Operation of Hydroelectric Facilities and the Boulder Canyon Hydroelectric Generating Plant *(*April 2008)

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***Abstract*—Boulder Canyon Hydroelectric Generating Plant has been in continuous operation since 1910. While the technology behind the operation has seen some upgrades, the infrastructure is mostly the same as it was almost a century ago.**

***Index Terms*— Breaker, Hydroelectric generators, Synchronization, Transformer, Water.**

I. History of Boulder Canyon Hydroelectric Generation Plant

Boulder Canyon Hydroelectric Generating Plant was originally part of an ambitious plan by Myron T. Herrick, a Republican politician from Ohio [1]. Herrick wanted to harvest the potential of water and create a network of power lines all across the Rocky Mountains. In the end, Herrick only saw the completion of Boulder Canyon and Shoshone [2].

Boulder Canyon was commissioned in 1906 by the Central Colorado Power Company and came online on August 4th, 1910 with two sets of turbines and generators producing 5000 kilowatts of power each. In 1936, each generator was upgraded to provide up to the present day 10000 kilowatts per a generator capability [3]. However, the facility often only produces 5000 kilowatts due to seasonal water limitations.

Throughout the 20th century, Boulder Canyon Hydroelectric facility came under the control of several different electric utility companies. In 2001, the city of Boulder purchased the Boulder Canyon Hydroelectric facility, along with the associated pipeline and reservoirs from Xcel energy [2].

In 1964, Generator "A" suffered a loss of excitation. The operator attempted to reestablish the field, however when he did, the generator was out of synchronization and severe inrush current uprooted and destroyed the machine. However, by the end of that same year, the generator had been fixed and was once again generating power.

Then in late 2000, shortly before Xcel sold the facility to Boulder, Generator "A" was destroyed again; this time due to a ground fault. The generator was not fixed or replaced and currently remains in place, but inoperable.

II. Generator Details

Spinning at 400 revolutions-per-minute, each alternating current generator is designed to output 1000 kilowatts and 12500 kilovolt-amps with a 0.80 power factor. Each generator is rated at 4000 volts, however actual output voltage ends up being 4160 volts. The generators were built in Schenectady, New York by the General Electric Company. Each generator has 18 poles as shown by (1)-(3).

$$f_e = 60\ hertz \quad (1)$$

$$n_m = 400\ \frac{revolution}{minute} \quad (2)$$

$$P = \frac{120 \times f_e}{n_m} = 18\ poles \quad (3)$$

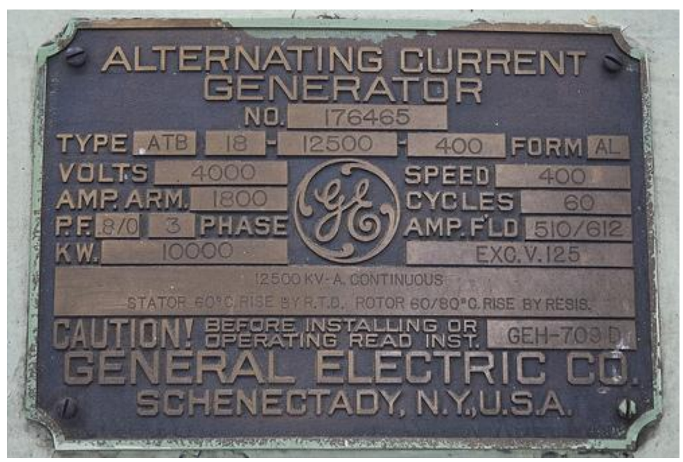

Fig 1. Name plate data for the alternating current generator at Boulder Canyon Hydroelectric.

III. Synchronization

Before a generator can be connected to the grid, the generator needs to meet four synchronization criteria: same frequency, same voltage, same phase shift, and same phase sequence [4].

