THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF MECHANICAL AND NUCLEAR ENGINEERING

ANALYSIS AND MODEL OF A HYDROELECTRIC POWER PLANT FOR SIMULATING RAMP RATES

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ABSTRACT

As the world seeks to produce power more efficiently while minimizing environmental consequences, hydro and wind power generation become increasingly important. Hydroelectric power plants have the flexibility of changing their power generation output more quickly than traditional power plants. Because of this, hydropower can complement wind farms whose power output is dependent on weather conditions. Also, because the demand for power is not static, hydropower can also be used to supplement nuclear or fossil fuel power plants as needed.

In order to meet the fluctuating power demands, it is important that these plants can adjust their output in a timely manner. Francis runners operate within a range of 60-100% of design capacity. The purpose of this thesis is to model a midrange plant with a Francis impeller with a maximum power output of 200 MW. The model will include the reservoir, penstock, and turbine. Most of the research has been done based on controlling the rotational speed of the turbine. However, as it has become possible to monitor shaft torque, this model attempts to control the power output directly. The simulated controller will detect a difference between the power required by the grid, and the power currently being generated. The controller then opens or closes the wicket gates changing the mass flow rate into the turbine as necessary. The whole concept hinges on the ability to design the gates so as to keep rotational speed constant.

The results show that the turbine is able to go from 60% to maximum capacity in twelve seconds and back down in fifteen seconds. These ramps were negotiated with only small deviations from desired speed: within 1.5% or better than design.

Overall, this model controls power proficiently, and if a proper wicket gate function can be implemented then the model can be useful to future designers.

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ACKNOWLEDGMENTS

I would like to thank Dr. Horacio Perez-Blanco for giving me the opportunity to conduct this research. He was my teacher, resource, and friend from start to finish. His help and guidance in the modeling and writing was invaluable, and without it I never could have completed this thesis.

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I would also like to thank Scott Richards for his information regarding grid frequency error limits.

Last, but not least, I would like to thank my girlfriend, family, and friends for keeping my spirits up when this work made me frustrated and there seemed to be no solution.

NOMENCLATURE

A	cross-sectional area of the penstock [m^2]
B	impeller flow depth [m]
D_p	diameter of the penstock [m]
f_p	friction factor of penstock [1]
g	acceleration due to gravity [m/s^2]
G	function of gate position [$m^{3.5}/kg^{0.5}$]
h	height of reservoir above turbine [m]
K	water time constant [m^4/kg]
MFR	mass flow rate [kg/s]
p_0	static pressure of water column [Pa]
p_f	pressure loss due to friction [Pa]
p_t	pressure at turbine admission [Pa]
P_{tur}	power generated by turbine [W]
q	volume flow rate [m^3/s]
q_{des}	volume flow rate, when gates fully open [m^3/s]
r_t	radius of turbine [m]
Tr	torque produced by turbine [J]
Tw	water time constant (head) [s]
u	absolute water velocity, in turbine [m/s]
u_r	radial component of u [m/s]
u_u	tangential component of u [m/s]
V	velocity of water in penstock [m/s]
α	openness of wicket gates [deg]
η_t	efficiency of the turbine [1]
π	pi [1]
ρ	density of water [kg/m^3]
ω	rotational speed of turbine [rpm]
Ω	rotational speed of turbine [rad/sec]

LIST OF FIGURES AND TABLES

CHAPTER 1 - INTRODUCTION

1.1 - Introduction

1.1.1 – History of Water Power

The idea of transferring the energy from moving water to mechanical energy has been around for thousands of years. The ancient Greeks invented the water wheel between the 300-100 BC. [1] These designs were passed on to the Romans, but their usage was limited because free labor in the form of slaves was abundant. However, during the first few centuries AD near what is now Fontvieille, France, water from an aqueduct was used to power eight water wheels for a flourmill. [2]

Figure 1: Roman aqueduct in Fontvieille, France [2]

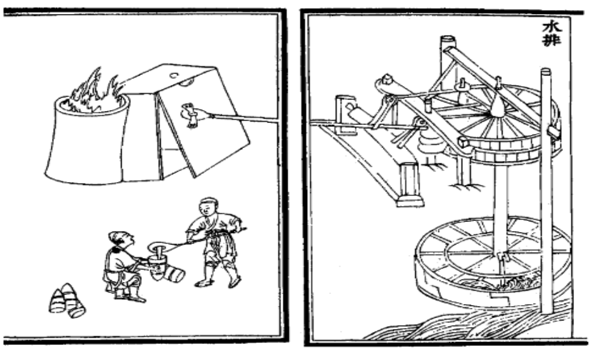


Figure 2: Ancient Chinese waterwheel system [3]

Waterpower in China was developed around the same time as the Greeks and Romans, however their wheels were often vertical, and used to power billows used in iron casting as shown in Figure 2. They also transformed this rotary motion into linear by installing a cam system. [3]

Water power use expanded in Europe during the middle ages for several reasons. These included new land being populated and the lack of workers resulting from the Black Death killing between an estimated 30-60% of Europe's population. It was common to use water to cut wood and to mine.

With the invention of the electrical generator in the late 1800's, it became possible to convert this source of energy into electricity. In 1882, the world's first hydroelectric power plant was opened on the Fox River in Wisconsin. [4] By 1889, there were 200 plants in the U.S. alone. By 1940 hydropower accounted for 40% of the country's electrical generation. The total energy generated from hydro in 1980 was triple that of what was possible in 1940. Because of the increased use of both coal and natural gas, and the invention of nuclear power, only 7.1% of all energy produced in the United States today is from water. [5]

1.1.2 – How It Works

The idea behind a hydropower plant is rather simple. It exploits the energy of a large amount of water moving downhill due to gravity. The amount of power generated is based on the change in elevation and the flow rate. Every hydro plant has four main components as seen in Figure 3.

The Reservoir: A large body of water that is used to feed the plant. Sometimes a river is used as a constant source of water. However, due to seasonal changes, the water level is not always constant. Most times, a dam is used to hold back the water allowing for a more constant supply. There can be multiple dams on a river at different elevations along the river's path. A dam can also be used to form a lake, where water is pulled from when the gates are opened. The water at this point is considered stored energy.

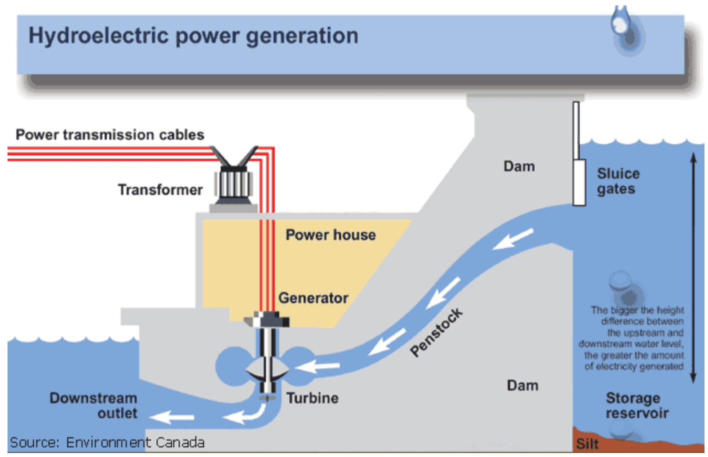


Figure 3: Schematic of a Simplified Hydroelectric Power Plant [6]

The Penstock: A pipeline that uses the pull of gravity to carry water to the turbine. It is often made of a smooth metal in order to reduce the amount of head lost to friction. More power can be produced with a greater change in elevation, so penstocks are often several hundred meters long. The power generated is also a factor of the mass flow rate. For this reason penstocks can have diameters of several meters. The energy in the water is kinetic due to its velocity ($V^2/2$), but it also has potential energy due to its pressure (P/ρ).

The Turbine: After flowing through the penstock, the water reaches the turbine where the energy is converted to a mechanical form. The water strikes the blades causing the turbine to rotate. Multiple turbines and penstocks can be used at the same plant to generate more power. Most modern plants use a Francis Turbine, so that is what will be used in this model.

The Generator: The turbine is connected to the generator by a vertical shaft. This shaft rotates large magnets past copper coils. Faraday's law of induction states that these changing magnetic fields create an electrical current.

1.2 - Motivation

1.2.1 – Pumped Storage

Besides being a renewable, environmentally conscious energy source, hydro power can be extremely advantageous in meeting the power demand. This is done through the use of pumped storage. In this scenario, after the water leaves the turbine, it does not flow further down the river. Instead it is kept in a lower secondary reservoir. During the day when the power demand is greater (and plants can sell power for a greater profit), water flows from the upper reservoir through the turbine providing energy and into the lower reservoir. At night when the demand is less (and prices are cheaper), it uses energy to pump the water back into the upper reservoir. Figure 4 illustrates this reversible flow.

Pumped storage is often used in conjunction with other forms of power generation. For instance, solar plants cannot produce electricity at night. During the day, some of the power produced is sold to the grid and some of it is used to pump water to the upper reservoir. Then at night, water flows back down producing the power that the solar panels cannot. Pumped storage can also be used for wind energy whose power production is based on variable wind speeds. [8] Although much work has gone into modeling what the wind speeds will be at the location of the wind farms, wind can still change at any moment. If wind is producing energy during a time of low demand it can be used to pump the water. The water is then used to sell power during higher demand. This type of service requires hydro plants that can modulate their output, of which only a few are in existence.

