AN ABSTRACT OF THE THESIS OF

Elliott Jackson for the degree of Master of Science in Electrical and Computer Engineering presented on June 14, 2017.

Title: Experimentation of Synchronous and Variable Speed Small Scale Hydropower Systems

Abstract approved: ______________________________

Ted K.A. Brekken

Hydropower is the one of the oldest renewable energy technologies and is wrongly thought of today as having little room to grow. The opportunity for new hydropower capacity is immense through both technology advancement and run-of-river new stream reach projects. Despite the age of hydropower, a divide in opinion is forming regarding how we should proceed with generating power from smaller undisturbed rivers and canals. Hydropower generation techniques have been primarily fixed speed since its inception in the late 19th century, but it seems as though variable speed generation could hold the key to more efficiently utilizing new stream reach resources. This research aims to provide a cost benefit analysis of fixed speed vs. variable speed hydropower generation topologies, and distinguish the performance advantages that variable speed generation could hold in other aspects of hydropower. Simulation results are validated with hardware.

Experimentation of Synchronous and Variable Speed Small Scale Hydropower Systems

by

Elliott Jackson

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Dean of the Graduate School

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Elliott Jackson, Author

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TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

Chapter 1: Introduction

This chapter provides a review of hydropower in the United States, covering the past, present, and projected future of the industry and energy source with information supplemented through a thorough literature review.

1.1 Hydropower in the United States

1.1.1 Past

Mankind has utilized the power of moving water for over a millenia in a similar fashion to how humans harnessed the kinetic energy of wind for hundreds of years before our modern electrical grid. One of the first hydropower generation stations was engineered in 1891 near Telluride, Colorado by Nikola Tesla and was part of a movement that marked the beginning of renewable energy integration for the United States Power Industry. Since this landmark moment, hydropower has worked its way to firmly establishing itself as a integral part of the United States energy mix [1]. The first hydropower plants were primarily smaller, run-of-river units, meaning that they produced less energy than today's monolithic dams and did not retain water in a reservoir.

A large majority of large scale hydropower can be identified as reservoir hydropower, which is what is most commonly thought of by those outside of the industry. Grand Coulee and the Hoover Dam are all known as reservoir hydropower systems. These iconic systems hold back water and only allow water through to generate electricity or to spill water for seasonal or environmental reasons. Smaller scale hydro, and some large scale hydropower, is generally run-of-river which means that no reservoir of water is created or withheld, and hydroelectric power is created while allowing the flow of the body of water to continue unobstructed. Run-of-river plants can be designed using large flow rates with low head or small flow rates with high head, relying on the natural range of the water flow in a river. Some run-of-river facilities have a dam across the width of a river to impound water, but the impoundment will keep water at levels generally within the river's banks. Diversion run-of-river channels a portion of a river using a canal or penstock to capture the river's flow head and flow for power generation prior to its release at an outlet downstream [2].

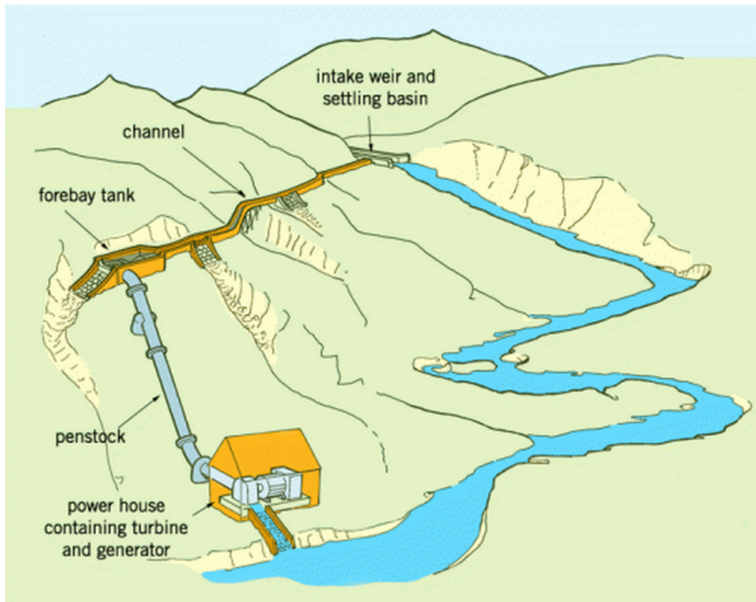

Figure 1.1: Typical layout of a diversion run-of-river hydropower system. The flow of the body of water is introduced to the hydropower system by entering the intake weir and the settling basin where sand and silt can be removed from the water. The channel follows the contour of the area so as to preserve the elevation of the diverted water. The water is then held in a reservoir known as a forebay tank where it then travels down the penstock and into the powerhouse where power can be generated, and then joining the water source that the diverted water began in [3].

During the 1950s, hydropower capacity in the United States exploded and plants began to be constructed all over the country. Large iconic dams such as Grand Coulee, Hoover Dam, and McNary Dam were all constructed during this time. The majority of hydropower generation was installed between 1950 and

1990 [4]. Since this boom of hydropower, new hydropower growth has plateaued and the industry has been continually looking for potential areas of expansion. Recently, small scale new stream reach projects are gathering the attention of investors and a new stage is being set for the future of hydropower.

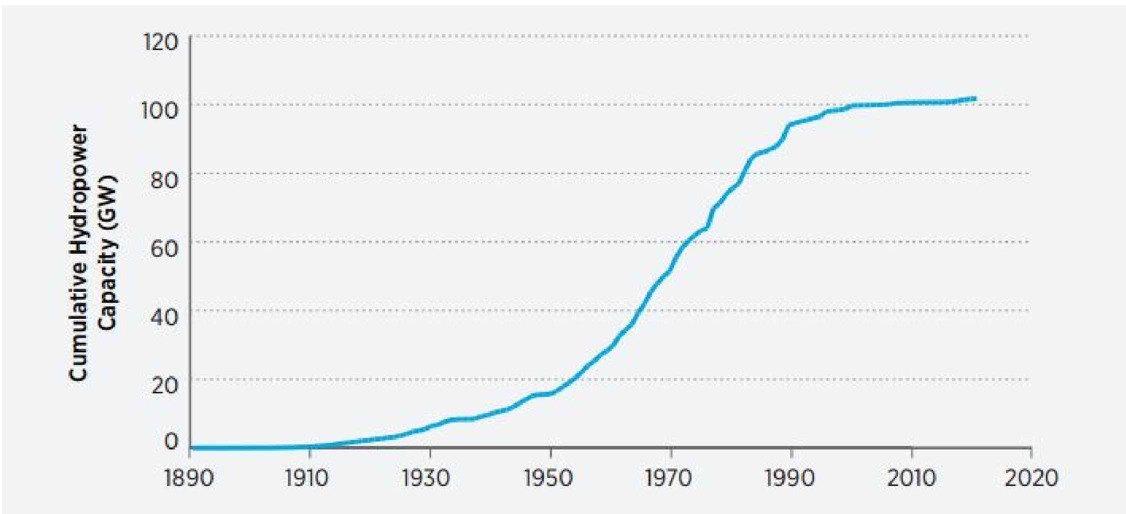

Figure 1.2: Hydropower capacity growth in the United States (GW), 1890-2015 [4].

1.1.2 Present

In 2015, hydropower provided 6.2% of net U.S. electrical power generation and 48% of all U.S. renewable power in 2015. The combined capacity of all U.S. hydropower is made up of 2198 active power plants with a total capacity of 79.6 GW of power [4]. To focus primarily on small scale hydropower, the US has 1640 small scale hydropower plants and have a combined generating capacity of approximately 3.67 GW. While it is not common for new large scale hydropower plants to be constructed, it should be noted that currently, only around 3% of the United States' roughly 80,000 existing dams include hydropower. A large portion of these non-powered dams are also held by the two largest US Hydropower owners, the United States Army Corps of Engineers and the Bureau of Reclamation [5]. We are seeing more renewable integration to the grid now than ever before and hydropower is changing with the grid. Large scale hydropower is not being added to the collection of energy resources the same way that solar and wind are, but that doesn't mean that the door is closed for hydropower growth. Small hydropower facilities that produce 1-20 MW of power have become increasingly attractive to lawmakers and developers alike because these projects are using low-impact designs that have minimal cost and environmental impact compared to conventional large scale hydropower [1].

