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Varying Generator Excitation to Control Draft Tube Surge

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VARYING GENERATOR EXCITATION TO CONTROL DRAFT TUBE SURGE

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ABSTRACT: The Bureau of Reclamation recently experimented with varying the excitation applied to a hydroelectric generator to control power swings caused by draft tube surging in a Francis turbine. Field testing was performed on a 48-MW unit at Blue Mesa Powerplant, near Gunnison, Colorado. A variety of signals were fed into the excitation system. Data acquired included: draft tube pressure, power output, vibration, and shaft runout. Results of the field test and additional analytical work are used to evaluate the concept.

INTRODUCTION

In most reaction-type turbines, operation away from the maximum efficiency point can result in a hydrodynamic instability related to swirling flow in the draft tube. This instability takes the form of a spiral vortex which rotates around the axis of the draft tube. Buildup and breakdown of this vortex causes periodic surging at a frequency related to the rotational speed of the unit and the draft tube geometry. Surging is responsible for many undesirable operating characteristics in hydroelectric plants. The pressure pulsations lead to disturbances in the rotating machinery (runner, shaft, generator rotor), fluctuations in the electrical output of the generator and increased variations in the penstock pressures.

A large volume of data exists on the phenomenon of draft tube surging. Rheingans [1940] was among the first to link power swings and draft tube surging. Falvey [1971] provides an excellent review and annotated bibliography of the subject. It is not uncommon to see power swings as large as 25-percent of the load. Due to the severity of these large fluctuations, many methods have been used in the field to control or eliminate the draft tube surge. Air admission, extensions to the runner

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core and fins or splitters mounted in the draft tube are a few of the more popular and effective methods used to break up the vortex causing the surging condition.

The feasibility of using a signal derived from the draft tube pressure fluctuations as feedback to the stabilizing circuit of the generator excitation system was studied by ACRES, [ACRES American Inc. 1981]. Through analytical studies and computer modeling, the idea was thought feasible and was recommended for testing at a hydroelectric plant.

Many years passed without verification of this concept, largely due to the inability to input the required signals into the excitation system. With its installation of a new large static exictation system, Blue Mesa Powerplant became a prime location to test the concept.

PROTOTYPE TESTING

Testing was performed on Unit No. 1 at Blue Mesa Powerplant. Blue Mesa Dam is on the Gunnison River about 30 miles below Gunnison, Colorado. The powerplant consists of two 48-MW generators, driven by two vertical shaft, 41,500-horsepower, 200 r/min hydraulic turbines. Each turbine is designed to operate at a maximum head of about 360 ft.

One 16-ft-diameter penstock conveys water to the two turbines and also provides water to the outlet works. After branching from the main penstock, each of the penstock laterals is controlled by 156-inch butterfly valves, fig. 1

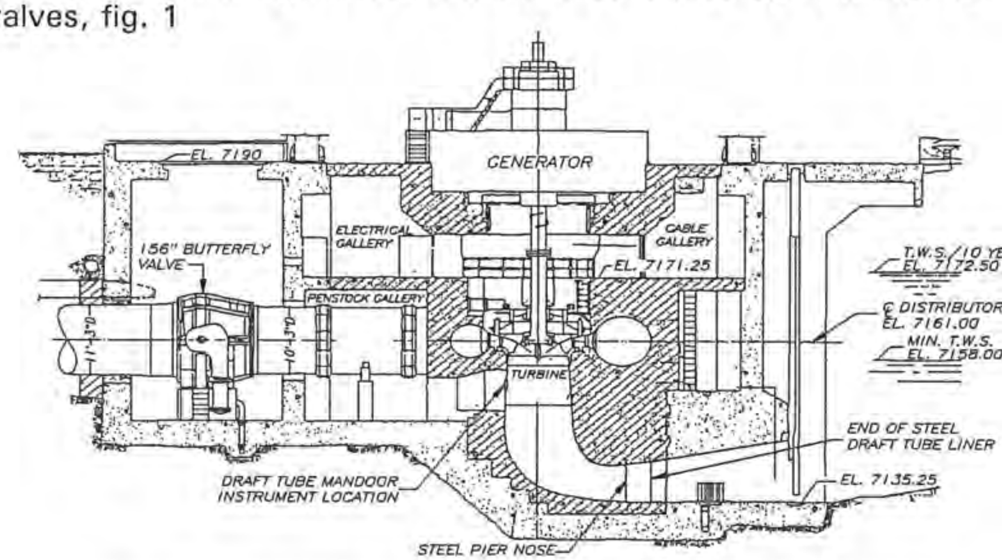

Figure 1: Elevation of Unit No. 1, Blue Mesa Powerplant.