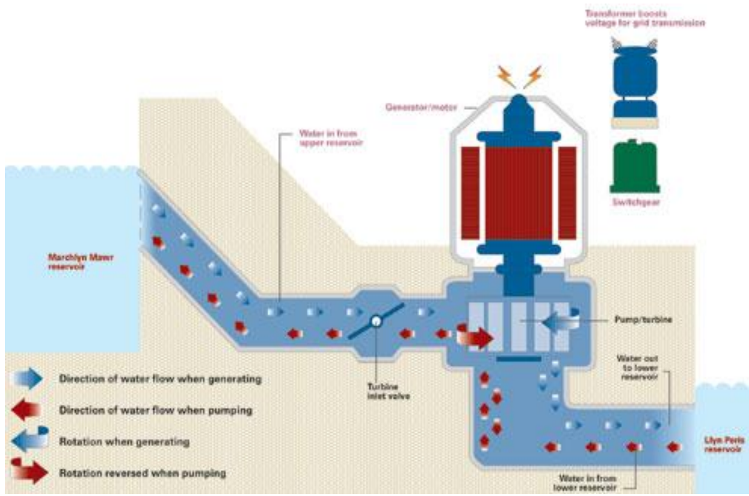


Figure 4: Water Flow for Generation and Pumping [7]

Hydro power can also be used to supplement power generation sources that cannot vary their power production quickly or efficiently, like nuclear power. During high demand the power from the nuclear plant and the hydro plant is sent to the grid. When the demand decreases below what the nuclear plant can produce or if the prices are too low, power is used to pump the water back to the upper reservoir to prepare for the next high demand time.

1.2.2 – Ramp Rates

The idea that the power demand fluctuates throughout the day (and year) is a well-documented one. For my work, I used research that had been conducted by Lisa Branchini from the *Universita di Bologna* with my thesis advisor, Dr. Horacio Perez-Blanco of *Pennsylvania State University.*

The following figures and table are from their article "Coupling Wind and Pump Storage Hydro: Capacity Constraints" that is in the process of being published. [9]

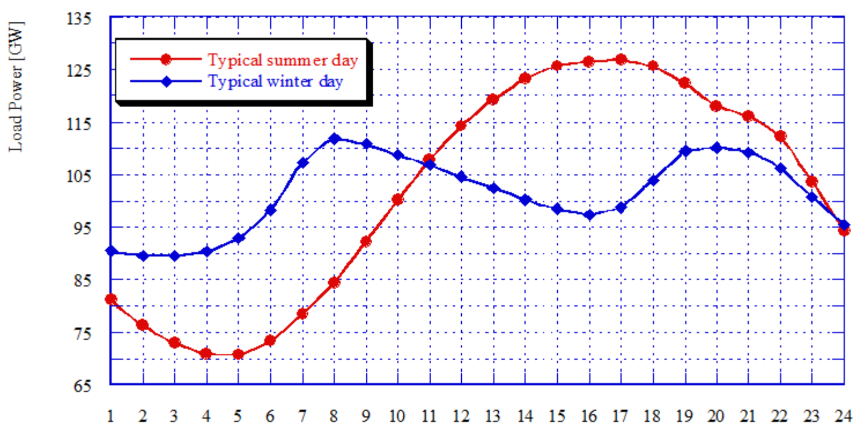


Figure 5: Load profile for PJM service area, for a typical summer and winter day [9]

As seen in Figure 5, the load power for the grid can vary by as much as 50 GW in a single summer day. These changes in demand are called ramp rates. Figure 6 shows the fluctuations in power generation for a wind plant. As seen in these graphs, if power demand is to be met, hydro power generation must be controlled quickly and accurately to compensate for load changes and variable wind production.

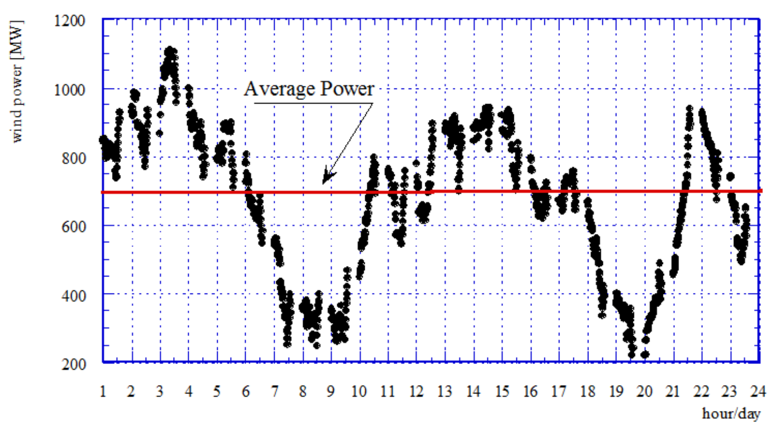


Figure 6: Wind generated power for PJM, for a typical winter day [9]

Table 1 shows the maximum ramp rates that can be expected on a typical winter day. My thesis will model a typical midrange plant, and determine how many turbines would be required to meet these ramp rates. Of course, these results are valid only for ramping up the power production outlined in Table 1. Actual ramp rates vary based on location, season and day.

Table 1: Load maximum and minimum ramp rates for a winter day [9]

	5 min ramp rates	10 min ramp rates	15 min ramp rates	20 min ramp rates	25 min ramp rates	30 min ramp rates	1 hr ramp rates	2 hr ramp rates
MAX UP [GW]	1.36	0.89	3.27	4.07	4.96	5.72	9.72	16.41
MAX DOWN [GW]	-0.82	-0.87	-1.89	-2.30	-2.83	-3.34	-5.96	-11.05

1.3 – Previous Models

The main goal of this thesis is to determine how quickly hydro plants can change their power generation. In order to do this, it is essential that the speed of the turbine remain near constant in order to produce electricity at the right frequency. For smaller turbines, a governor can be used to control the speed. It essentially flips switches that correspond to different loads which connects or disconnects them from the generator. The more load that is connected to the generator the slower it rotates; the less load on a generator the faster it rotates. If it is rotating too fast, loads are connected to slow it down, and vice versa. [10]

Larger turbines keep their frequency constant differently. When the load on the grid is larger, the turbine rotates slower. To counteract this, more water is allowed to flow in. The excitation current in the generator's electromagnet must then be adjusted in order to balance the increased power generation. This causes a decrease in load, which in turn means the controller lets less water in, and the process must be repeated with an increase in current. This causes a constant varying of water flow and current attempting to balance things out. [11]

As explained by De Jaeger, there is a function G, which relates the flow to the pressure at the turbine inlet. [12] This function is calculated after the plant has been built. This thesis will show that if a specific function can be designed, the need for the constant varying of flow and current disappears, because with a wicket gate function, the power to torque ratio can be kept constant no matter what the flow of water is. That would cause the rotational velocity to be constant, and would improve control accuracy and response time.

CHAPTER 2 – APPROACH

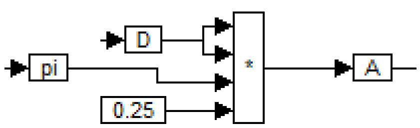
2.1 - Penstock Equations

The following are equations used to model the penstock. They start by using specifications decided on in the previous section and build up from there.

The block diagrams used in the VisSim model are included below the corresponding equation. A complete block diagram is included in the appendix (Figure 25).

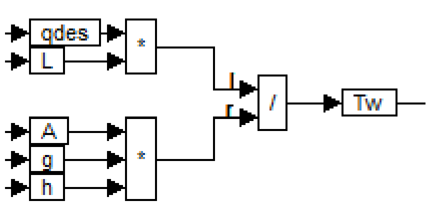
The area of the penstock can be expressed as,

$$A = \pi \cdot \left(\frac{D_p}{2} \right)^2 \quad (1)$$



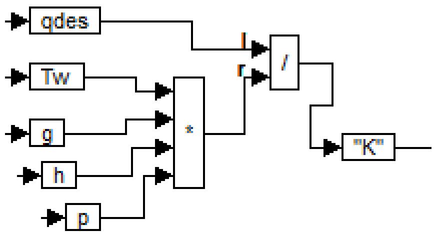
When the wicket gate is adjusted, it takes some time for the water flow in the penstock to adjust to new conditions. This time constant was calculated in two steps, based on [14].

$$Tw = \frac{q_{des} \cdot L}{h \cdot g \cdot A} \quad (2)$$



The time constant is used to relate the change in flow rate to a change in head. This model relates it to a change in pressure, so by using (2), K can be calculated.

$$K = \frac{q_{des}}{h \cdot \rho \cdot g \cdot Tw} \quad . \tag{3}$$

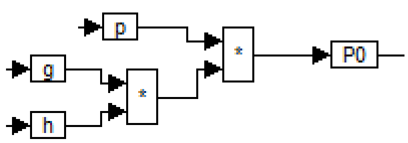


Where the assumption is made that the water is incompressible:

ρ = constant = 1000 kg/m^3.