The frequency of the generator is determined by the frequency of the grid and the number of poles in the generator. Using (3), the revolutions-per-minute of the generator can then be calculated. The generator is then spun up to the appropriate revolutions-per-minute and held at that speed.

The output voltage of the generator is matched to the grid power by adjusting the excitation field current of the generator. By reducing the field current, the excitation field strength is also reduced. This results in less voltage output of the generator. It should also be noted that the generator does not generate transmission-line level voltage. Instead, power generated by the generator is sent to a series of step-up transformers.

Phase shift between the generator and the grid is compensated for by very slowly adjusting the speed of the generator faster or slower to bring the generated voltage in line with the grid voltage phase. Once the phases are matched as closely as possible, the speed of the generator should be returned to the speed needed for correct frequency generation.

Finally, phase sequences of the generated power and the grid power much match. This is easily accomplished by ensuring that the generator turns in proper direction during power generation.

Fig 2. Control panel showing the synchroscope (top), hertz meter (middle), and voltage meter (bottom) at the Boulder Canyon Hydroelectric facility.

To aid in the synchronization of the generator to the grid, a device called a synchroscope is employed, as seen in Fig 2. The synchroscope displays the phase relationship between the generated voltage and the grid voltage and includes a dial to indicate if the generated voltage phase is ahead of (faster) then the grid voltage phase or if the generated voltage phase is behind (slower) the grid voltage phase. The synchroscope also has two light bulbs in series to indicate the peak of the combined generated voltage and grid voltage.

The synchroscope, along with a voltage meter and a frequency meter, display three of the four states of the synchronization since it is assumed that the generator will turn in the correct direction during power generation and will not suddenly switch direction.

Fig 3. Syncroscope for generator "B" at Boulder Canyon Hydroelectric facility.

To synchronize the generator, the speed is first set to 60 Hz (or 400 RPM). A governor, seen in Fig 3, is used to assist in keeping the generator rotating at 400 RPM. The mechanical governor is attached to the Pelton wheel via gears and a system of balls is attached. The balls move in and out due to the varying centripetal force that occurs with different rotational speeds. As the balls move, they move a lever that controls the angle of water hitting the buckets on the Pelton wheel. Less water hitting the buckets cause the wheel to slow down while more water hitting the buckets cause the wheel to speed up.

The generated voltage is set by adjusting the excitation current. Finally, the speed is adjusted in slight increments to bring the generated voltage phase almost perfectly in line with the grid voltage phase. Then, as soon as both synchroscope lights are dim, the paralleling breaker is closed and the generator is now connected to the grid.

IV. Boulder Canyon Pelton Turbine

Boulder Canyon Hydroelectric uses a Pelton turbine. Peltons are a type of impulse turbine and are generally used when the hydraulic head is in excess of 800 feet [3].

The shape and operation of a Pelton wheel is similar to that of water wheel. Water enters Boulder Canyon's turbine through a penstock, which is a long pipe that runs from Kossler Forebay to the plant [2].

Fig 4. Piston that controls water flow at the end of the penstock at Boulder Canyon Hydroelectric facility.

Fig 5. Buckets on the "A" Pelton wheel at Boulder Canyon Hydroelectric facility.

A piston at the end of the penstock acts as a gate for the water entering the plant, as seen in Fig 4. The water then goes through an articulating needle valve which controls the flow of the water.

Boulder Canyon is unique in that its needle valve articulates up and down, moving in the water stream in and out of the Pelton bucket. Almost all other Pelton turbines use a deflector to block the flow of water from the Pelton buckets.

The Pelton turbine is fitted around its rim with several w-shaped buckets. Water hits the divider between the two sections of each bucket and is redirected almost 180 degrees. The pressure of the water forces the bucket to move, which turns the Pelton wheel.

After the water hits the bucket, the water is of no more use mechanically. It exits below the Pelton wheel and flows into the tailrace where it rejoins the river.