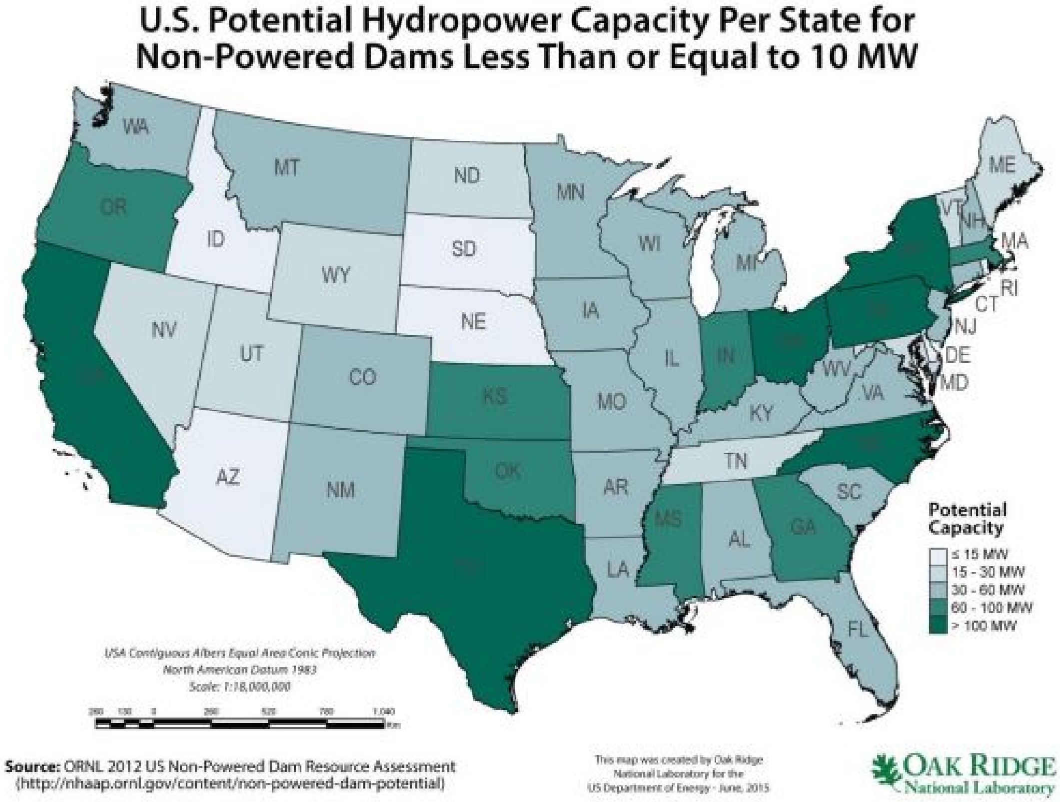

Figure 1.3: Energy density potential of untapped small hydropower potential on existing NPDs and their energy capacity by state. [5]

Present day definitions of hydropower scale vary from country to country. In the United States, the power capacity for small scale hydropower is anywhere from 1 MW - 30 MW, mini hydropower has a capacity of 100 kW - 1 MW, and micro hydropower is any hydropower plant with a capacity to generate 100 kW or less. Generally, the most individually cost-effective hydropower sites available are correlated with the sizing. For example, small scale hydropower plants are more cost effective than mini hydropower plants, which are more cost effective than micro hydropower plants [6]. The electrification of non-powered dams (NPDs) could greatly allow for a decrease in implementation costs which is a large factor when considering the construction of a new small scale hydropower plant. Using pre-existing dam structures for small scale hydropower expansion would be a fantastic strategy for the widening of small scale hydropower growth given that to be cost competitive with fossil fuels, current estimates are that renewables need to have development costs similar to $2000/kW. There are hundreds of small hydropower sites that come in under $2000/kW, but the current average is around $5000/kW [6].

Recently, lawmakers have worked to ease federal regulations and streamline requirements to promote the development of hydropower's untapped small scale potential. In 2013, small-scale hydropower received a regulatory makeover when Congress unanimously passed two laws, the Hydropower Regulatory Efficiency Act, and the Bureau of Reclamation Small Conduit Hydropower Development and Rural Jobs Act. The HREA exempted hydropower projects with a capacity of 10 MW or less from FERC licensing requirements, directed FERC to explore the feasibility of a two-year licensing process for adding hydropower to existing dams and closed-loop pumped storage projects, and promoted conduit hydropower by not requiring FERC licensing for qualifying conduit hydropower projects. Qualifying conduit hydropower facilities are defined as projects with an installed capacity of 5 MW or less that use existing water conveyance infrastructure that are primarily operated to distribute water for agricultural, municipal, or industrial consumption rather than to create electricity. The Hydropower Development Act granted Lease of Power Privilege to non-federal hydropower projects in Bureau of Reclamation conduits and allowed for exclusion from the environmental impact statement requirement. The hope has been to incentivize new project development because it will save project proponents millions of dollars and years of time [1].

At the time of this research, the US Bureau of Reclamation has examined energy development potential on Reclamation owned facilities and found that 191 canals had at least some level of hydropower potential, with 70 of those sites being considered economically viable for development. From these canals alone, it was concluded that there are 104 MW of potential capacity and 365 GWh of potential generation at the 373 Reclamation canals studied [5].

1.1.3 Future

The future of hydropower is bright. While the construction of large scale hydropower projects may be at a halt, the potential for new hydropower, specifically small scale new stream-reach projects have all the room in the world to expand. With only 3% of all dams in the United States being power producing sites, the studies performed by the US Bureau of Reclamation, and the Department of Energy's Hydropower Vision Report, the path for the expansion of hydropower has never been clearer. Small scale hydropower is going to be the proving ground for hydropower industry over the next few decades. Considerations will need to be taken with how to proceed and the choices we make early in small scale hydropower's expansion could determine what the long term future looks like.

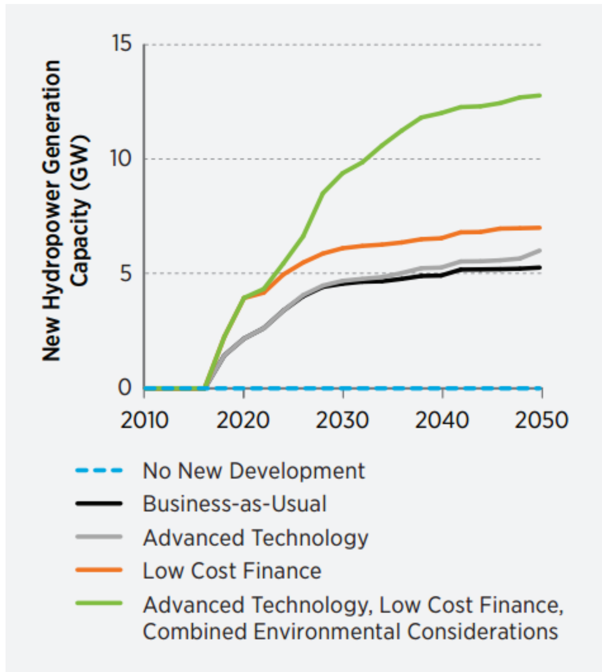

Figure 1.4: The various projections of growth in new hydropower generation capacity under the assumptions of no new plants, continuing with the business as usual growth that we are seeing today, newer technologies being implemented to increase existing and new plant efficiencies, the effects of lower financing costs and up-front capital costs, and finally all these factors combined along with environmental considerations toward low-impact systems [4].

With small scale hydropower, developers will need to take into account various factors not commonly seen with large scale counterparts. Developers will need to think about obvious variables such as customer specifications, existing infrastructure, and environmental surroundings, but also more critically about location, technology, and energy production constraints consistent with present-day hydropower. As discussed earlier, there is large potential for small scale hydropower in canals and NPDs, but when it comes to servicing the private sector and customers with no pre-existing infrastructure, location becomes much more of a pertinent problem. If the customer is a farmer with adequate water flow and head through an irrigation canal for a hydropower plant, considerations must be taken for creating a minimally invasive, cost-effective, and low maintenance hydropower project [7].

The technology utilized by developers will also be subject to scrutiny when applied to smaller scale hydropower. If the customer wants a fire and forget method of power generation, the fewer moving parts the better. This means that simpler and more robust solution is preferable and with less control schemes. This is a hard sell for private contractors currently due to the aversion to risk many conduit owners experience when given the choice between the way things have been done for over a century, and new technology [5]. Finally, energy production constraints are critical piece of understanding for developers for a successful road forward. If again considering a independent project for someone looking for energy offset solutions and distributed generation, net-metering may be the best execution method for a project manager. If this is the case, control schemes and attitudes will vary from how large-scale is operated. If however, this is a small scale project for an individual or company that is working with grid operators to provide base electrical power, energy production constraints become a lot simpler and defined.

These last two concepts, technology and energy production strategies, are of prime focus and have been recognized by many groups. The new technologies that could be utilized by small scale hydropower could include new hydrokinetic turbines, new generation topologies, and new control strategies. New technologies could increase our plant efficiencies under different environmental fluctuations and cut down on the amount of water even needed to produce the same amount of power. Energy production strategies could pertain to those listed above, but also to the permitting and licensing process that currently takes place in small hydro. A faster legal process has the potential to cut down on overhead costs and the time it takes to implement a new project [2, 5].