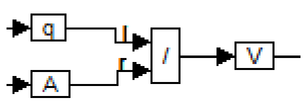
The static pressure at the turbine position is the pressure caused by the water column sitting in the penstock above the turbine. As such, it is calculated as,

$$p_0 = \rho \cdot g \cdot h \tag{4}$$



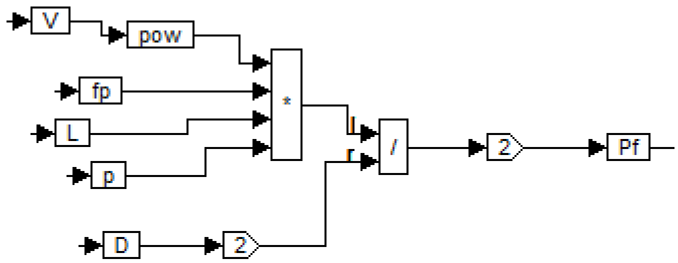
Later, the flow rate (q) is calculated, but for now we will use it in several equations. Using (1), the velocity of the water in the penstock is known to be related to flow rate as follows,

$$V = \frac{q}{A} \tag{5}$$



Now that the velocity of the water is known (Eqn 5), the pressure lost due to friction in the penstock can be calculated using the Darcy-Wesibach equation as follows,

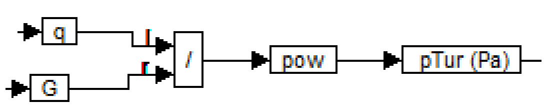
$$P_f = \frac{V^2 \cdot L \cdot \rho \cdot f_p}{2D} * 2 \qquad (6)$$



where f_p is the Darcy-Weisbach resistance coefficient and estimated to be 0.009 based on a Moody resistance diagram. The entire equation is multiplied by an arbitrarily chosen constant "2", to account for additional losses due to bends in the pipeline. It was chosen so that frictional loses were more comparable to real life plants. [13]

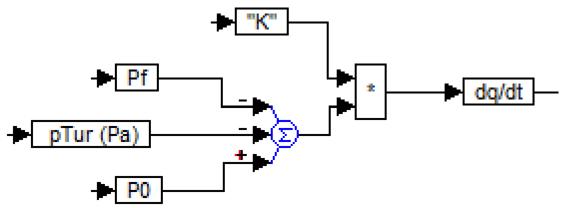
G is a function based on the position of the wicket gates (α). In traditional models, G is calculated by tests after the plant is running. This thesis suggests that future plants should design the gate beforehand so that G has specific values at known alphas. It is shown later why this offers such a considerable benefit. For now, the inlet pressure is calculated as

$$p_t = \left(q/G \right)^2 \qquad (7)$$



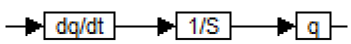
Using the laws of momentum and equations (3), (4), (6), and (7) the change in flow rate can now be calculated by,

$$\frac{dq}{dt} = K\left(p_0 - p_t - p_f\right) \tag{8}$$



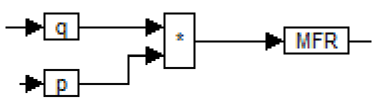
Integrating this result gives the volumetric flow rate (q),

$$q = \int \frac{dq}{dt} \tag{9}$$



and can be fed back into equations (5) and (7) of the model. The mass flow rate is simply

$$MFR = \rho \cdot q \tag{10}$$



2.2 - Turbine Equations

The following are equations used to model the turbine. They start by using specifications decided on in Section 2.1, variables calculated in Section 2.2 and build up from there.

The block diagrams used in the VisSim model are included below the corresponding equation. A complete block diagram is included in the appendix (Figure 25).

The efficiency of the turbine is calculated by using the graph shown in Figure 7.

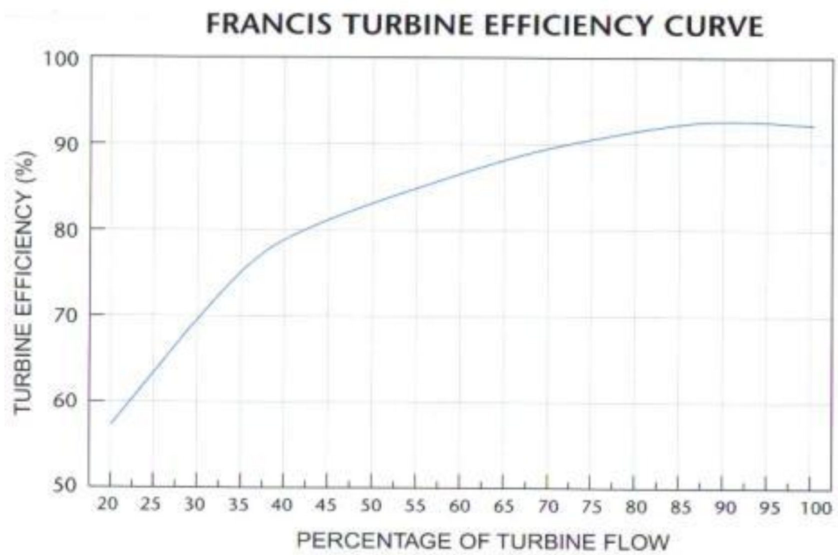
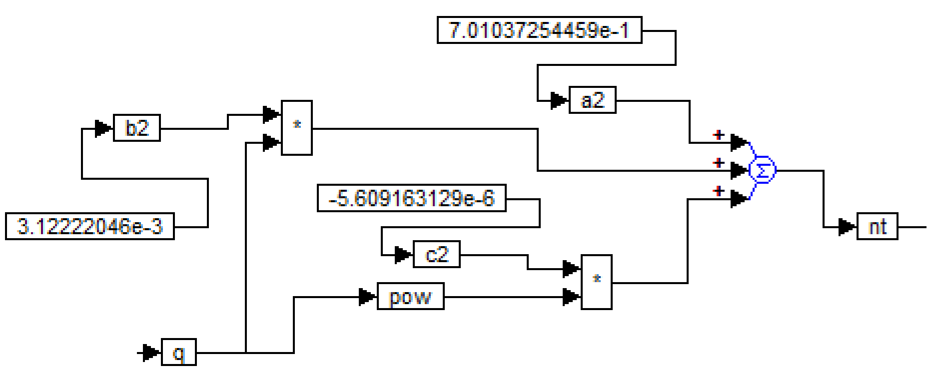


Figure 7: Francis Turbine Efficiency Curve [14]

This was taken from a project done by the University of Strathclyde at Glasgow. [14] Using curve fitting and the flow rate at maximum capacity, the efficiency was estimated to be

$$\eta_t = 0.7010 + (3.1222 * 10^{-3})(q) - (5.6091 * 10^{-6})(q^2) \qquad (11)$$



The power generated by the turbine can be closely estimated using (7), (9), and (11) to be

$$P_{tur} = q \cdot p_t \cdot \eta_t \qquad (12)$$

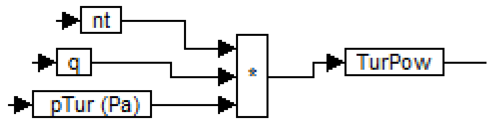
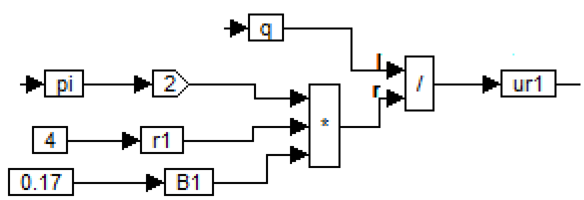


Figure 8: Sketch relating u_u, u_r, and α

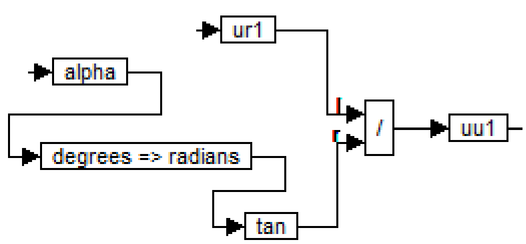
The torque is slightly more difficult to calculate. As shown in Figure 8, the water has a tangential and radial velocity, u_u and u_r respectively. The angle varies between 20-12 degrees for this model. This angle controls how much water is entering the turbine, and at what angle it strikes the blade. u_r can be calculated by

$$u_r = \frac{q}{2\pi \cdot r_t \cdot B} \qquad (13)$$



where B is the depth of the impeller and r_t is the radius of the turbine blades. u_u can be calculated using (13) and the angle of the wicket gates as shown in Figure 9

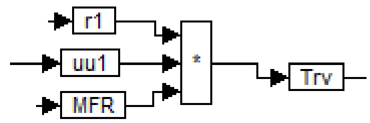
$$u_r = \frac{u_r}{\tan(\alpha)} \qquad (14)$$



where α is in radians.

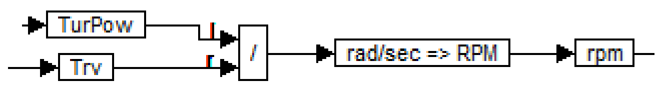
Torque can finally be calculated using (10) and (14) to be

$$Tr = MFR \cdot u_u \cdot r_t \tag{15}$$



Because the pressure at the inlet of the turbine is a function of G, if G can be controlled by its design, then inlet pressure becomes a function of the wicket gate position. More importantly, the power and torque produced by the turbine become a function of α because they are controlled by the inlet pressure. What this means, is that hypothetically a specific gate function can be designed such that the torque and power have a constant ratio. This is important because

$$\Omega = \frac{P_{tur}}{Tr} \tag{16}$$



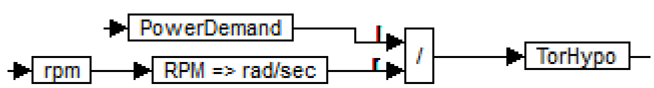
This means that if the ratio is kept constant, the rotational speed of such a turbine stays constant as long as it is running within the operating range.

In order for power to be put onto the grid it must be produced at a specific frequency and that frequency must not vary more than 1.5%. That means that this constant ratio is very important because operators of the plant would no longer have to open or close the wicket gates slowly to give time for the rotational speed to settle; they could just produce the power needed by opening the gates to the corresponding angle. The design for G will be discussed later.

2.3 - Controller Equations

Because the designed gate function keeps the rotational speed constant, the controller for this model is rather simple. The power generated is simply the torque times the rotational speed (which in the case of this model ~100 rpm at all times). Recent technology has allowed for the measurement of minute changes to the torque within a shaft. HBM has developed a digital torque transducer that has a 19-bit resolution that can measure at up to 6000 Hz. [15]
This allows power generation to be calculated easily and precisely almost instantly.

In order to match the required power, one must simply control the torque. To calculate the necessary torque a variation of Equation 16 is used:



(16)

Where “PowerDemand” is what the plant needs to generate, and “TorHypo” is what the alpha controller uses to determine the necessary gate position. The torque can be measured constantly to make sure that everything is going according to design.

Because the torque is a function of α, a graph was plotted and a curve fit generated as shown below in Figure 9.