Electrical Equipment - The plant was first put into operation in 1967. At that time, there were two 33,333 kVA, 0.90-power factor, 200 r/min generators. The generators operated at 60 Hz (36-pole machines). Each generator was equipped with a main exciter rated at 160 kW. The exciters were direct connected and had 6 poles. In 1988 an uprating took place. This uprating included increasing the capacity of the generators to 48,000 kVA through rewinding of the stator. In addition, the exciter was replaced with a static excitation system with a continuous rating of 220 kW and a ceiling forcing of 650 kW. The exciter in conjuction with the power systems stabilizer, can provide excitation and control for generator operation. However, with the power system stabilizer in operation at normal gain levels, large power swings occur when the unit is in a draft tube surging range.

Instrumentation - Instrumentation provided for the test included: a pressure transducer on the draft tube mandoor, an accelerometer mounted on the draft tube mandoor (fig. 2), proximity sensors on the upper and lower guide bearings and the turbine guide bearing, and a megawatt transducer measuring power output. In addition, several variables were recorded from the control panel, such as reservoir elevation, tailwater elevation, and wicket gate positions. We also were able to record the excitation input and several other electrical parameters which allowed for evaluation of the data.

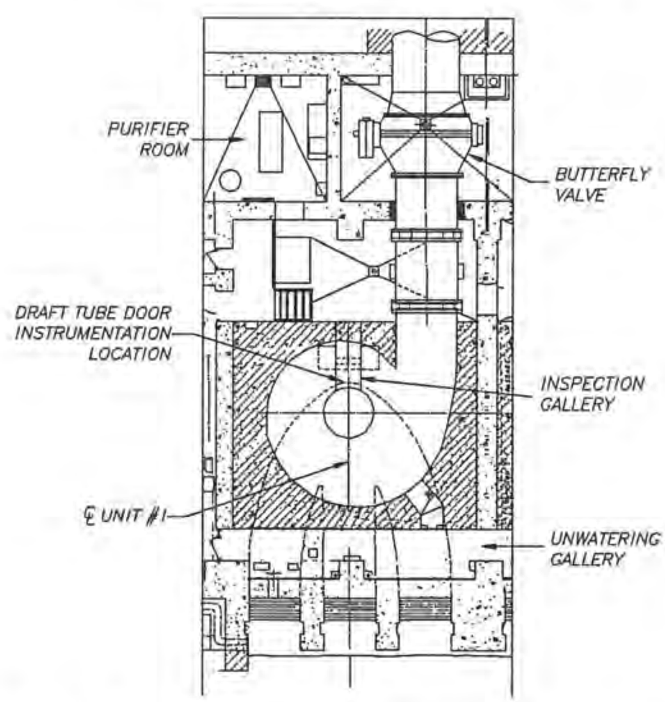

Figure 2: Plan view of Unit No. 1, Blue Mesa Powerplant.

Data were recorded by two methods. A hard copy of the testing was generated by a strip chart recorder while an 8-channel DAT (Digital Audio Tape) recorder captured raw data for future analysis. All instrumentation leads were terminated in the control room. Inputs to the generator exciter were provided by a standard function generator and also from direct signals measured on the machine as it operated (i.e. draft tube pressure signals and output power fluctuations).

Test Procedure - The testing took place over 2 days. The first task was to identify the *rough* zone of the unit. An initial run was made taking the unit from a speed-no-load condition up to a fully loaded condition in approximately 5-MW increments. With each change in load, a few minutes of data were collected to provide a baseline. Once the maximum load was achieved, the unit was shut down in a normal procedure. Additional test runs included inputting various signals into the generator exciter. These signals included a sine wave swept from 0.8 to 2.2 Hz, the output power signal, and the draft tube pressure. The signals were input while the unit was in both smooth and rough zones of operation. During each of the test cases, instrument responses were recorded.