V. Switchyard

The generator outputs voltage at 4160 volts. It is then sent to the switchyard where it is stepped up to 115000 volts for transmission to the Xcel power grid.

When the power reaches the city, it is then stepped down to 25000 volt distribution lines.

VI. Step-up transformers

Boulder Canyon has two transformers in the switchyard adjacent to the facility. Each transformer is rated for 12500 volt-amps at 5000 feet; 115000 volts Wye / 4000 volts Delta [4]. However, the Boulder Canyon facility was built at 5885 feet and thus the transformer needs to be derated because there is insufficient cooling for operation at 12500 volt-amps.

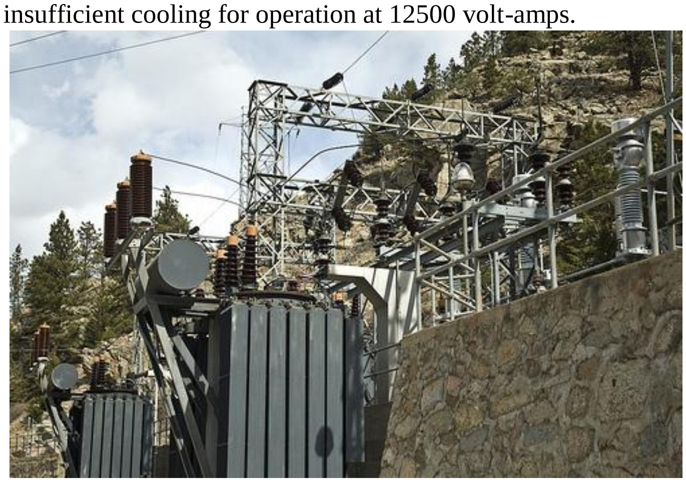

Fig 6. Switchyard next to Boulder Canyon Hydroelectic. The two 12.5 kVA; 115kV Wye/ 4kV Delta transformers can be seen near the bottom left quadrant.

Protection is offered through several relays and breakers, including a series of sulfur hexafluoride breakers.

The large transformers seen in Fig 6 contain 4827 gallons and weigh 94000 pounds each. They are cooled by purified mineral oil and radiator fins. A third transformer now shown in Fig 6 also has a forced-air, forced-oil system.

VII. Black Start Capability

Black start capable is the ability of a power generation facility to deliver power to the grid without any external electricity necessary, such as when the grid is dead from a catastrophic power outage.

Boulder Canyon does have the ability to black start. Using a bank of batteries, Boulder Canyon can provide itself enough

enough energy to move the articulating needle into place, open the gates to allow the water to flow, and power the electronics to set the Pelton wheel to synchronization standards (although one should note that there is nothing to synchronize to).

VIII. Circuit Breakers

Several different types of circuit breakers are employed at the Boulder Canyon Hydroelectric facility.