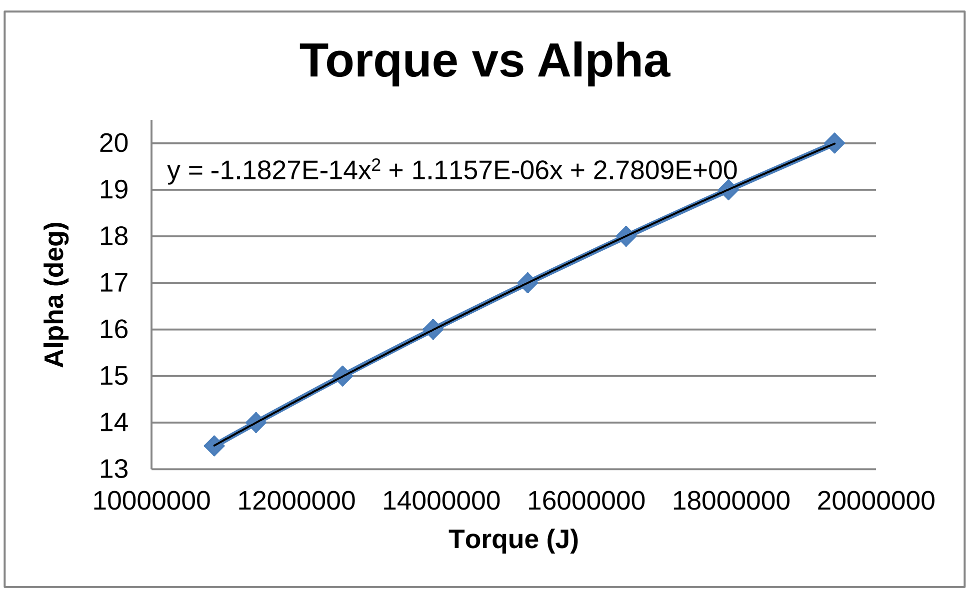
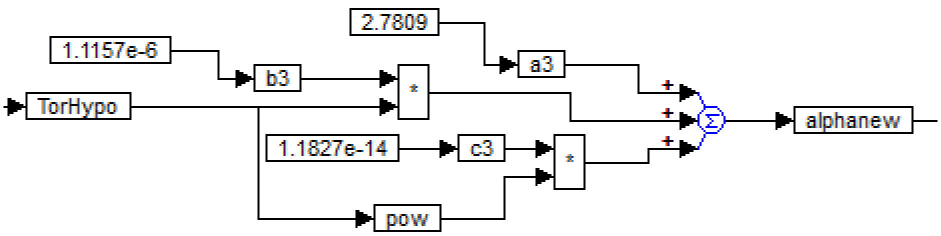


Figure 9: Alpha as a function of torque

Using the curve fit, a basic controller can be designed:

$$\alpha = 2.7809 + (1.1157 * 10^{-6})(Tr) - (1.1827 * 10^{-14})(Tr^2) \quad (17)$$



Now, when a certain torque is required (to produce the corresponding power), the controller simply opens the gate to the correct angle.

Figure10 shows a comparison of this model's Torque vs Alpha curve and one that was generated using an efficiency hill graph from [13]. The graph is in included in the appendix as Figure 26.They have the same general slope and shape; the main difference is the steep slope at the end of the efficiency hill curve. This is because their data indicates a decrease in efficiency when running at full load, while the efficiency curve used here does not. [14]

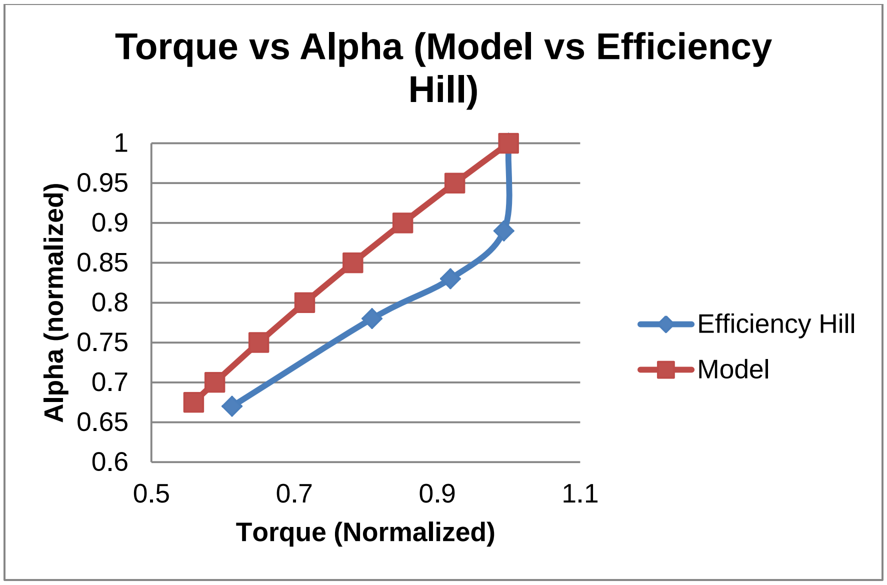
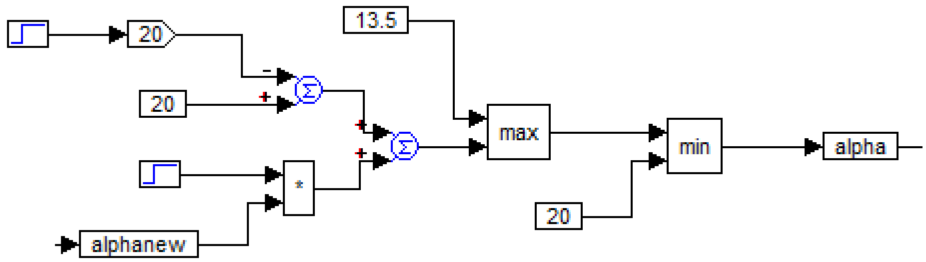


Figure 10: Comparison of Torque vs Alpha calculations

The following is how the α calculated from the curve fit is entered into theVisSim controller:



There are two important things to note. First, it keeps α at 20 degrees for the first second of simulation using step functions. This ensures that the model starts up properly. Second, it sets limits so that α cannot open or close too far. This ensures that the system stays within the planned operating range.

The final step comes from the previously mentioned G function. As mentioned before, the final purpose of the G function is to keep the ratio between power and torque at 10.47 by controlling the pressure at the inlet of the turbine. The design of such a gate is beyond the scope of this thesis and is discussed further in the conclusion. However, the equation of such a gate can be determined by inverse manipulation of the observed behavior.

$$10.47\frac{rad}{s} = 100rpm = \frac{P_{tur}}{Tr} = \frac{q \cdot p_t \cdot \eta_t}{r_t \cdot u_u \cdot MFR} = ... \tag{18}$$

Working further backwards will show that it becomes a function of *G*, and α and *q*, which are both functions of *G*. From this, *G*(α) was graphed and curve fitted with a polynomial function as shown in Figure 11.

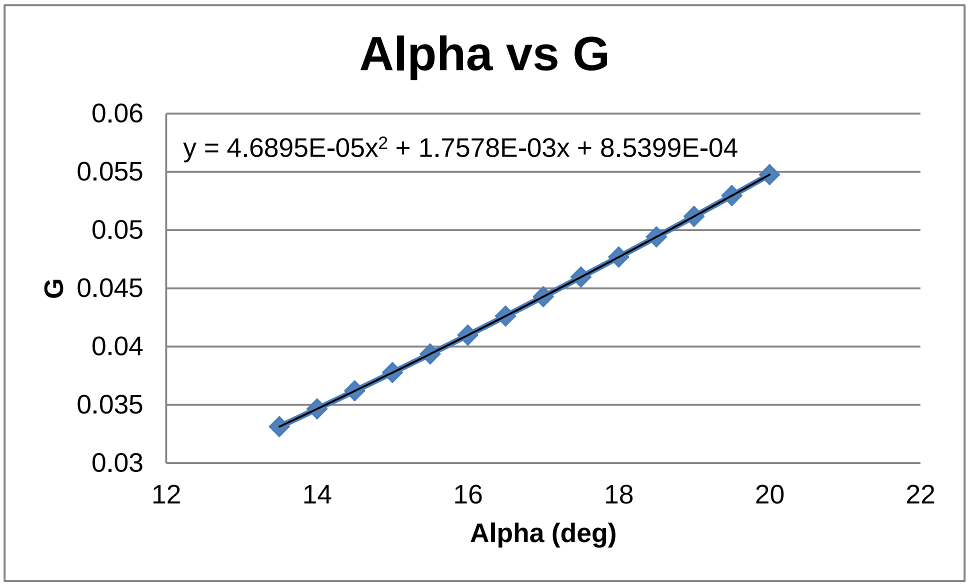
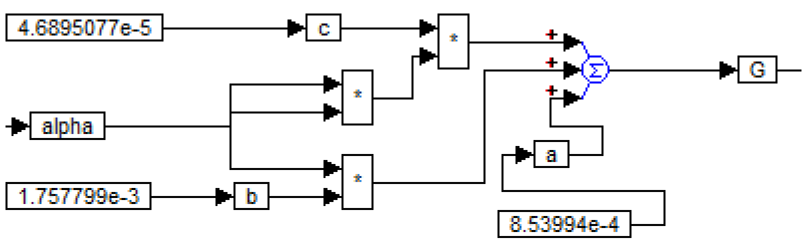


Figure 11: G as a function of alpha

This curve fit gives us the following equation:

$$G = 8.5399E^{-4} + (1.7578E^{-3})(\alpha) - (4.6895E^{-5})(\alpha^2) \tag{19}$$



This equation is used to calculate the inlet pressure as shown in Equation 7. See the Figure 25 for further clarification.

These calculations can be fine-tuned to allow designers of any size turbine to use them.