Chapter 2: Hydropower Operation and Equipment

2.1 The Role of Hydropower in Today's Energy Market

Hydropower has historically operated as a significant portion of our nation's base load. Overall, hydropower tends to compose up an annual average of around 7% of our nation's energy portfolio. If we were to look at states like Oregon, we could see a large amount of almost 45% of the base load being made up of hydropower [8]. It is because of hydropower "base load" production on our electrical grid that allow for the price of residential electricity in most states across the nation to be so low, typically around \$0.12/kWh. In Idaho where the cost of electricity is lowest in the country at \$0.08/kWh, the cause is clearly linked to hydropower where there are no fuel costs and the cost of construction and up front capital is spread out over many decades. Hawaii has virtually no hydropower and produces most of its electricity from crude oil which has high costs and pays \$0.33/kWh [9]. Hydropower as a renewable base load, is incredibly important to the health of our nation's grid stability. Without reliable base loads like hydropower, newer, variable supply renewable dispatchable generation like solar or wind power would not be able to be reliably integrated into our power grid.

What most people don't know, is that when you turn the lights on in your home, that electricity is being produced at the same instant that the switch is flipped. This means that when there is a demand from the grid for power, it must be produced almost instantaneously to ensure that the frequency of our grid stays at a healthy 60 Hertz. This is known as primary frequency control and is regulated heavily by FERC (Federal Energy Regulatory Commission) for the benefit of our grid [10]. When variable supply renewable energy technologies are constructed and connected to our grid, we do our best to utilize all the energy being produced in order to offset the cost of the new cutting edge renewable technology. Consequently, when the wind picks up and produces power in wind turbines, we must make sure that there is a demand from consumers at that instant for that power. To accomplish this, wind turbines are allowed to produce their power while we reduce the power being produced from our base loads. Conversely, when the wind stops blowing and power is no longer being produced by wind turbines, we need to ensure that we are able to instantaneously make up for this energy deficit by increasing the power being produced by our base loads.

This delicate balance of energy production and consumption is constantly changing throughout the day, the week, and the seasons. On a day to day basis, this is known colloquially as the duck curve. The duck curve is a pattern of power demand throughout the day that must be matched by dispatchable and base-load generation. A typical daily demand curve rises in the morning and peaks in the afternoon, and it hits a second highest peak in the early evening. Hydropower allows for the majority of the peaks in the duck curve to be handled by variable generation such as wind or solar, and dispatchable generation which is energy production that is operated on a need basis [11].

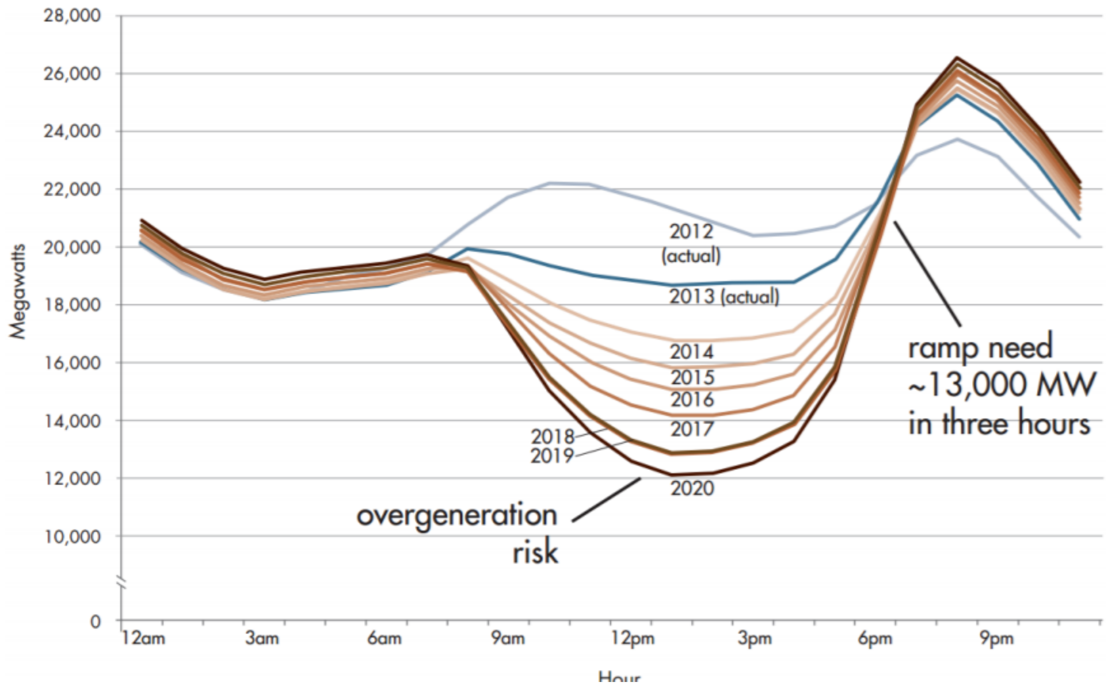

Figure 2.1: An example duck curve depicting the morning and evening spikes in energy demand commonly seen by the electric grid. Each line of the curve depicts the actual and projected trends for the duck curve in past and coming years. The majority of the morning and evening peaks must be filled by dispatchable generation and renewable sources such as wind or solar while the belly is maintained by base load generation [11].

If there is too much power being produced and not enough demand, the frequency of the grid increases above its normal value of 60 Hz. If there is not enough power being produced to meet demand, the frequency of the grid deviates below 60 Hz. If this occurs too drastically or too quickly, blackouts occur and power protection systems are needed to prevent damage to generators, buses, and transmission lines. The most reliable way to prevent any of this from happening is to have a reliable and controllable base load that is able to be adjusted on the fly to meet demands or lack thereof to ensure the health of the nation's power grid.

2.2 Environmental Concerns of Large Scale Hydropower

Large scale hydropower projects were constructed at an amazing pace during the 1940s and 1950s. Thanks to the hard work to construct these large energy infrastructure projects, the base load provided by hydropower that we have today was made possible. However, conventional hydropower has become controversial in recent years due to concerns over potential adverse impacts on the environment. When dams flood significant portions of land upstream, turning rivers into lakes, the change in habitat can affect wildlife and have especially dramatic impacts on migratory fish populations. Even the spilling of water from dams can force atmostpheric gases into solution in the basin water below, making the basin water supersaturated and has the potential to kill fish [2].

One of the largest environmental concerns of large scale hydropower projects is the safety and health of the local ecosystems. In the northwest, the biological focus of the effects of dams is the impact on salmon. Up until 1991 on the Columbia River, salmon were forced onto the list of endangered species due to their lack of protection from dams and the danger involved in their passage around dams without passing through the turbines themselves. The decline of snake river salmon also began to quickly die out starting in the 1960s [12]. Since then, legislation of the operation of dams on the Columbia River has made energy production the last item on the list of functions that dams execute and instead made flood control, fish and wildlife, navigation, irrigation, recreation, water supply and water quality, and cultural resources the top priorities [13].

With the production of new large scale hydropower projects, another important environmental concern is the change caused to the surrounding environment due to the rerouting of water. This causes erosion of surrounding river and stream banks, the change of river flows, and subsequently, the redistribution of local ecology. Many large scale power plants require reservoirs of water that cause these issues and vary from location to location. This is almost entirely avoided by run-of-river systems since no reservoir is needed and most water is allowed to pass the hydropower plant without needing to pass through any bottleneck of any kind. The main issue that lies with run of river systems however is the lack of long term energy dispatch planning due to the lack of a water supply sitting behind the generators. The availability of water on-demand in some locations could be incredibly variable based on seasons.

2.3 Benefits of Small Scale Hydropower

The definition of small scale hydropower varies based on location, but in the United States, small scale hydropower is defined as any hydropower plant that produces more than 1 MW but less than 30 MW, although there is no internationally agreed upon definition [6, 14]. Small scale hydropower has the potential to have very similar environmental concerns of large scale hydropower, but more often than not, have more flexibility in their planning that allows for the mitigation of these effects. For that reason, the benefits of small scale hydropower will be explored in terms of performance and production of energy.

Small scale hydropower has one major benefit of not necessarily being needed to operate as a base load. This means that for a small scale hydroplant that is allowed to net meter (produce as much power as possible and sell it to the grid), no one is needed to constantly monitor the plant and modify power production based on power demands by the grid. For an ideal net metering small scale hydropower plant, once it is constructed, it would ideally never need to be shut down and always be allowed to produce energy. For the autonomy of the plant and environmental protection, a run-of-river setup would be best so that a reservoir is not needed to be managed.