RESULTS and DISCUSSION

The initial test run provided a map of the operating zones for the unit at the particular net head (330 ft) available during the test. A vortex began causing pressure fluctuations in the draft tube at about a 10- to 12-MW load. As the load continued to rise, a periodic surge was noted. The amplitude peaked at about a 22 MW load (59.9-percent wicket gate opening), with a peak-to-peak fluctuation of about 12 lb/in^2 at a frequency of 1.016 Hz, fig. 3.

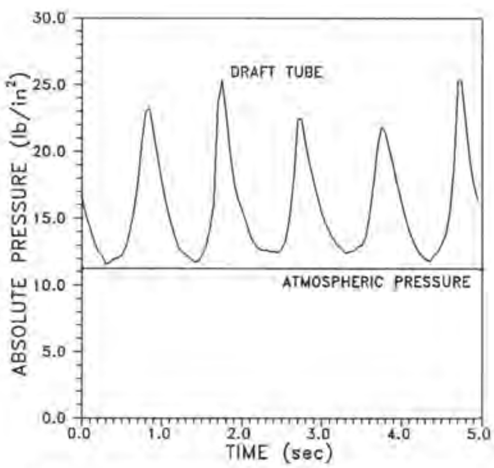

Figure 3: Maximum draft tube pressure fluctuation.

Above a 25-MW load, the unit ran smoothly until the maximum wicket gate opening. With this condition, a semiperiodic negative surge appeared. This surge is caused by flow swirling in the opposite direction from the periodic surge due to the maximum efficiency point being passed.

While the draft tube pressure fluctuations were at a maximum, outputs from the other sensors also indicated energy at the surging frequency. The surging frequency of 1.016 Hz agrees with predictions based on previous work ($f_s \approx 1/4$ to $1/3$ of the unit's rotational frequency). The power output of the unit showed a maximum peak to peak fluctuation of about 5 MW out of 22 MW, or 22 percent.

To evaluate what physical effects we can have on the unit by varying the generator excitation, we need to consider the relationship between electrical degrees and mechanical degrees for a multipole machine,

$$\theta = \frac{p}{2}\theta_m \tag{1}$$

where:
- p = number of poles
- θ = electrical degrees
- θ_m = mechanical degrees

Since the generator has 36 poles, there are 18 electrical degrees for each mechanical degree. Through our testing, we were able to force about 1/4 of an electrical degree in movement. This translates to only about 0.0138 mechanical degrees in movement.

If we calculate the mechanical torque which results from a ± 2.5 MW power swing,

$$T = \frac{P}{2\pi s} \tag{2}$$

where:
- P = power (ft-lb/s)
- T = mechanical torque (ft-lb)
- s = speed (r/s)

a torque fluctuation of $\pm 88{,}040$ ft-lb results. If we convert the small mechanical angular displacment into an angular velocity, we can then calculate the torque associated with this additional movement of the generator rotor. An additional torque of ± 100 ft-lb, or roughly 0.1-percent of the fluctuating torque predicted by Equation 2 results. You can see that the torque which results from the small angular movements due to the variations in the generator excitation can not physically affect the turbine runner with enough force to disrupt the draft tube vortex. This was reinforced during our tests as we saw no change in the draft tube pressure fluctuations, vibration, or shaft runout under any variation in the exciter input.

While we were not able to modify the draft tube vortex through variations in the exciter input, we were able to affect the amplitude of the power fluctuations. Figure 4 shows the effect of a sine wave input to the exciter at a frequency of 1.8 Hz (near the resonant point of the electrical system). The power output fluctuations are amplified as the power system enters a resonant condition. With the unit in the roughest operating zone, direct feedback of the power output signal and the draft tube pressure signal to the exciter had little effect at all but high gain levels. This modified the power output response, fig. 5, however, the draft tube surge remained unchanged. The ringing or reactance portion of the power output fluctuation was reduced, forcing a drop of approximately 30-percent of the peak-to-peak amplitude of the power swings.

CONCLUSIONS

The control of draft tube surging can provide many positive dividends in the operation of a hydroelectric powerplant. Maintenance of the major mechanical features of a turbine-generator will likely be reduced if vibration and shaft runout can be minimized. In addition, by controlling power swings which are output to the grid, operating ranges of the unit can be extended.

The traditional methods for dealing with draft tube surging involve physical modifications to the unit, such as fins or splitters in the draft tube, extension cones or snorkels on the runner, or injection of air - usually in large quantities. The concept which was evaluated at Blue Mesa Powerplant did not require any physical modifications.