Remember that Equation 7 tells us that G is simply used to calculate the pressure at the inlet of the turbine. Using the previous equations, designers can come up with a gate or control system that makes the inlet pressure appropriate to match G(α) and thus keep speed constant. This is discussed further in Section 4.2.

2.4 - Model Specifications

After researching several papers including [16] and [17] and considering the purpose for this model, it was determined that the plant should produce ~200MW at full capacity. (Both of these papers created models for examining the dynamic response of constructed plants and provided examples of possible dimensions of both the penstock and turbine.) This would allow it to model a mid-sized plant, or be hypothetically connected in parallel to several others in a large plant. A penstock frictional loss between 1-2% of the static head was deemed acceptable in modeling a real life plant based on these papers, as was a velocity of ~7m/s through the penstock.

Using the equations from the previous sections, rough estimates of the specifications of the plant were decided. Throughout the modeling, some constants where changed as necessary. The following are the final design specifications:

B=0.17 m, h=260 m, L=300 m, r_t=4 m, q_{des}=87 m/s, D_p=4 m

ω would be aimed at a constant speed of 100 rpm

α would range from 20-12 degrees to control power between 100-60% of capacity

Figure 12 shows a rough sketch of the hypothetical plant.

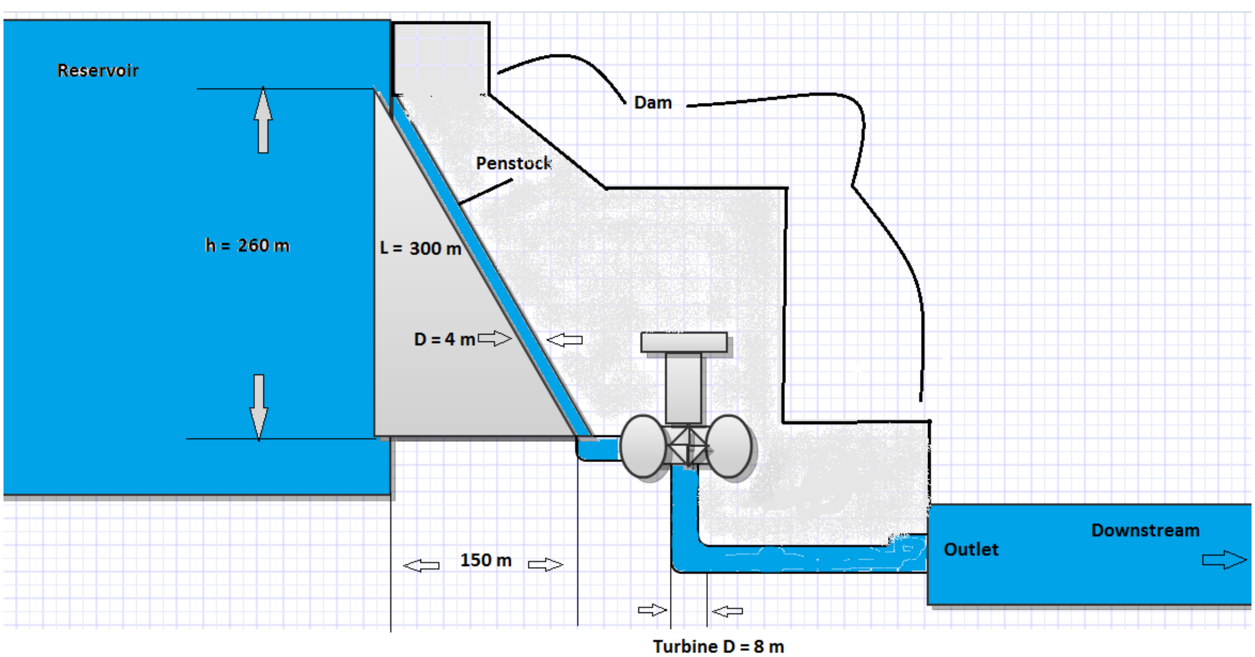


Figure 12: Sketch of the Model Plant

CHAPTER 3 – RESULTS

3.1 – Discussion

The results of this model shed light on important key features related to the performance and operation of the power plant. It is shown that the turbine can ramp up from 60-100% capacity in twelve seconds and back down to 60% in only another 15 seconds.

In order to meet the 5 minute ramp rates from Table 1, it is estimated that 5, 400 MW impellers would be needed. The other ramps could also be met in the specified amount of time, but more impellers would be needed to increase the total capacity.

Figures 13 and 14 show the simulated power demand, and the resulting power that is supplied. The system was run for ten seconds from start up in order to allow the system to settle before the ramp was applied. These show how quickly this model is able to change its power output. This is crucial when using hydro power to complement wind power as discussed previously.

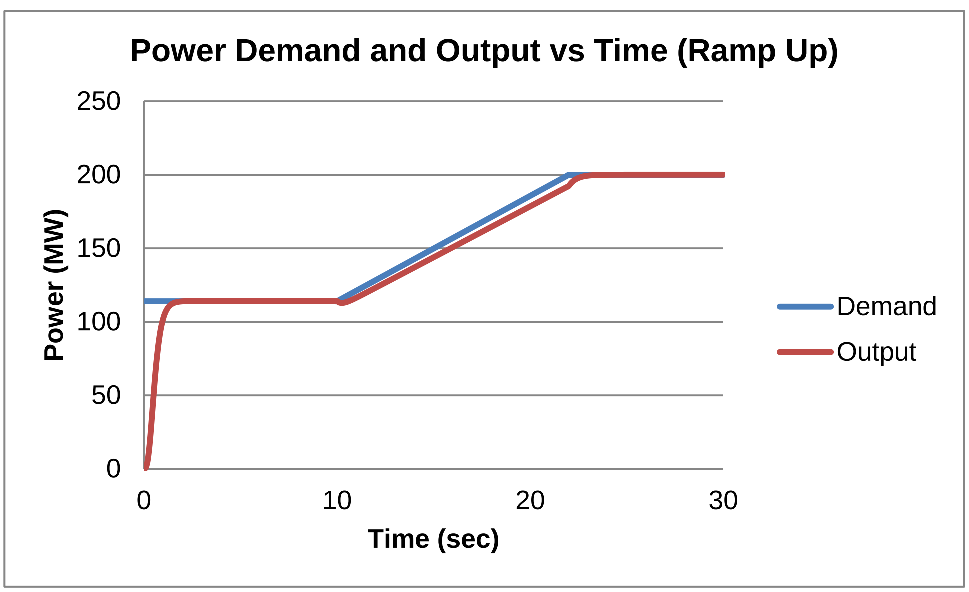


Figure 13: Power Demand and Output vs Time (Ramp Up)

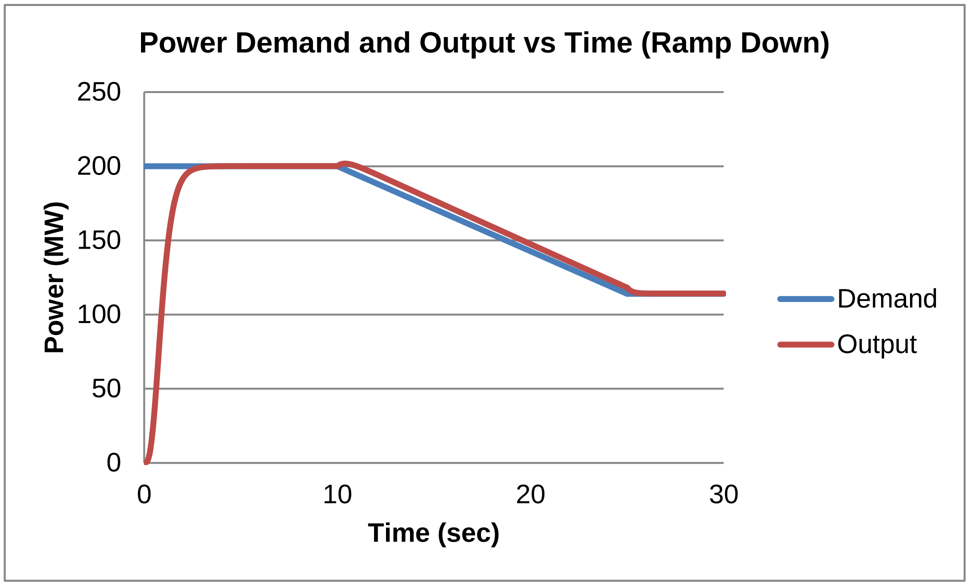


Figure 14: Power Demand and Output vs Time (Ramp Down)

Figures 15 and 16 show the difference between power demand and supply during the ramps. It also shows the difference between the rotational speed and the target speed (100 rpm).