Another benefit of small scale hydropower not often thought of by most that work with large scale systems is that if there is a new or emerging hydropower technology, it is more likely to be adopted first by small scale hydropower systems and later applied to large scale systems since small scale hydropower systems tend to be primarily privately funded whereas large scale hydropower systems tend to be publicly owned and have a greater effect on grid health [15].

The final benefit of small scale hydropower to be discussed lies with the majority of hydropower potential capacity in the United States lying with small scale hydropower. There are few potential large scale hydropower sites left that haven't already been taken advantage of in some form or another. As discussed earlier, the capacity for new small scale hydropower is immense. Looking only at electrification of NPDs, of which 97% of all dams infrastructure can be classified, it becomes clear that the number of small scale hydropower projects could be a growing part of the hydropower industry [5]. According to Oak Ridge National Labs, the National Hydroelectric Power Resources Study, led by the US Army Corps of Engineers, examined information for more than 50,000 existing dams and 10,000 undeveloped sites provided jointly by USACE dam safety personnel, state engineers, FERC and the USGS concluded that 46 GW of capacity and 124 terawatt hours of annual energy may be available from 1948 candidate sites, of which 27 GW of capacity and 76 TWh of annual energy were from 541 undeveloped sites [16]. This is simply too much potential for hydropower to be ignored and we can expect to see this potential utilized in the coming years.

2.4 Typical Equipment

The four main components of most hydropower plants are explored and explained in general detail. All hydropower plants tend to be comprised of a turbine runner, a governor system, an excitation system or power electronics based control system, and the electric generator. The methods of governor operation are also depicted.

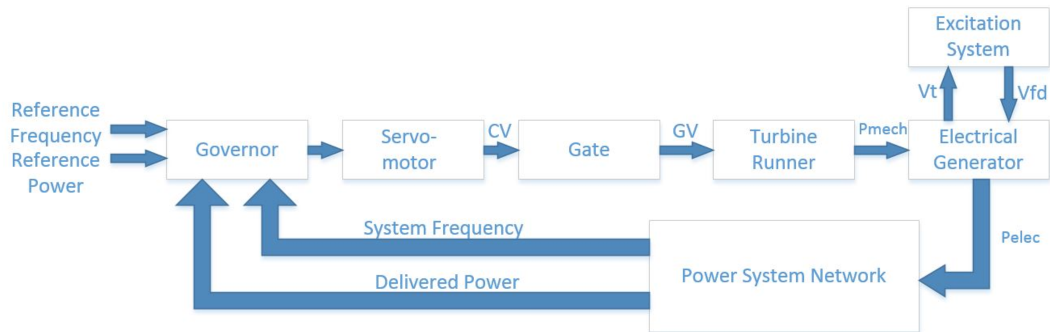

Figure 2.2: A flowchart displaying the relationship of each component of a typical hydropower plant that will be discussed in section 2.4.

2.4.1 Turbine Runner

The turbine runner, otherwise known as the prime mover, is the mechanism for which the kinetic and potential energy of the water passing through the hydroplant is harnessed for energy production. There are many different types of hydroturbines and each is selected based upon the operating conditions expected by the hydroplant. To begin, there are two categories of turbines, impulse, and reaction turbines. Impulse turbines are comprised mainly of turbines that cause the fluid, in this case water, to be re-directed as it comes in contact with the runner. An example of this is a Pelton turbine. Reaction turbines function by reacting to the water and moving thusly. The water enters a reaction turbine travelling in the same direction that it exits. Francis and Kaplan turbines are very common examples of reaction turbines.

For example, if a hydroplant was being developed in an environment in which there is high available head, but a low flow rate, a Pelton turbine would be most efficient. Conversely, if the hydroplant were expected to operate under low head high flow conditions, a Kaplan turbine would be the most efficient choice. For the purposes of this research, a Francis turbine was selected for simulations due to its versatility in terms of expected head and flow, and the rate at which it is used in the real world. [17].

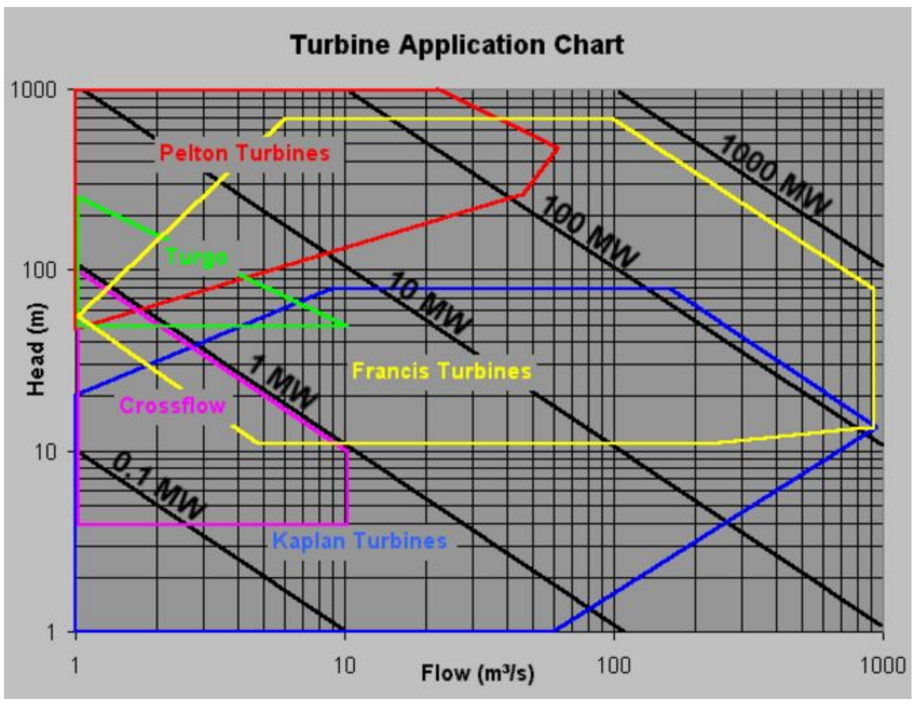

Figure 2.3: General turbine application graphic, showing which turbine type should be selected, given various heads and flows for the particular site [17].

The equations utilized in this research to model a Francis turbine in simulations and hardware are described below.

$$\frac{dq}{dt} = (h_o - h - h_l)a_{gravity}\frac{A}{L} \tag{2.1}$$

Where h_o is the initial steady-state head, h is the hydraulic head at gate, and h_l is head losses due to friction in the conduit, $a_{gravity}$ is the acceleration due to gravity, A is penstock cross sectional area, and L is conduit length. When this equation is normalized under the per-unit system, the equation may be rewritten as:

$$\begin{gathered} \frac{dq}{dt} = \frac{1 - h - h_t}{T_{w_rated}} \\ \text{Where...} \\ T_{w_rated} = \frac{L_{qbase}}{a_{gravity}Ah_{base}} \end{gathered} \tag{2.2}$$

The output power of the hydraulic turbine is then described as follows.

$$P_m = A_t h(q - q_{noload}) \tag{2.3}$$

The full block diagram model of the Francis turbine can be found below in section 2.4.2. A table lookup using hill curves of efficiency for the simulated Francis turbine are utilized to take into account the efficiency of the turbine based on the gate opening, speed of the turbine, and the flow [18, 19]. The Francis turbine hill curves utilized in this research were taken from research done in Norway and the specific efficiency hill curves can vary from turbine to turbine and based on the manufacturer. Due to the use of fixed speed for the entirety of hydropower's history, the Francis turbine is generally most efficient at the synchronous speed of the generator. The idea behind utilizing the hill curves in this research is to determine the efficiency of the turbine model based on gate opening and speed, the latter of which being most important due to the exploration of variable speed hydropower in this research [20].

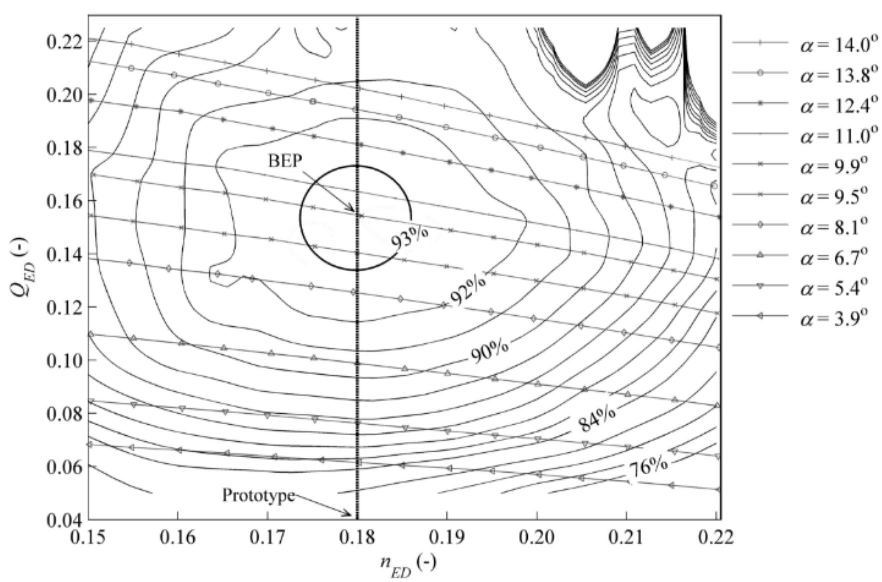

Figure 2.4: A Francis turbine efficiency hill curve diagram. The x-axis of the figure indicates dimensionless speed, the y-axis refers to dimensionless flow, the longitudinal lines correspond to the gate opening of the governor, and the quasi-circular curves indicate efficiency of the turbine. [20].