Variation of the generator excitation did not actually control or modify the vortex present in the draft tube during a surging condition. However, a reduction in the output power swing was achieved. With the unit in its roughest operating zone, a 30-percent decrease in the peak-to-peak fluctuation was achieved. However, this reduction came at the expense of an increase in terminal voltage output. Future application of this technique to control power swings is still undetermined. It would seem to have some promise if a unit is required to operate in a surging region. The question still remains whether a 30-percent reduction in power fluctuations is beneficial enough to allow for the increased oscillations in the terminal voltage of the generator and the mechanical wear and tear that a unit will be exposed to if operated for extended periods in a surging zone.

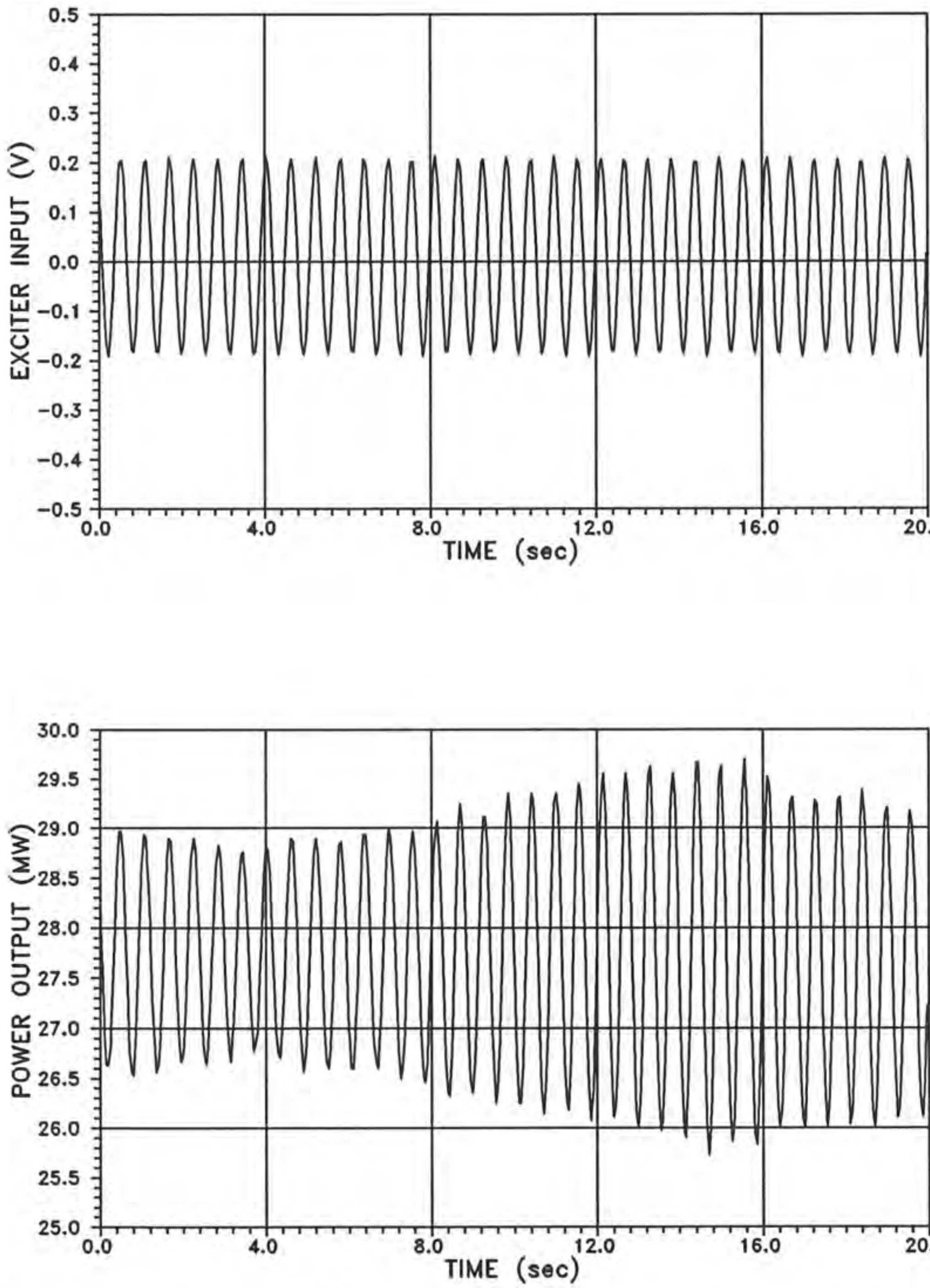

Figure 4: Amplification of the power output as a swept sine wave reaching 1.8 Hz is input into the exciter.