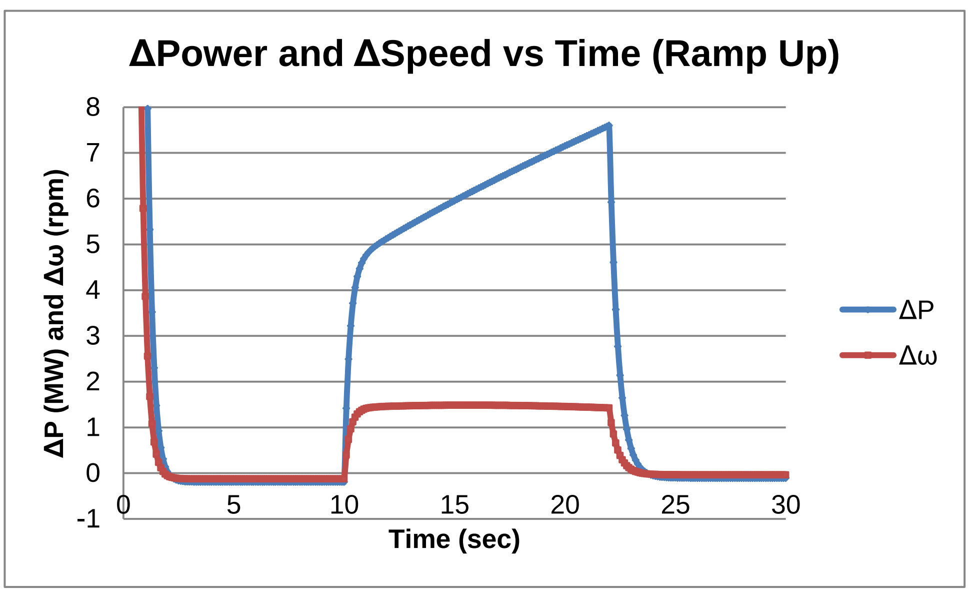


Figure 15: ΔPower and ΔSpeed vs Time (Ramp Up)

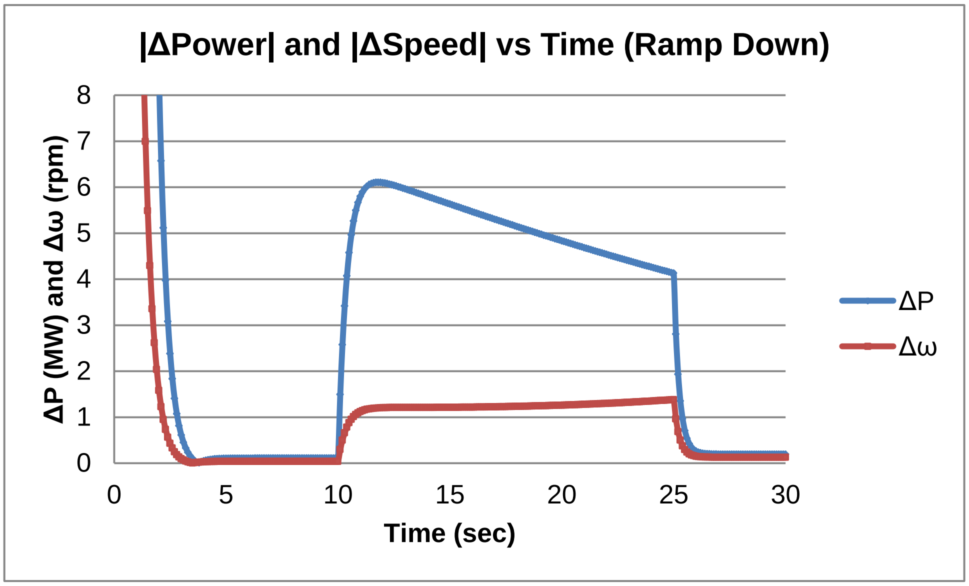


Figure 16: ΔPower and ΔSpeed vs Time (Ramp Down)

It is known that a plant will lose synchronization with the grid when it is off by +1.5Hz in order to prevent significant damage or above average wear to the equipment from occurring. [18] This model has a target rotational speed of 100 rpm, which is equal to 1.67 Hz. This means that to reach the grid frequency of 50 Hz it must employ a gear ratio of 30. Therefore, to stay within the +1.5 Hz range on the grid, it must stay within 0.05 Hz at the turbine stage, which is 3 rpm. As an added factor of safety, this model cuts that in half and does not stray more than +1.5 rpm from its target at any time while still meeting these ramps.

The ΔPower may seem very large in the graphs, and it is. There is a significant lag affecting the output. However, it is important to note that this is only while the ramp is in progress. Within 3 seconds of the end of the ramp, difference in power reaches steady state at ~0. This is shown in Figures 17 and 18. These are magnifications of Figures 15 and 16 respectively with the data beginning one second before the end of the ramp.

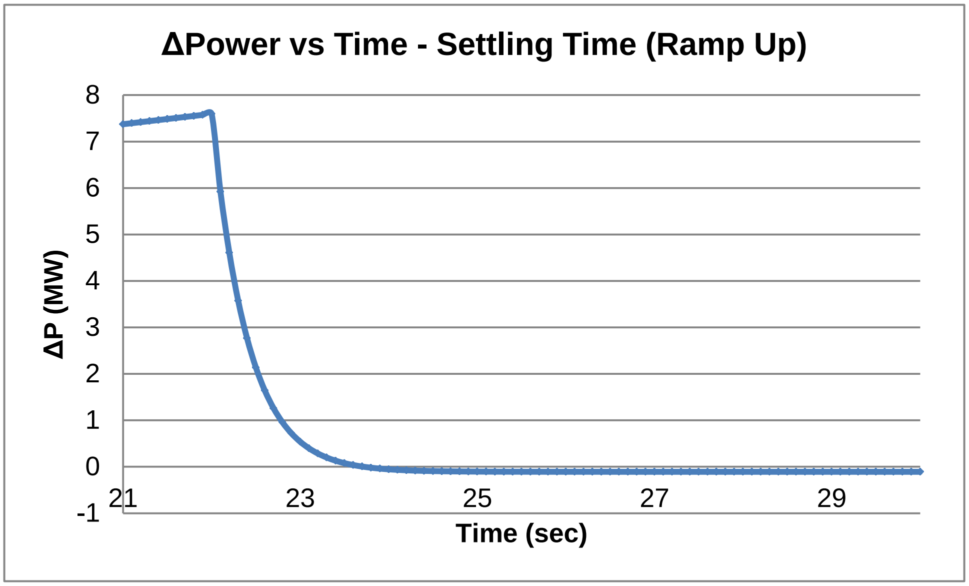


Figure 17: ΔPower vs Time - Settling Time (Ramp Up)

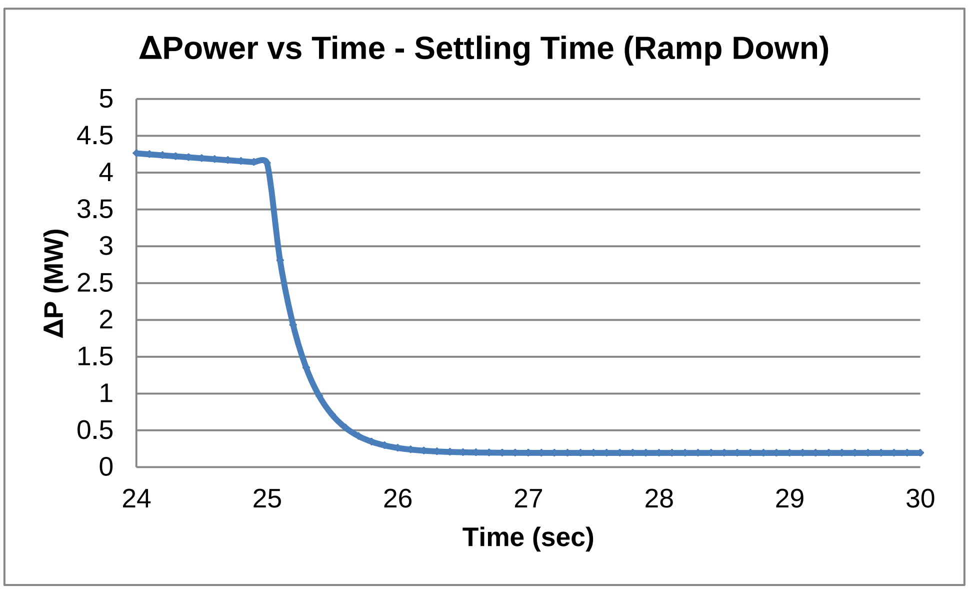


Figure 18: ΔPower vs Time - Settling Time (Ramp Down)

Figures 19 and 20 show MFR and α versus time for both ramps. As expected, in order to increase power, a larger flow is needed. In order to achieve this, the wicket gates are opened further. The opposite is true for the down ramp.

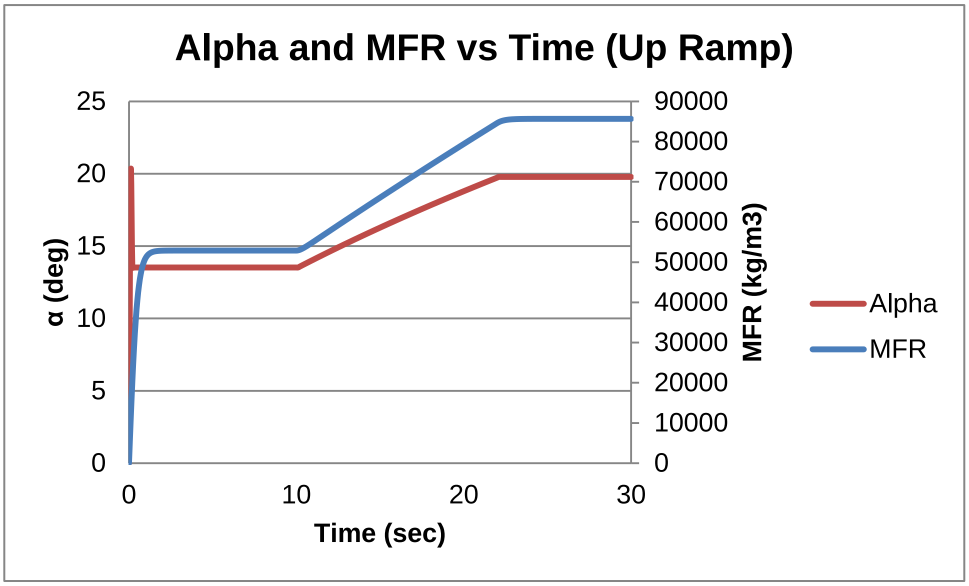


Figure 19: Alpha and MFR vs Time (Ramp Up)