The dimensionless flow and speed can be calculated using the equations below Where Q is the actual flow, D is the turbine runner diameter, n is the operating speed, H is the effective head, and g is acceleration due to gravity.

$$\begin{aligned} Q_{11} &= \frac{Q}{D^2\sqrt{H}} \\ N_{11} &= \frac{nD}{\sqrt{H}} \\ Q_{ed} &= \frac{Q}{D^2\sqrt{gH}} \\ N_{ed} &= \frac{nD}{\sqrt{gH}} \end{aligned} \tag{2.4}$$

2.4.2 Governor System

The governor is the main controller of water entering the turbine runner, supplying mechanical power to be converted to electrical power by the generator. The governor functions by detecting the rotational speed of the turbine runner and the electrical power output and compares both values against set reference values. If the governor system detects that the generator is not producing enough electrical power, the governor operates a servo motor to open wicket gates, allowing more water to enter the turbine chamber. Similarly, if the governor detects that the generator is producing more power than intended, the governor closes the wicket gates until the produced power is equal to the set-point power. Most governor systems operate on the basis known commonly as droop control, although isochronous control is also utilized in some smaller, more isolated systems.

The governor system utilized for this research is known as the PID ”hyg3” model. The control algorithm chosen was PID as opposed to double derivative for tuning purposes and similarities with previously encountered models. The simple table lookup in the turbine section of the block diagram was replaced with the hill curves mentioned above and utilized similarly in [21–23].

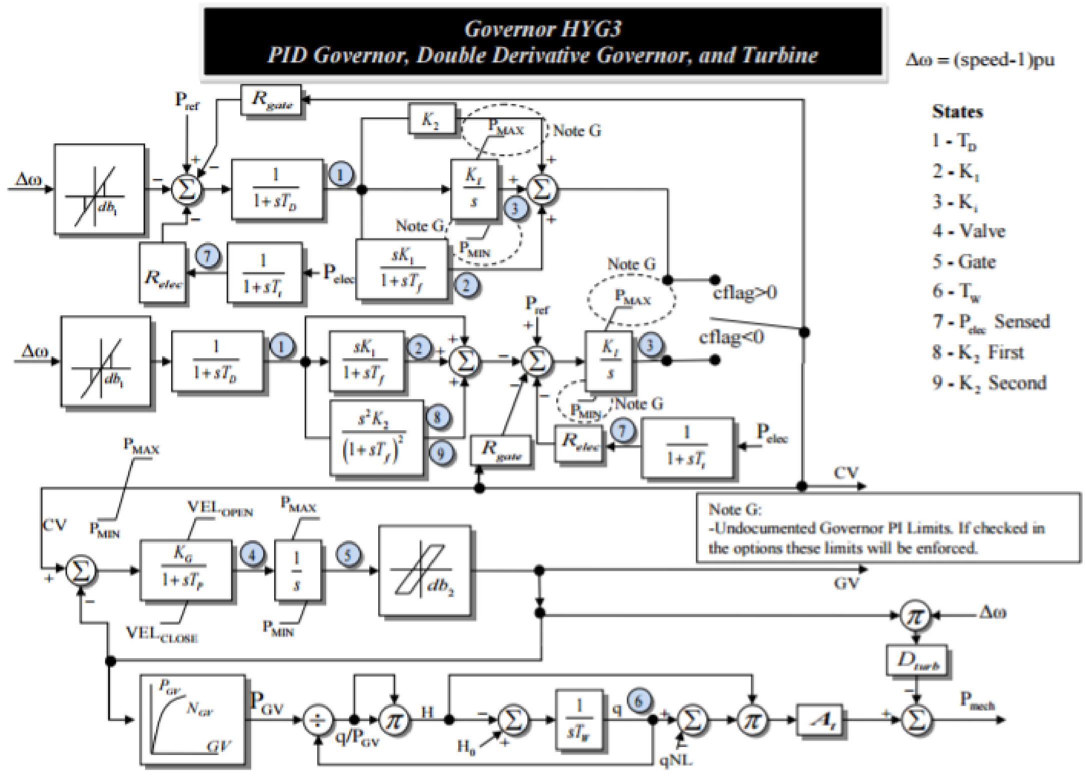

Figure 2.5: The hyg3 governor turbine model consists mainly of three portions. The PID controller, the servo motor, and the turbine runner. The PID controller consists of the top of the model and leads to the servo motor with the CV value. The Servo motor begins with a CV values and outputs a GV value. The GV value is then fed to the turbine runner model [24].

2.4.2.1 Wicket Gate Control and Operation

Wicket gates are essential for the control of mechanical power to the hydraulic turbine. Around the turbine unit there is a ring of gates that are able to rotate and therefore allow the passage of water, enabling the transfer of mechanical power to the turbine. As a method of controlling these gates, two methods of control have been utilized throughout hydropower's history. The two methods of control are typically referred to as speed droop and power droop.

In older hydroelectric systems, a flyball mechanical governor system was used to control the speed of the unit. The unit of measurement for the variation in mechanical speed of the unit is referred to as a droop factor. If a hydropower unit is set to a control value of 5% droop, and the mechanical speed of the system fluctuates from the desired value by a factor of 5%, the wicket gates are commanded to open or close 100%. This control of the mechanical speed of the turbine is very valuable for the output of 60Hz electricity to the grid. The second type of droop is referred to as power droop. Operating on similar principles, if the power being output from the generator deviates +/-5% of the desired output, the wicket gates will open or close to 100%. A numerical example of droop and open/close commands can be found below.

2.4.2.2 Droop vs. Isochronous Control

Droop, as explained previously, is the command of wicket gates based on the comparison of speed or power with the desired speed or power of the generator system. Isochronous control is an older method of control not seen as commonly today that controls the flow of water to the turbine runner based on the frequency of the grid. If the frequency of the grid begins to lag below 60Hz., the governor wicket gates will open up to accommodate this increase in grid demand. If the frequency of the grid begins to exceed 60Hz., the wicket gates begin to close to account for the decrease in grid demand. This method of wicket gate control is more common in islanded systems and in microgrid communities that are more drastically affected by small changes in electricity demand.

Isochronous control has a quicker reaction time to changes and is able to open the wicket gates much faster in order to quickly provide stability to systems that are much more susceptible to instabilities. Droop control is very useful in slowly changing systems and is perfect for the production of a base electric supply due to the control mechanism being based on set values for power output. A simple method for understanding the difference between isochronous control and droop control is to think of two people riding on a tandem bicycle, with each person representing a generator. In the isochronous case, let's say that one of the two bicyclists stops peddling, the isochronous bicyclist will realize that the surrounding system is slowing down, and will begin to attempt to rectify this change by providing more power to the system. In the droop case, if one bicyclist stops peddling, the droop bicyclist will continue providing the same amount of power to the system because his or her power output has not changed from their set or desired power. This illustrates that isochronous governor control is very important and valuable to microgrid systems and helps provide the surrounding grid with primary frequency control. Droop control is also shown to be very valuable for base supply production.

2.4.3 Excitation System

An excitation system is a very common piece of almost all hydroelectric power plants. In most plants, the generators utilized to convert mechanical power to electrical power are almost all of the synchronous, or fixed speed, variety. In hydropower, large power generation systems, the generators are capable of more than just the ability to efficiently output electrical power, but also control the power factor, or ratio of active power to reactive power. This is accomplished by controlling the torque angle at which the rotor spins compared to the stator. The working principles of an excitation system can be boiled down to simply measuring the magnitude of the terminal voltage of the generator, and comparing with a predetermined desired value of terminal voltage, and then supplying a DC voltage to the field winding of the rotor to link the rotor torque angle with the stator to achieve the desired terminal voltage.