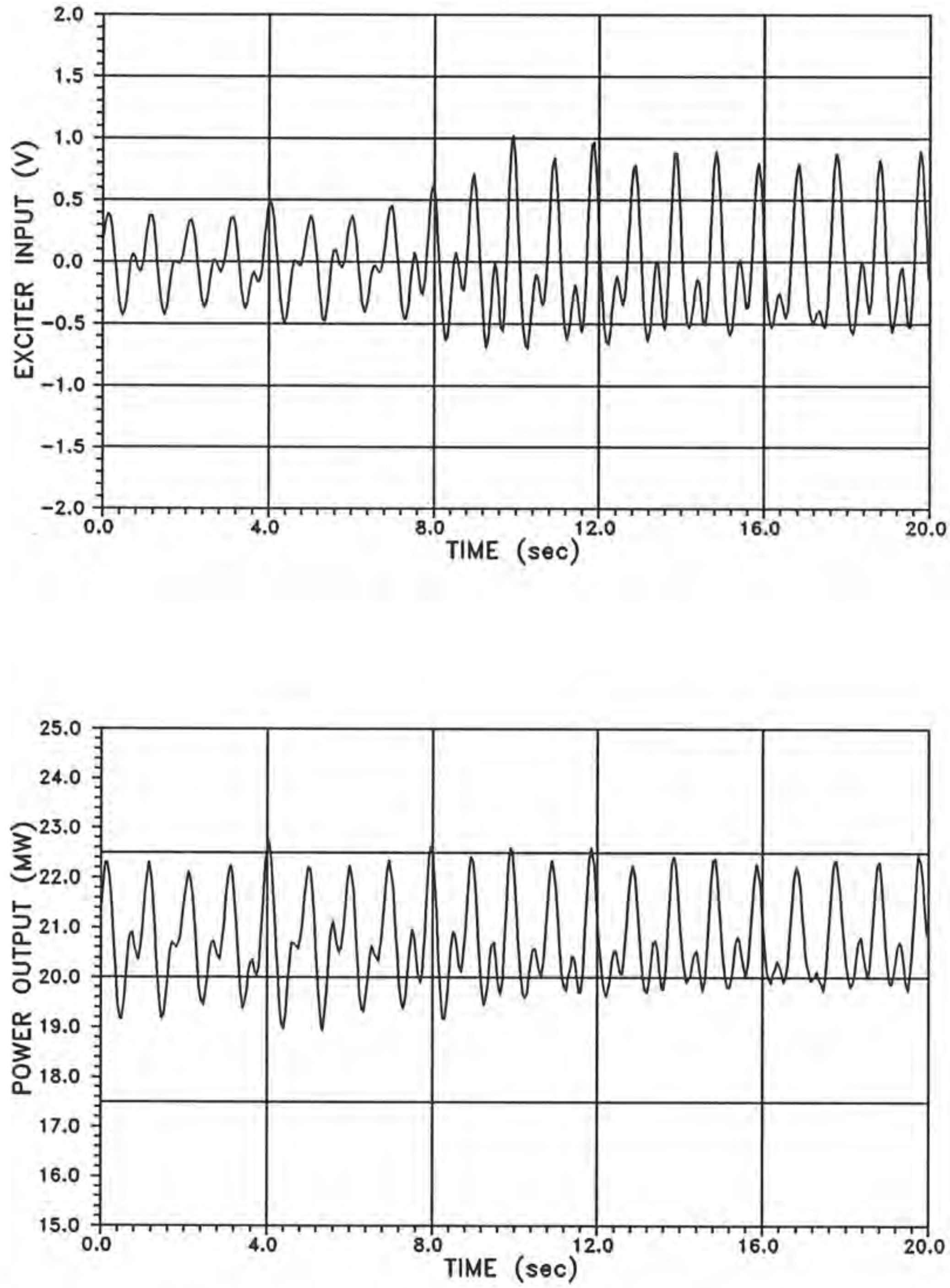

Figure 5: Reduction of power output fluctuation amplitude (~30-percent) due to change in polarity of feedback (power output) signal into exciter.

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