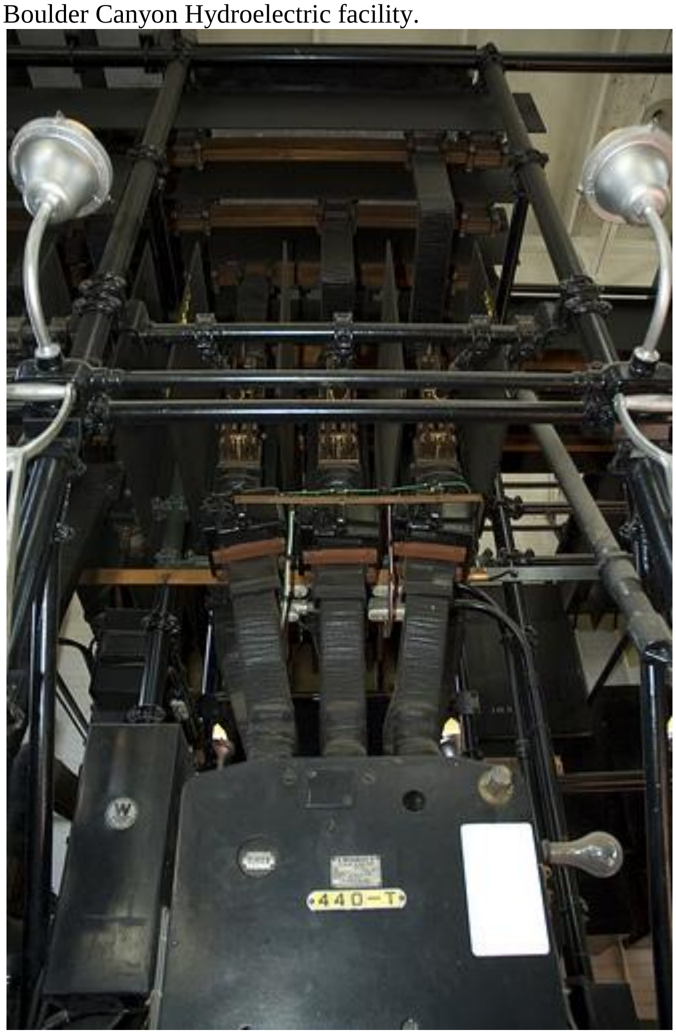

Fig 7. Breakers immediately adjacent to generator "B" at Boulder Canyon Hydroelectric facility.

A. Vacuum

Vacuum circuit breakers are similar in operation to a traditional circuit breaker one might find in their home. However, the contacts are placed inside a vacuum. This is done so that when the circuit is tripped, there is virtually no arcing since there is no air (or other gas) to ionize [5].

B. Oil

Oil circuit breakers are also designed to reduce the arc caused by a breaker opening or closing. However, instead of the contacts being placed in a vacuum, the contacts are immersed in nonconductive oil. The oil helps to quench the arc quickly and can also cool the breaker.

C. Recloser

Recloser breakers are just like any other breaker except for the fact that they have an embedded computer to make the breaker "smart." When the breaker is tripped, the computer will wait for a few minutes before automatically closing the contacts again. If the breaker trips again, the computer will wait even longer before attempting to close the contacts. If, after several attempts, the breakers will still not close, a signal is sent to the utility company to alert the company to problem.

Reclosers are beneficial to electric utilities because they don't require a maintenance person to be sent every time the breaker is tripped.

IX. Other Types of Hydroelectric Turbines

Peltons are obviously not the only kind of turbines at the disposal of engineers. There are several different types of types of turbines which are show in Fig 8.

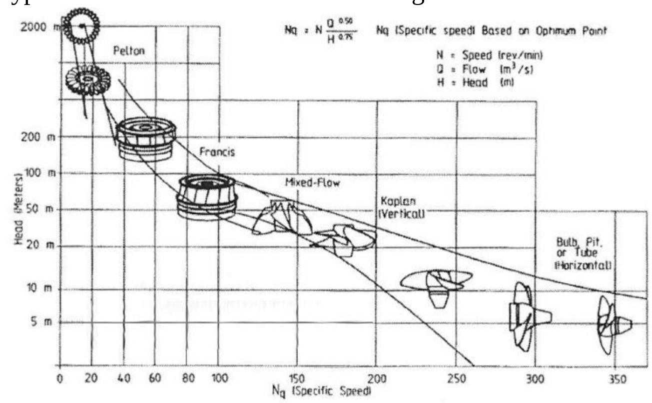

Fig 8. Chart showing turbine types for meters of head versus specific speed [3].

The Pelton impulse turbine is ideal for situations where significantly high head is available. They offer very high efficiency over a wide range of water velocity in a compact and simple design. However, the one major fault of the Pelton turbine is that downstream pressure *must* be zero since there is an air gap between the nozzle and the tailrace [3].

