Appendix A

Adjustable Speed Hydro Generation

This appendix, which relates to Chapter1, §1.3, describes the benefits associated with adjustable speed machines related to the angle stability of an interconnected bulk power transmission system. The stability benefits are:

- First swing stability,
- Oscillatory stability.

Generator dynamic benefits are the result of the ability of an adjustable speed machine to change power quickly over a large range. With adjustable speed machines it's possible to exchange energy between the rotating mass of the machine and the transmission system. It's therefore possible to provide system damping during transient periods.

Doubly-fed machine. The doubly-fed machine consists of a three phase stator winding of the same type required by a salient pole synchronous machine. The rotor consists of a laminated steel cylinder with slots in which distributed three phase windings are installed. The three phase rotor windings are connected to an external exciter by slip rings mounted on the shaft. The stator windings are energized from the constant frequency bulk power system, and a synchronous alternating magnetic field is established [1-67]. The rotor is excited from an adjustable frequency voltage source. See Figure A-1 for a schematic representation.

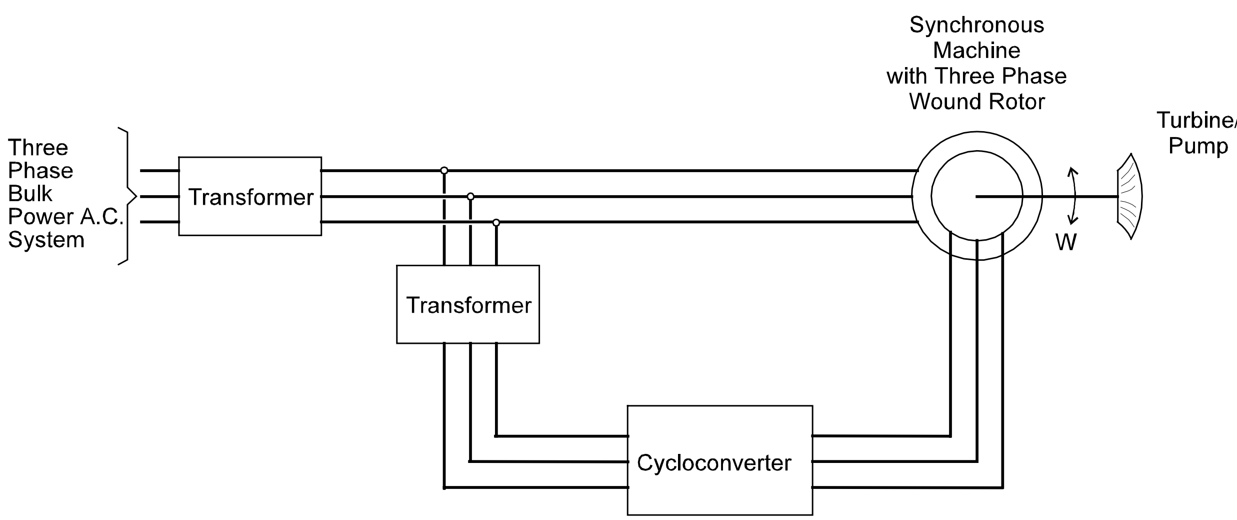

Fig. A-1. Doubly-fed machine with cycloconverter.

A rotating magnetic field is established in the rotor when a three phase excitation current of frequency f_E flows through the rotor. The speed of the excitation field is given as:

$$n_E = 2\, f_E * 60/P \text{ (rpm)} \quad \text{where P = number of rotor poles}$$

n_E represents the motion of the magnetic field when viewed from the rotor. When viewed from the stator the mechanical motion of the rotor (n_M) is added. The equation for the speed of the magnetic field n_S as viewed from the stator is expressed as:

$$n_S = n_M \pm n_E$$

where n_S is the speed of rotation of the stator as determined by the frequency of the bulk power system. When $n_E = 0$ the rotor and stator are at synchronous speed, $n_M = n_S$. When the frequency of the rotor excitation n_E is adjusted above or below dc, then shaft speed n_M can be made faster or slower than synchronous speed. Rotor shaft speed is equal to the algebraic sum of the synchronous frequency of the power system on the stator and the frequency of the rotor excitation. Thus mechanical shaft speed can be adjusted above or below synchronous speed by adjusting rotor excitation frequency:

$$n_M = n_S \pm n_E$$

The “doubly fed” designation describes the application because electric energy can be interchanged between the machine and the bulk power system through both the stator windings and the rotor windings.