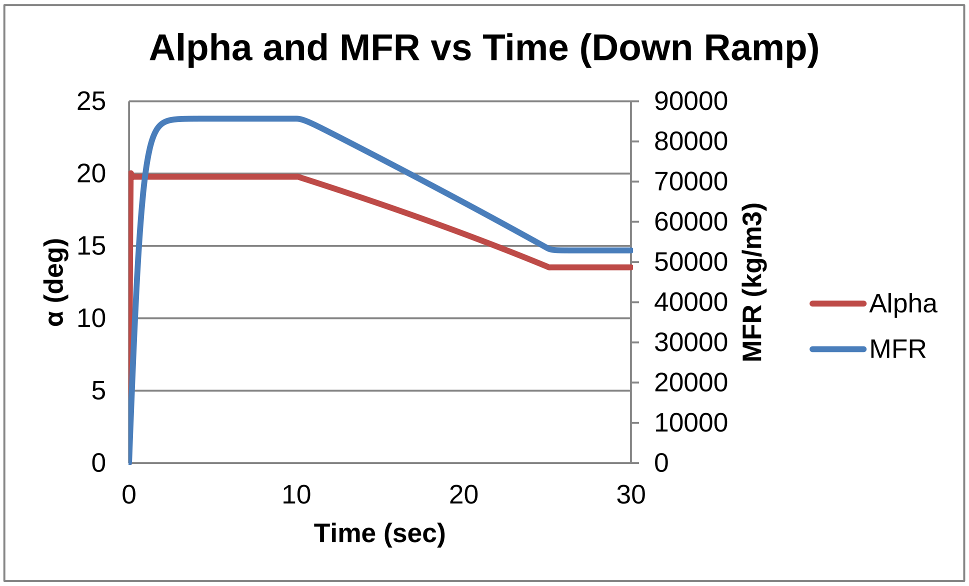


Figure 20: Alpha and MFR vs Time (Ramp Down)

Figures 21 and 22 show that there is a slight decrease in pressure at the turbine inlet during the ramp up. There is a corresponding increase during the ramp down. Looking at Equations 7 and 8, we can see that this is necessary in order to allow for the increase/decrease in flow.

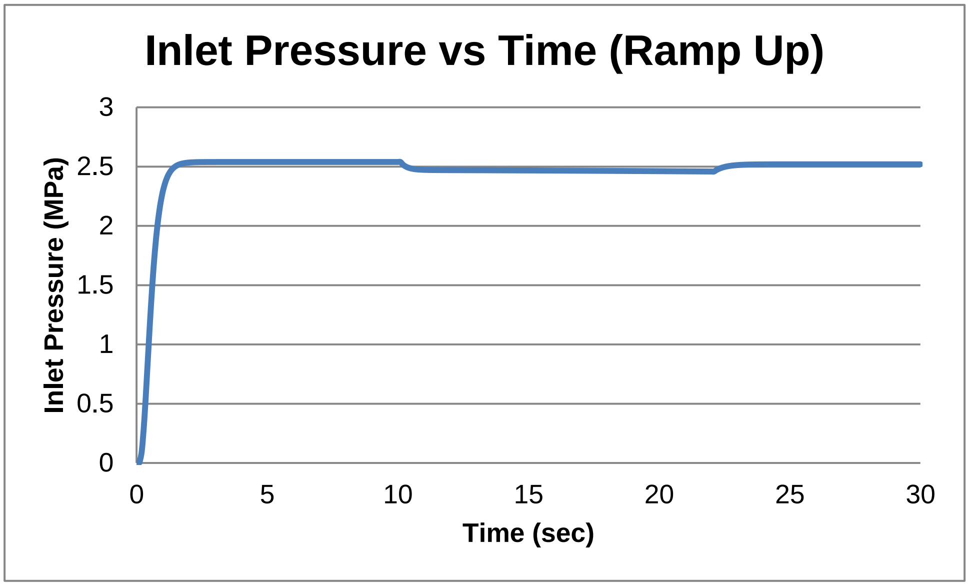


Figure 21: Inlet Pressure vs Time (Ramp Up)

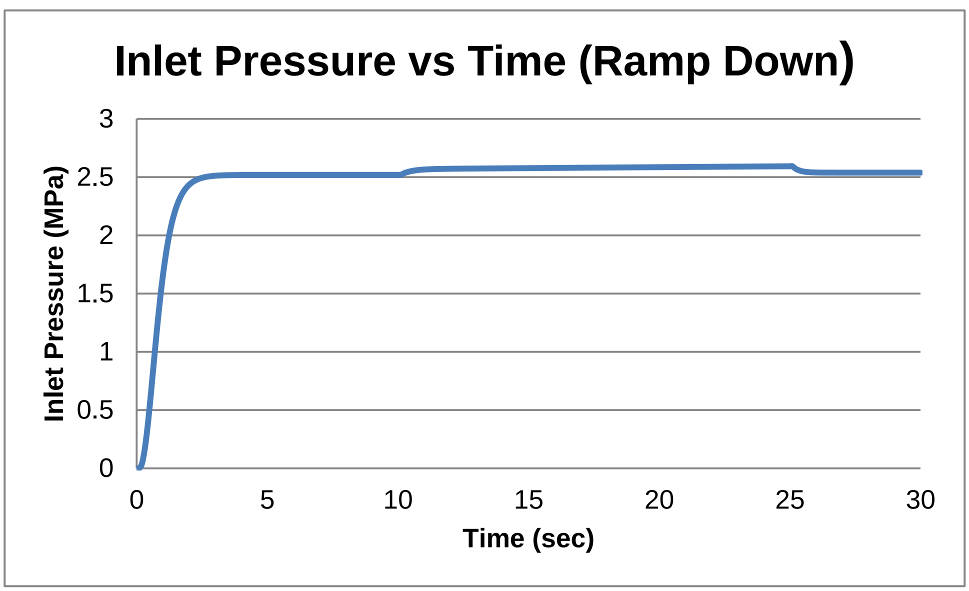


Figure 22: Inlet Pressure vs Time (Ramp Down)

Figures 23 and 24 show the maximum ΔP and Δω that occur if the system is given more time to go from 60-100% capacity. If the system is given more time to achieve the same change in power generation, the ramps are shallower. This allows the system to have a slower reaction time. The result is that the maximum differences between the demand/design and the actual, decrease. These could be implemented if it is necessary to keep ΔP and Δω smaller throughout the ramp. These figures show that if given one minute to change from 60-100% capacity, the maximum ΔP and Δω become very small.

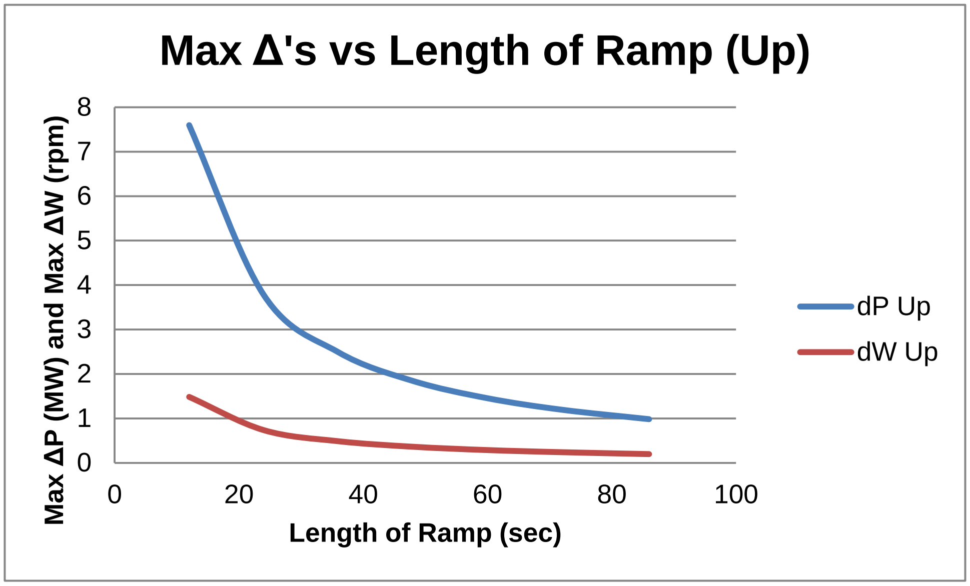


Figure 23: Max Δ's vs Length of Ramp (Up)

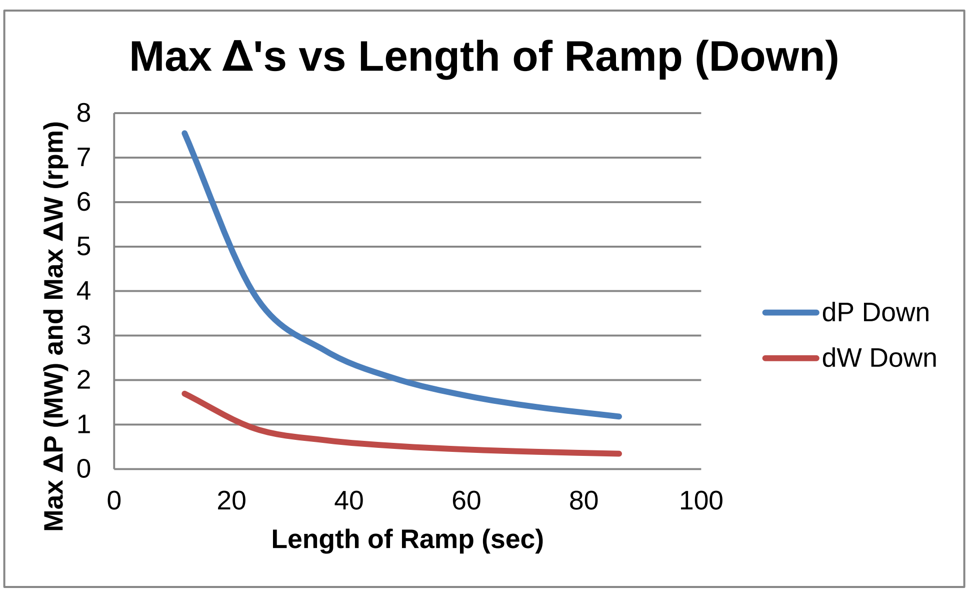


Figure 24: Max Δ's vs Length of Ramp (Down)

Chapter 4 – Conclusion

4.1 – Final Remarks

This thesis focused on modeling a hydroelectric power plant. This plant could be a standalone, or could work in conjunction with wind, solar, or nuclear power in order to enable them to meet the daily changes in demand of the power grid. It used a newly elucidated gate function that enabled a constant turbine rotational velocity.