Excitation Systems have many different topologies divided into three categories based on the needs of a proposed hydropower plant. DC Excitation Systems, AC Excitation Systems, and Static Excitation Systems are the three most common types of excitation systems [1, 26, 27]. DC Excitation Systems utilize a DC generator with a commutator as the source of excitation system power. AC Excitation Systems use an alternator and either stationary or rotating rectifiers to produce the

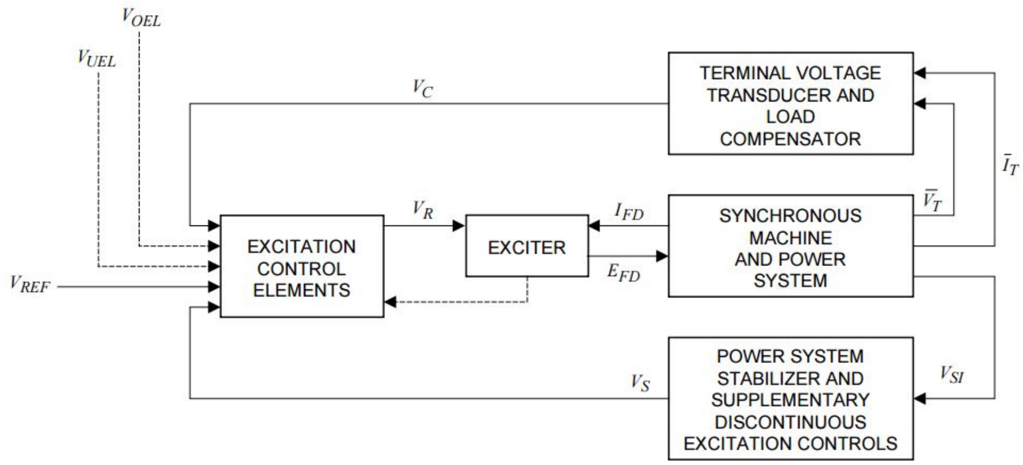

Figure 2.6: A block diagram of a wound rotor synchronous generator and excitation system functional relationships [25].

direct current required for the synchronous machine field windings. Static Excitation Systems are excitation systems that have power supplied through transformers or auxiliary generator windings and rectifiers [27].

As seen above in Figure 2.5, in a general excitation system, there are four main components that work together in tandem with the synchronous generator. These components are a terminal voltage transducer and load compensator, excitation control elements, an exciter, and a power system stabilizer. The supplementary discontinuous excitation controls are optional in this system but are commonly used based on need.

2.4.4 Electric Generator

The generator is the crucial piece of the hydroplant where mechanical power is converted into electrical power. The technology where the most variation can occur from one site to another is the decision of what type of generator to utilize. There are many different types of generators and the decision of which type to use can be daunting. Even after the type of generator is chosen, the method of control must be taken into account since most generators are meant to be controlled very differently than one another. If you had a wound rotor synchronous machine, you would attempt to control the machine using the field windings on the rotor. However, if you had a permanent magnet synchronous machine, you would have to control the machine by manipulating the stator voltage since there are no windings on the rotor to control. There are many possible factors that can lead to the decision to pick one generator over another ranging from cost, size, control scheme, raw materials, and maintenance.

Electric generators primarily function to convert mechanical power to electrical power by using rotating magnetic fields induced by applied AC current in generator windings to provide power to the grid. There are three phase windings located in the stator, or outer shell of the generator, and three phase windings located in the rotor, or inner portion of the generator. The stator always remains physically static while the rotor is able to rotate within the cylindrical shell of the stator. In general, electrical power is produced in the stator of an electric generator when both the rotor and stator are magnetized and a mechanical torque is applied to the rotor. This causes an electromagnetic torque to be induced in the stator, which causes the flow of current to flow out of the stator and generally into a transformer to be input to the grid. The specific relationships of currents, voltages, and flux linkages that create conditions for power production are outlined below with each machine model explored in this research.

2.5 Available Technologies

The hydropower technologies explored in this research were selected based on their abundance in the hydropower industry today and the ease in which they could be implemented with common hydropower plant designs. Because the majority of hydropower plants all share the same components, ie. similar turbines, governor systems, transformers, etc, the primary distinctions made between available technologies will focus primarily on the generator design. All generators described in this section are outlined in the dq-reference frame, converting three-phase abc equations to two-phase dq equations using the Park transformation.

The general mechanical equations for a rotating electric machine can be found below in equation 2.1. When a rotating electric machine is operating without any acceleration, we can see from the equations below that the electromagnetic torque must be equal to the sum of the mechanical torque and the force due to friction of the machine. When motoring, the mechanical torque applied to the machine is positive and does indeed slow the mechanical speed of the machine as equation 2.1 indicates. In the generating mode, the applied mechanical torque is seen as a negative value, causing the machine to experience positive mechanical acceleration assuming no control mechanism is in place.

$$\begin{aligned}
\frac{d\omega_{mech}}{dt} &= \frac{1}{J_{eq}}(T_{em} - T_{mech} - B_{fric}\omega_{mech}) \\
\omega_m &= \frac{p}{2}\omega_{mech} \\
\omega_d &= \omega_m
\end{aligned} \tag{2.5}$$

The equations for electrical active and reactive power are described below and are consistent for each type of generator described in this research.

$$\begin{aligned}
P_{elec} &= V_{sd}I_{sd} + V_{sq}I_{sq} \\
Q_{elec} &= V_{sq}I_{sd} - V_{sd}I_{sq}
\end{aligned} \tag{2.6}$$

2.5.1 Wound Rotor Synchronous Generators

The most common generator in large scale hydropower plants, the wound rotor synchronous generator has been in use since the beginning of hydropower's career in the national electric infrastructure. In the dq reference frame, the wound rotor synchronous machine consists of dq stator windings, dq rotor windings, and a d-axis field winding. the dq rotor windings are shorted and act the same as the windings in a squirrel cage induction machine. The d-axis field windings are used to create a flux linkage between the d-axis of the rotor and the d-axis of the stator to maintain a desired torque angle between the rotor and stator.

2.5.1.1 Machine Model

Electrically, the wound rotor synchronous machine can be described by the following series of 5 equations. ω_d signifies the rotational speed of the stator, while ω_{dA} signifies the difference between the rotational speed of the stator and the rotor. If the wound rotor synchronous machine is indeed perfectly synchronous, the rotor magnetic field and the stator magnetic field rotate at identical speeds, meaning that ω_{dA} becomes zero.

$$
\begin{aligned}
V_{sd} &= I_{sd}R_{sd} + \frac{d\lambda_{sd}}{dt} - \omega_d\lambda_{sq} \\
V_{sq} &= I_{sq}R_{sq} + \frac{d\lambda_{sq}}{dt} + \omega_d\lambda_{sd} \\
V_{rd} &= I_{rd}R_{rd} + \frac{d\lambda_{rd}}{dt} - \omega_{dA}\lambda_{rq} \\
V_{rq} &= I_{rq}R_{rq} + \frac{d\lambda_{rq}}{dt} + \omega_{dA}\lambda_{rd} \\
V_{fd} &= I_{fd}R_{fd} + \frac{d\lambda_{fd}}{dt} - \omega_{dA}\lambda_{rq}
\end{aligned}
\tag{2.7}
$$

Given the flux linkages of each winding, the current of each winding can be extracted by dividing by the inverse of a matrix of inductance values. These currents are then applied in a closed loop into equations 2.1.

$$
\begin{aligned}
\lambda_{sd} &= (L_{md} + L_{ls})I_{sd} + L_{md}I_{rd} + L_{md}I_{fd} \\
\lambda_{sq} &= (L_{mq} + L_{ls})I_{sq} + L_{mq}I_{rq} \\
\lambda_{rd} &= (L_{md} + L_{lrd})I_{rd} + L_{md}I_{sd} + L_{md}I_{fd} \\
\lambda_{rq} &= (L_{mq} + L_{lrq})I_{rq} + L_{mq}I_{sq} \\
\lambda_{fd} &= (L_{md} + L_{lfd})I_{fd} + L_{md}I_{sd} + L_{md}I_{rd}
\end{aligned}
\tag{2.8}
$$

From the derivation of the individual winding currents, the number of poles in the machine, and inductances, the electromagnetic torque can be derived which is created within the generator in order to counteract the mechanical torque [28].

$$
T_{em} = \frac{p}{2}[L_{md}(I_{fd} + I_{rd})I_{sq} + (L_{sd} - L_{sq})I_{sd}I_{sq} - L_{mq}I_{rq}I_{sd}] \tag{2.9}
$$

2.5.1.2 Control Theory

In general, wound rotor synchronous machines are controlled in hydropower plants by excitation systems which were described earlier in this chapter. For this research and for the simplicity of implementation on hardware due to the lack of a true excitation system, a PI controller was utilized to achieve the same purpose. The implementation is described in the equation below describing the definition of per-unit terminal voltage. The end purpose of any hydropower excitation system and the PI controller in this research is to measure the per-unit terminal voltage and subtract it from the desired per-unit terminal voltage, and make adjustments based on the error from the subtraction. To maintain the terminal voltage at 1.0 per-unit means that the rotor and stator are perfectly aligned and zero reactive power is produced. Controlling the per-unit terminal voltage is essentially equivalent to controlling the power factor of the machine.

$$V_{Terminal,pu} = \frac{\sqrt{V_{sd}^2 + V_{sq}^2}}{V_{base}} \tag{2.10}$$

When there is reactive power being produced or consumed by the generator, the power factor of the generator is increased or decreased. Introducing this angle between active and reactive power creates a net increase or decrease in the magnitude of the terminal voltage. Production of reactive power involves increasing the magnetic field to raise the generator's terminal voltage. Increasing the magnetic field requires increasing the current in the rotating field winding. Absorption of reactive power is limited by the magnetic-flux pattern in the stator, which results in excessive heating of the stator-end iron, the core-end heating limit [29].