Oscillatory stability. The wound rotor and cycloconverter or self-commutated inverter excitation of an adjustable speed machine provides an ideal mechanism to damp power system oscillations. The voltage applied to the rotor of an adjustable speed machine by the cycloconverter or self-commutated inverter can be modulated to provide the same damping that can be provided by a stabilizer on a conventional synchronous machine. However, the frequency of the voltage applied to the rotor can also be modulated to provide an even larger component of damping power, perhaps twice that available from a high performance excitation system on a conventional machine.

Modulating frequency applied to the rotor effectively accelerates the speed of the flux movement across the face of the rotor, thereby directly increasing or decreasing the power flowing across the air gap through the machine terminals into the power system.

The Kansai Electric Power Company of Japan [1-83] has constructed a four unit pumped storage hydro plant with two adjustable speed machines. The machines are rated 400 MVA, and have a wound rotor with cycloconverter excitation. The rotor is smooth, with a three phase distributed winding, and the stator is a conventional synchronous machine stator. Each machine has a 72 MVA cycloconverter that allows speed to be adjustable between 330 rpm and 390 rpm.

The speed adjustment is accomplished by changing the frequency of the rotor flux. Each machine can change power in steps of at least 32 MW in the generation mode, and at least 80 MW in the pump mode. The power changes are accomplished in 0.2 seconds.

From the angle stability viewpoint, the most attractive feature of the adjustable speed machine is the ability to interchange (inject or absorb) energy with the power system. One of the adjustable speed machines at the Ohkawachi pumped storage plant was in service on the morning of January 17, 1995 when the Hanshin earthquake occurred. It’s reported that the machine functioned satisfactorily and absorbed transmission line power disturbances in random spikes.

Adjustable Speed Hydro Projects in Japan. Table A-1 lists information and data about adjustable speed hydro installations in service and under construction in Japan [1-84,1-85].

Table A-1

Adjustable Speed Pumped Storage Projects in Japan

PLANT NAME	SERVICE DATE	PUMP INPUT MW	GEN MVA	SPEED RANGE rpm	COMPANY	UTILITY
Yagisawa no. 2	1990	53 to 82	85	130 to 156	Toshiba	TEPCO
Takami no. 2	1993	54 to 140	140	208 to 254	Mitsubishi	HOKKAIDO
Ohkawachi no. 2	1993	331 to 392	395	330 to 390	Hitachi	KANSAI
Shiobara no. 3	1995	200 to 330	360	356 to 394	Toshiba	TEPCO
Ohkawachi no. 4	1995	240 to 400	395	330 to 390	Hitachi	KANSAI
Yagisawa no. 3	1996	53 to 82	85	130 to 156	Toshiba	TEPCO
Okukiyotsu no. 2	1996	230 to 340	345	408 to 450	Toshiba	EPDC
Kazunogawa	2005	NA	500	500 synch	NA	TEPCO
Omarugawa no. 3	2005	230 to 330	340	576 to 624	Mitsubishi	KYUSHU

First-swing stability. First-swing stability is the problem of synchronous machines pulling out of step following faults and tripping of key transmission lines. When faults suppress power transfer between areas in the network, generators on the “sending area” side of the fault accelerate, and generators on the “receiving area” side decelerate.[1] If the fault duration is long, the two areas lose synchronism and system separation and possibly a blackout result. As transfers increase, the system becomes less stable in that it will become unstable for a lesser disturbance. For a given fault type and duration at the worst-case fault location there is a maximum transfer, or “stability limit” at which the system will remain stable.

During the power swing that follows the fault, voltages swing downward substantially near the electrical center of the system (about halfway between the sending and receiving areas). In some regions of the United States utilities have agreed that an operating condition will be ruled ‘unstable’ if the voltage at any substation serving customers drops below some threshold such as 70 or 80% of nominal during simulations of the worst-case disturbance. This voltage criterion may limit transfers to a level below that at which generators would remain in synchronism.

Raising the first-swing stability limit requires investment in series capacitors, static var compensators, braking resistors, high ceiling/high initial response excitation systems, etc.

1 In some situations both sending and receiving areas are accelerated by the fault, but the sending area is accelerated much more than the receiving area with the same stability consequences described in this paragraph.

