failure from an internal fault that requires the unit to shut down for its protection, and estimates the temperature of the thyristors based on the current passing through them and allows operation to continue provided the thyristors remain within their permitted operating range. By using this protection mechanism, if a grid fault occurs, excitation can continue without causing a short-circuit in the excitation circuit while making use of the ability of the thyristors to withstand over-current.

Control Method

The excitation modes used for a parallel grid connection can be broadly divided into "slip excitation mode" and "synchronous excitation mode" and the system can switch between these depending on the operating conditions.

Slip excitation mode is used during standard adjustable-speed operation and active-power-based control is performed by detecting the active power at the output terminal (system output) and using the output voltage of the exciter to control the phase of the field current so that the active power is equal to the reference value. Also, excitation is performed at the "slip frequency" which is the difference between the grid frequency and rotor frequency.

From the perspective of the motor-generator, slip excitation mode controls the phase of the field current and, because this corresponds to controlling

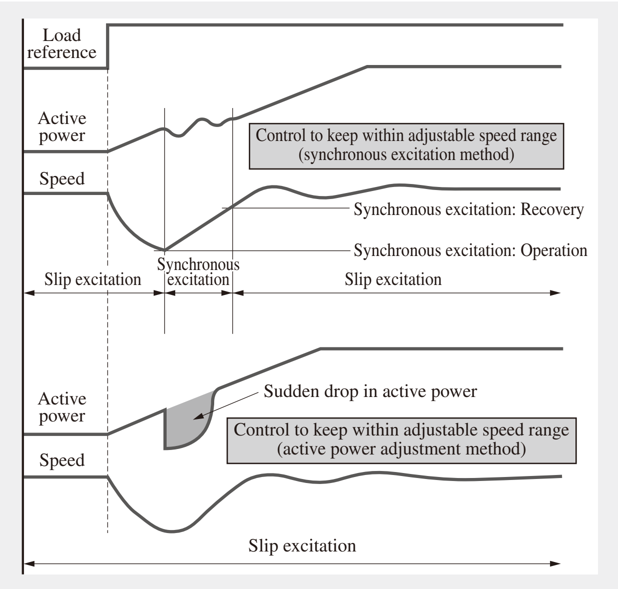

Fig. 8—Control to Keep within Adjustable Speed Range.
Using synchronous excitation to control the speed to within the adjustable speed range results in a smaller variation in active power than when the speed is controlled by adjusting the active power, and this reduces the effect on the grid during the transient.

the internal phase difference angle in a synchronous machine, it means that active-power-based control can be performed at high speed. This control method allows operation to continue without loss of synchronism in situations such as when a grid earth fault causes a sudden change in the phase of the grid voltage or the rapid re-closing of the circuit associated with such a fault occurs.

Because active-power-based control is used, governor control only operates as a speed control mechanism and, during adjustable-speed operation, the turbine output is adjusted and its speed controlled so that it does not diverge dramatically from the adjustable-speed operation range. Because operating in slip excitation mode causes a deviation in the active power and pump-turbine torque and this deviation manifests as a change in speed, deviations between the actual speed and the speed reference value set to the governor occur more often than for a constant-speed system and therefore the control method needs to work in harmony with active-power-based control.

Synchronous excitation mode is used when controlling the operation to prevent the speed diverging from the adjustable-speed operation range. The effective head changes suddenly if the guide vanes are rapidly opened due to a sudden increase in load or similar. If as a consequence the speed is at risk of going outside the adjustable speed range, a synchronizing force is generated by using a constant excitation frequency to lock the speed at the speed corresponding to that excitation frequency. Although a variation occurs in the active power corresponding to the change in effective head because the generator characteristics in this case are the same as for a constant-speed machine (synchronous machine), because this variation in active power is kept to a lower level than would be the case when controlling the speed by adjusting the active power, using this control method has less of an effect on the grid during the transient condition (see Fig. 8).

Also, because synchronous excitation mode can lock the speed by using a synchronizing force independently of control, there is no need to switch from active-power-based control to speed control and it can be used in situations such as when starting or stopping pumping and when an emergency stop is triggered by a protection function.

CONCLUSIONS

This article has described the background to the development of adjustable-speed pumped-storage generation systems, their technical characteristics, and other related topics.

The adjustable-speed pumped-storage generation system was initially developed based on the concept of using a pumped-storage power plant to balance supply and demand during the night, and since then Hitachi has continued to develop and implement functions for improving the operational convenience and reliability of the system which extend beyond just ensuring the reliability of the equipment to also include functions such as active-power-based control, continuity of operation in the event of a grid fault, and synchronous excitation mode.

Active-power-based control is a method for manipulating the operation of a synchronous machine by controlling its internal phase difference angle, and connecting such a system to the actual electricity grid for testing is subject to considerable risks. Although the technology was developed using an analog simulator that simulates the turbine, motor-generator, exciter, control system, and electricity grid to avoid these risks, it was ultimately necessary to verify the operation on the actual electricity grid.

To minimize the effect on the electricity grid while still allowing the necessary testing to be carried out, the development of the technology for the 400-MW-class adjustable-speed pumped-storage generation system at the Okawachi Power Plant of Kansai Electric

Power was able to be performed using a 17.5-MW demonstration plant at the Narude Power Plant that was connected to the actual electricity grid and used to conduct a large number of tests.

Similarly, the ability to build adjustable-speed pumped-storage generation systems with large capacity and high speed was made possible by the installation of an adjustable-speed pumped-storage generation system at the Omarugawa Power Plant of the Kyushu Electric Power Co., Inc. which featured a very high speed of 576 to 624 min^{-1} and a pump head that, at more than 700 m, was unprecedented even among existing pumped-storage power plants.

For the pumped-storage generation equipment that had already been installed and was in operation at the Okutataragi Power Plant of The Kansai Electric Power Co., Inc., Hitachi also undertook technology development to convert the system to adjustable-speed operation and this is expected to lead to even wider adoption of adjustable-speed pumped-storage generation systems.

The technology that has already been developed has contributed to a reduction in CO_2 emissions by allowing pumped-storage power plants to be used for electricity supply and demand balancing during the night and thereby extending the length of time that thermal power plants can be shutdown. Even if the proportion of renewable energy increases, new needs are emerging for large-scale energy storage systems capable of adjusting the input and output of electric power and Hitachi intends to continue to develop technology and contribute to the reliable supply of electricity.

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