When the operator of a hydropower plant wants to operate the generator to only produce active power, the per-unit terminal voltage that is desired is simply 1. To supply reactive power to the grid, the desired terminal voltage is greater than 1. Similarly, the desired terminal voltage to consume reactive power from the grid is less than 1. For very small generators, controlling power factor directly is a viable alternative to controlling the terminal voltage but still accomplishes the same end result.

2.5.1.3 Operational Advantages and Disadvantages

The wound rotor synchronous machine has many advantages thanks to the use of the technology over the last 100+ years. The wound rotor synchronous machine has the advantage of being made entirely of copper windings, allowing for cheaper construction costs based on rated power, especially when compared with generators that utilize permanent magnets. The control theory behind maintaining the synchronous speed of a wound rotor machine is relatively simple, has been widely used for over a century, and there are over 50 different exciter models to choose from based on project specifications.

The disadvantages of a wound rotor machine are few thanks to their longevity in the hydropower marketplace. One of the few areas that could be improved upon wound rotor synchronous machines is in their downtime to repair burnt out windings. Over time the insulated coating on the copper windings begins to degrade due to heat. When the insulation breaks down enough, it can cause arcing and electrical faults within the generator. In large scale hydropower plants the process to repair this damage can take months which means a major loss of revenue. Another disadvantage to the choice of a wound rotor synchronous machine is that if you are already in the marketplace for a fixed speed generator, and you can stand to spend more money, permanent magnet synchronous generators are more efficient due to the the lack of copper losses in the rotor.

2.5.2 Permanent Magnet Synchronous Generators

One of the most efficient hydropower generators, the permanent magnet synchronous generator is common for most medium scale hydropower plants. In the dq reference frame, the permanent magnet synchronous machine consists of dq stator windings, and a fixed flux linkage between the d-axis of the rotor and the d-axis of the stator. The fixed flux linkage is due to the magnetic field produced by the permanently magnetic material embedded in the rotor of the generator. Because the flux linkage in the rotor is fixed, to maintain the desired torque angle between the rotor and stator, the flux linkage in the stator must be manipulated.

2.5.2.1 Machine Model

Electrically, the permanent magnet synchronous machine is described by the following series of 2 equations. Observing this, it is obvious that the permanent magnet synchronous machine and wound rotor synchronous machine both have identical stator equations, the primary difference between the two being the relationship the stators have with their respective rotors.

$$\begin{aligned} V_{sd} &= R_s I_{sd} + \frac{d\lambda_{sd}}{dt} - \omega_d \lambda_{sq} \\ V_{sq} &= R_s I_{sq} + \frac{d\lambda_{sq}}{dt} + \omega_d \lambda_{sd} \end{aligned} \tag{2.11}$$

Using the above equations, the flux linkages are derived and the currents of each winding can again be extracted using the followig relationships between flux linkage and inductance values. λ_{fd} is a fixed value caused by the magnetic flux that is inherent to the permanent magnets that are implanted in the rotor of the generator.

$$\begin{aligned} \lambda_{sd} &= (L_{md} + L_{ls})I_{sd} + \lambda_{fd} \\ \lambda_{sq} &= (L_{mq} + L_{ls})I_{sq} \end{aligned} \tag{2.12}$$

The torque experienced by the rotor is a bit simpler to calculate with a permanent magnet synchronous machine than a wound rotor synchronous machine due in part to the fact that there are less variables involved in a permanent magnet machine and there is no current in the rotor. Below are three variations of the torque equation for a permanent magnet machine [28].

$$\begin{aligned} T_{em} &= \frac{p}{2}(\lambda_{sd} I_{sq} - \lambda_{sq} I_{sd}) \\ &= \frac{p}{2}[(L_s I_{sd} + \lambda_{fd}) I_{sq} - L_s I_{sq} I_{sd}] \\ &= \frac{p}{2}\lambda_{fd} I_{sq} \end{aligned} \tag{2.13}$$

2.5.2.2 Control Theory

Referring above to equation 2.13, it is observed that since p, or number of poles, is a fixed value inherent to the machine, and λ_{fd} is a fixed value inherent to the permanent magnets embedded in the rotor of the machine, that the only way to adjust the speed of the machine is to control I_{sq}. To accomplish this task, a simple PI controller can be used to first manipulate current based on the speed error. This reference current output is then used to manipulate voltage of the stator based on the current error. However, this does not affect the power factor or reactive power output of the machine. A second PI controller can be used to manipulate the d-axis current, I_{sd}. To accomplish this, the same type of cascading control for speed is then used for reactive power. Taking the reactive power being produced at any moment and subtracting it from a reference amount of VARs. This gives a reference current for the d-axis windings which is then used similarly for controlling the d-axis voltage of the stator. This is a method known as flux weakening.

Flux weakening is a method of control of electric machines that reduces the total amount of magnetic flux in the machine in order to achieve the highest possible torque. By controlling the q-axis current as discussed above, we are able to achieve torque control in order to achieve desired speeds. By introducing d-axis current, we reduce the total amount of power the machine is consuming/producing by reducing the power factor. The downside to this method of control is that we reduce the amount of available torque we can induce on the rotor while still staying within rated current and voltage limits. While this does limit our ability to control speed, it does insure that all power being output from the generator is active power.

2.5.2.3 Operational Advantages and Disadvantages

Permanent Magnet Synchronous Generators have many perks when used in a hydropower plant. The largest perk that they bring is that because there are no copper losses in the rotor of the generator due to the use of permanent magnetic material. Additionally, because there are magnets embedded in the rotor, which are more power dense than copper windings, the size of a permanent magnet synchronous generator is significantly more compact than a wound rotor synchronous machine of similar power rating.

The largest disadvantage of permanent magnet synchronous machines is that they are expensive. Copper is abundant and inherently cheaper than any machinery that does not require rare earth magnetic material. Over time this up front capital cost could be overcome thanks to the higher efficiencies. The control theory behind a permanent magnet synchronous machine is a bit more complicated than the wound rotor synchronous machine, and due to the changing magnitudes of stator voltage to control rotor torque, an AC/DC-DC/AC converter inverter system is needed before being able to supply power to the grid. While more complicated, permanent magnet synchronous generators have been used in hydropower plants for a very long time and literature on how to integrate the technology is abundant.

2.5.3 Doubly Fed Induction Generators

One of the most common generator topologies for wind power, the doubly fed induction generator could be implemented similarly in new, small scale hydropower plants. Instead of using wind to rotate the rotor of the generator, water is used. The same operating principles are utilized for hydro as we already do for wind. The doubly fed induction generator operates identically to the wound rotor synchronous machine, with a few critical differences. There is no d-axis field winding and the dq rotor windings are not shorted but instead connected to voltage sources, allowing for the current to be controlled. The rotor is able to rotate at whatever speed is commanded by the current controller while still producing 60 Hz power in the stator.