These are fairly costly devices. They also complicate system operation and thus provide systems that are stable if all systems operate correctly. Hence though a system may meet stability criteria, it may not be as reliable as the criteria would indicate if many ‘stabilizing’ devices must be used.

An adjustable speed machine can literally be “pushed quickly up the power-angle curve” by reducing the frequency applied to the rotor, and then pushing the frequency ahead to keep the machine near the top of the power-angle curve. In effect, the control ‘flattens’ the top of the power angle curve as shown in Figure A-2. This may as much as double the synchronizing energy that an adjustable speed machine can develop compared to a conventional machine, allowing it to remain in synchronism when a conventional machine would pull out of step. This is accomplished by modulation of the frequency the cycloconverter applies to the rotor.

An adjustable speed machine in a pumped storage or hydro plant, with the appropriate supplementary controls, will be significantly more stable than a conventional hydro unit, and it may also improve angle stability of nearby plants. The improved stability may help avoid the need for a new transmission line or allow a lower voltage transmission line to be used. However, with the multitude of devices that can be added to transmission networks to improve first-swing stability, it’s unusual to need a new line to provide stability. These devices can push stability limits up to thermal limits. Losses are high when transmission systems are operated close to thermal limits, but in a deregulated system losses seem not to be a major factor.

The stability benefit of an adjustable speed machine will thus be primarily from the avoided use of series and shunt compensation, and static var compensators or synchronous condensers.[2]

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[2] Recently escalating SVC prices, improvements in synchronous condenser efficiency, the overload capability of condensers, and stability advantages have again made the rotating machine competitive with SVCs in some applications. Several U.S. and foreign utilities have chosen synchronous condensers over SVCs since 1992.

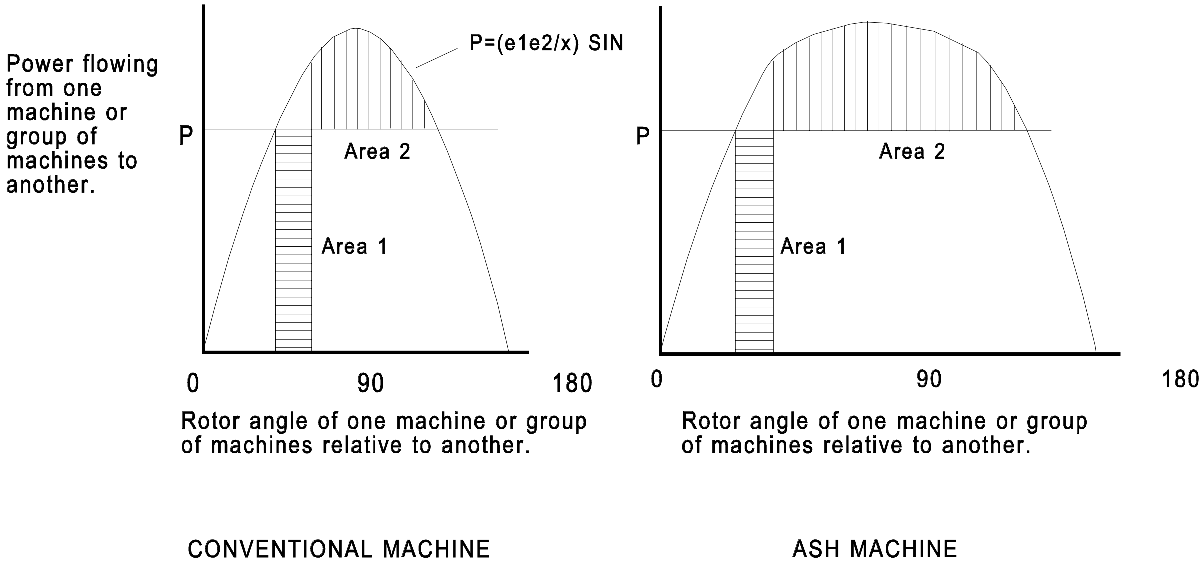

Fig. A-2. The power-angle curve shows graphically the stability dynamics of turbine-generators. A fault depresses power and accelerates one machine or group of machines relative to another so that the angle difference between their respective rotors increases. Area 1 represents the energy stored during the fault. Area 2 represents the 'synchronizing' power transfer that flows as the accelerated machines(s) move(s) away from the others. The system is stable if area 2 is larger than area 1.