The simulation called for a penstock model. This model relied on calculating the flow from the laws of momentum and the differences in pressure between the turbine inlet and the surface of the reservoir. The friction based on the flow velocity was estimated. It also determined how long it would take the water in the penstock to react to a change in the wicket gates based on the pipeline's dimensions.

Then the turbine was modeled using tangential and radial velocities on the Francis impeller to calculate the torque. After a simple calculation for the power was done, the model showed that the rotational velocity stays constant within the operating range.

Working backwards and using a curve fit, an equation was obtained for torque as a function of the wicket gate position. This enabled a simple, yet effective, controller for power output.

The results show that the turbine was able to go from 60% to maximum capacity in twelve seconds and back down in fifteen. These ramps were negotiated with small deviations from desired speed, within 1.5% or better than their design.

Overall, this model controls power proficiently, and if a proper G function can be created then the model can be useful to future designers, factoring in increased renewable penetration.

4.2 – Future Work

The main point of this thesis is to show how effective a hydroelectric plant could be at meeting the required ramp rates. This would be possible only if the suitable G function could be designed, not to actually design the valve/gate/etc. That being said, I believe there might be several ways this could be achieved in the future.

Remembering that the G function is not a physical entity, but simply a way of relating the flow rate to the pressure of the turbine inlet and it is a function of α, one way to get around producing a proper G function might be to separate q from α. In this scenario, another gate could be inserted before the penstock reaches the turbine. This gate would control q, and thus inlet pressure. It would leave alpha to only affect the torque by controlling the angle at which the water entered the turbine. This would allow the torque to be more directly controlled and thus keep the ratio with power constant, which in turn keeps the rotational speed constant.

There are several other areas that should be addressed by anyone wishing to further this work. One is the idea of rotational inertia. Because these turbines are very large, they would take time to speed up or slow down, which is not accounted for in this model. However, the rotational inertia could be accounted for by the rather steep ramps that the controller enables.

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APPENDIX

Figure 25 is a screenshot of the portion of the VisSim model that connects the penstock and turbine equations

Figure 26 is an Efficiency hill for a Francis Turbine [15]

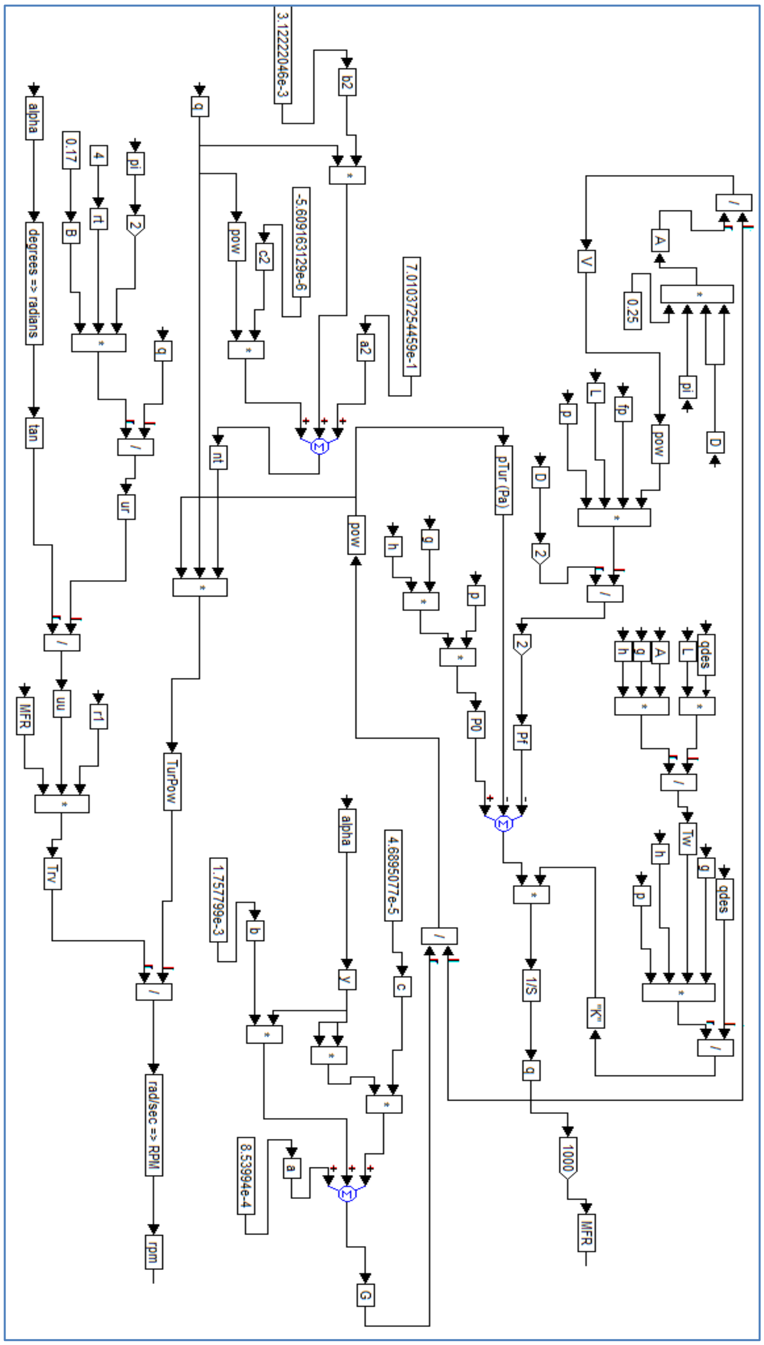

Figure 25: Combination of Penstock and Turbine equations from VisSim

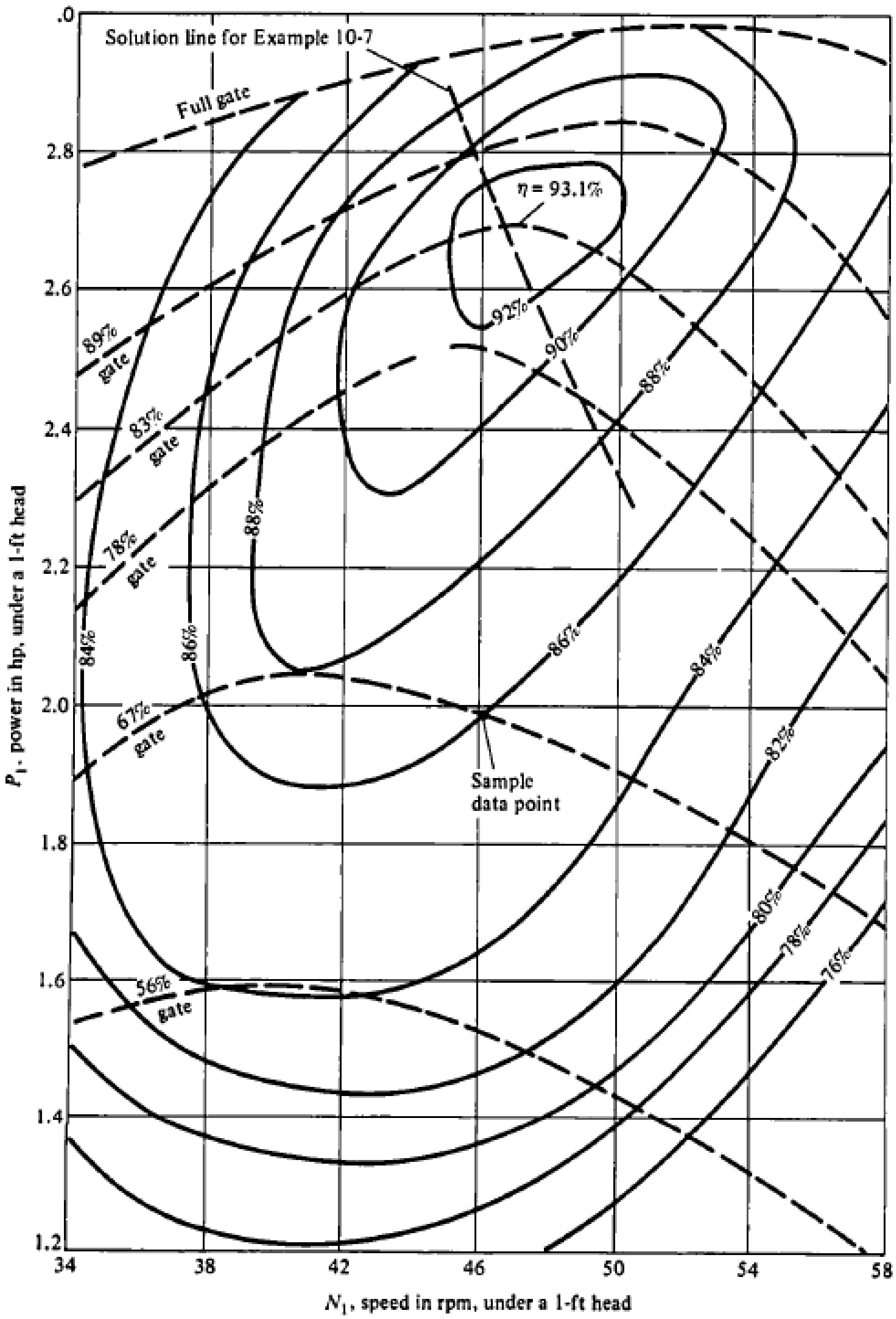

Figure 26: Efficiency hill for a Francis Turbine [13]

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