On the other end of the spectrum, fixed and adjustable-blade propeller reaction turbines are used where there is very little head (perhaps as little as 5 meters), yet relative velocity of water very high. An ideal place for a propeller turbine would be in a flowing river, where the head is slow, but there is constant and relatively high water velocity.

Another type of reaction turbine is Francis. However, the Francis turbine is unique because in addition to being used as a generator, it can also be used as a pump. This is ideal for situation where a public utility company would normally want to generate electricity from water flowing downstream. Yet, but in cases of emergency, they also desire the capability to pump water to higher elevation.

Unlike Pelton and other impulse turbines, reaction turbines (such as the Francis and blade turbines) can have downstream pressures above zero. However, this causes load rejection to cause water hammer either upstream (in the case of the Francis) or downstream (in the case of the propeller).

X. Three Phase versus Single Phase

Direct current systems have two lines connecting the load to the power: a line to deliver the electricity and a line to return it. Alternating current can use the same system, in a single phase current. However, there is a more economical way to deliver power using a three phase system.

In a three phase system, three delivery lines are used which each voltage being 120 degrees out of phase from the other two phases. When summed together, the net energy delivered is zero. Since only three lines (and a fourth smaller line to handle load imbalances) are used, the cost of installing and maintaining lines is roughly half the cost of maintaining six lines. Additionally, since only three lines are used, the I^2R losses are also cut in half, maximizing the efficiency of the power delivery system.

XI. Environmental impact of hydroelectric power

Hydroelectric power is not completely free of environmental impacts. There are several environmental externalities associated with building and maintaining a hydroelectric plant that must be taken into account.

Most hydroelectric facilities employ the use of a dam to collect water. Ignoring the effects caused by the construction processes, dams cause problems for many species of indigenous wildlife. Along the east and west coasts of the United States, salmon populations are particularly affected by dams and pipelines since the fish often have a much harder time getting back upstream to their breeding grounds. Even when fish ladders are installed, not all salmon are able to return to their spawning ground [6][7].

Additionally, water flow may be temporarily diverted during dam construction or permanently diverted after construction if the dam cannot be built on the existing river. Altering the flow of water either upstream or downstream of the dam poses problems for the immediately local wildlife, including both plant and animal life.

Boulder was fortunate that much of the critical infrastructure, including dams and pipes were already in place and all that had to be built were the actual hydroelectric facilities. This severely cut down on the environmental externalities.

XII. Financial return of Boulder Hydroelectric

Excluding Boulder Canyon Hydroelectric, the Boulder system of hydroelectric facilities are very new, having seven new sites completed between 1985 and 2004. The Boulder system of hydroelectric facilities generates over $2 million in annual revenue from selling power to Xcel energy. At this rate, Boulder is able to pay for all the facilities, including interest, within 15 years [3][8].

XIII. Other Hydroelectric Facilities in Boulder

There are seven additional hydroelectric plants currently operating around Boulder. The Maxwell, Kohler, Orodell, and Sunshine facility were built between March 1985 and September 1987 and each uses a Francis reaction turbine with an induction motor. Additionally, the Francis turbines at the Maxwell and Kohler facilities are also designed to pump water in the event of an emergency and known as pump/generators [3].

Meanwhile, the Betasso, Silverlake, and Lakewood were built between December 1987 and December 2003 and each uses a Pelton impulse turbine with a synchronous generator.

XIV. Future of hydroelectricity in Boulder

Boulder Canyon Hydroelectric is required to maintain a Federal Energy Regulatory Commission (FERC) license to operate. The current FERC license expires at the end of August 2009 and the City of Boulder is currently in the process of filling a conduit exemption since the pipeline that delivers water to the Boulder Canyon Hydroelectric plant is primarily used for municipal use and not power generation. However, “[the] City intends to continue limited operation of the remaining functional turbine to generate power for as long a period as the remaining equipment can be kept running [9].”

The other hydroelectric facilities around Boulder are considerably newer and should see continued service for a very long time.

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