2.5.3.1 Machine Model

The basic machine model of the doubly fed induction generator is very similar to the wound rotor synchronous machine and is the same as for a simple induction machine. Where these generators differ is with their assumptions that are made due to the nature of a changing rotor speed but a continuous electrical speed.

$$\begin{aligned} V_{sd} &= I_{sd}R_{sd} + \frac{d\lambda_{sd}}{dt} - \omega_d\lambda_{sq} \\ V_{sq} &= I_{sq}R_{sq} + \frac{d\lambda_{sq}}{dt} + \omega_d\lambda_{sd} \\ V_{rd} &= I_{rd}R_{rd} + \frac{d\lambda_{rd}}{dt} - \omega_{dA}\lambda_{rq} \\ V_{rq} &= I_{rq}R_{rq} + \frac{d\lambda_{rq}}{dt} + \omega_{dA}\lambda_{rd} \end{aligned} \tag{2.14}$$

Similar again to the wound rotor synchronous machine, the equations to derive the current values from the flux linkage is identical with the exception of no field winding relationship.

$$\begin{aligned}
\lambda_{sd} &= (L_{md} + L_{ls})I_{sd} + L_{md}I_{rd} \\
\lambda_{sq} &= (L_{mq} + L_{ls})I_{sq} + L_{mq}I_{rq} \\
\lambda_{rd} &= (L_{md} + L_{lrd})I_{rd} + L_{md}I_{sd} \\
\lambda_{rq} &= (L_{mq} + L_{lrq})I_{rq} + L_{mq}I_{sq}
\end{aligned} \tag{2.15}$$

The calculation for torque is relatively simple in an induction machine and is described by the mathematical relationship below.

$$\begin{aligned}
T_{em} &= \frac{p}{2}(\lambda_{rq}I_{rd} - \lambda_{rd}I_{rq}) \\
&= \frac{p}{2}L_m(I_{sq}I_{rd} - I_{sd}I_{rq})
\end{aligned} \tag{2.16}$$

2.5.3.2 Control Theory

While to most electrical engineers in the hydropower industry may feel flustered at the concept of allowing the rotor to spin asynchronously with the stator, the control theory is relatively straightforward. The key to understanding the control of the doubly fed induction generator is to focus on the mechanical equations and divide them amongst the d and q axis rotor currents. For example, when controlling the torque on the rotor, examine the torque equation and expand as performed below [30]:

$$\begin{aligned} T_{em} &= \frac{p}{2}L_m(I_{sq}I_{rd} - I_{sd}I_{rq}) \\ &= \frac{p}{2}L_m((\frac{\lambda_{sq}}{L_s} - \frac{L_m}{L_s}I_{rq})I_{rd} - (\frac{\lambda_{sd}}{L_s} - \frac{L_m}{L_s}I_{rd})I_{rq}) \\ &= -\frac{p}{2}\frac{1}{\omega_d}\frac{L_m}{L_s}V_{sd}I_{rd} \end{aligned} \tag{2.17}$$

Similarly, by taking our reactive power equation as related to the q-axis current, we can further expand the relationship between q-axis stator and q-axis rotor current to determine how best to control the q-axis rotor current.

$$\begin{aligned} Q_{elec} &= -V_{sd}I_{sq} \\ &= -V_{sd}(\frac{\lambda_{sd}}{L_s} - \frac{L_m}{L_s}I_{rq}) \\ &= \frac{V_{sd}^2}{\omega_d L_s} + \frac{L_m}{L_s}V_{sd}I_{rq} \end{aligned} \tag{2.18}$$

By rearranging the above equations, we can derive our command d and q axis rotor currents as follows.

$$\begin{aligned} I_{rd}^* &= -\frac{2}{p}\frac{L_s}{L_m}\omega_d\frac{T_{em}}{V_{sd}} \\ I_{rq}^* &= \frac{L_s}{L_m}\frac{1}{V_{sd}}(Q_{elec} - \frac{V_{sd}^2}{\omega_d L_s}) \end{aligned} \tag{2.19}$$

2.5.3.3 Operational Advantages and Disadvantages

The operational advantages of a doubly fed induction machine are numerous. When used as a generator, the doubly fed induction machine really shines. The variable speed nature is able to allow for the rotation of the rotor at its most efficient speed to allow for higher efficiencies than a conventional fixed speed system. They are also relatively cheap systems since they can be thought of as an induction machine with the rotor windings connected to voltage sources. This means that you can have the advantage of the wound rotor synchronous machine when it comes to price due to being made purely of copper and also has the advantage of the permanent magnet synchronous machine of being highly efficient due to the ability to spin at any speed while still producing 60 Hz electricity on the stator.

The operational disadvantages of a doubly fed induction machine in a hydropower project are the control of the generator and the likelihood of adoption. Because a doubly fed induction generator has never been used in commercial hydropower, the hardware and control design would be brand new for hydropower, but many notes could be taken from the wind power industry where doubly fed machines are quite common. The larger disadvantage is the likelihood of adoption. Fixed speed hydropower is how we have always produced power from running water and the viability of variable speed technology is surprisingly sparse within the hydropower community. If this obstacle is to be overcome, the awareness of the hydropower community regarding a common generation method of the wind industry must be understood and accepted.

Chapter 3: Variable Speed Generation as a Viable Road Forward for Hydropower

Variable speed generation techniques are significantly newer than their fixed speed counterparts and have seen some push back by industry regarding their adoption in hydropower. To an extent this is understandable considering all the years of technology advancement that has been researched for fixed speed hydropower that would potentially not be needed with variable speed generation. A summary of traditional fixed speed hydropower and a review of the operational methodology of variable speed hydropower production techniques are found below.

3.1 Traditional Hydropower Summary

Traditionally, hydropower has been fixed speed, synchronous to the grid, since its inception and incorporation into America's electrical infrastructure. In large scale hydropower plants, the main source of variance from project to project is the decision of what excitation system and what hydroturbine to utilize. In very large scale hydropower systems, the wound rotor synchronous machine is the most prevalent generator throughout the US. In a large hydropower plant with few units that each output large quantities of power, wound rotor synchronous machines are most common due to their use of copper windings to create magnetic poles within the stator and rotor. In similar hydroplants with the same overall power output but a higher amount of power producing units, permanent magnet synchronous machines are commonly utilized due to their compact size and efficiency.

Wound rotor synchronous machines are common in large scale hydropower due to their ease of control and their wide use of copper. The control mechanism of wound rotor synchronous machines is covered above but the excitation unit can be easily purchased off the shelf and there are over 50 different exciter models to choose from that are widely used throughout industry. Based on need, any exciter that could possibly be needed can be purchased from a number of manufacturers. The use of copper throughout the entire generator also makes for the production and purchasing cost of the generator to be cheaper than their permanent magnet counterparts. The drawback to these generators is primarily twofold. If over time a winding burns out or degrades over time, the cost and decommissioning time needed to repair damage could amount to a large amount of money lost when power could be produced. The second drawback is that with a large amount of copper making up the windings, there are inherent losses of power proportional to the resistance of the windings.

Permanent magnet machines are less typical, but still present throughout much of the hydropower industry. Their method of control is not performed via an excitation system but are still relatively simple to control. Where wound rotor synchronous machines fall short in efficiencies due to copper losses, permanent magnet machines thrive due to their highly efficient magnets that reside within the rotor. Copper windings still exist in the stator and still face risks of burning out over time, but the chances are cut almost in half since half of the generator now consists of magnets. The main drawback that permanent magnet machines face is cost. Neodymium, a rare earth magnetic material used in electric machines, is a very expensive resource and a large amount is needed to make a functional generator unit. The higher the power output necessary of the generator, the larger and more power dense magnets that will become necessary for extended use.

3.2 Variable Speed Operational Methodology

The reasoning behind the viability of variable speed hydropower is relatively straightforward. If instead you imagine utilizing an electric machine as a motor instead of a generator driving a pump, and your goal was to pump a given amount of fluid at a specific flow rate given a certain amount of pressure, there is some optimal speed to spin the turbine. Being that most if not all hydropower today is fixed speed, this means that if there are variations in rated head and flow, the turbine is not always operating at the highest efficiency point. The methodology behind the control of the doubly fed induction generator is to utilize the Francis turbine hill curves and run at the optimal speed [21–23]. Most of the time, the doubly fed will most likely run at near synchronous speed due to the fact that Francis turbines are generally designed to be most efficient at synchronous speed when operating at rated head and flow. However, during transient periods where there are variations in head or flow away from their rated values, the doubly fed should be less effected by changes due to not being fixed at a given operational speed.

This ability to vary speed of the turbine based on head and flow characteristics has the added benefit of decreasing the chances of cavitation occurring. Cavitation is caused by static and dynamic components of the hydraulic effects on the turbine. The dynamic pressure of the liquid is by virtue of flow velocity and static pressure is the actual pressure being applied by the fluid. Static pressure also governs the process of vapor bubble formation or boiling. Thus, cavitation can occur near the fast moving blades of the turbine where the local dynamic head increases due to action of blades which causes static pressure to fall [31]. The dangers that cavitation occurrences have on hydraulic turbines are severe and have the ability to cause irreparable damage to a turbine over the long term. By allowing for the speed of the turbine to vary based on flow and head, rough zones are actively avoided by allowing for most efficient set-point speeds at all times.

Chapter 4: Small Scale Hydropower Cost Benefit Analysis Development Guide

4.1 Introduction

This section will explain the benefits and drawbacks of both philosophies of hydropower generation, fixed speed and variable speed, as they pertain to their potential use in small scale hydropower development. Examining fixed speed operational advantages and disadvantages was accomplished by examining the performance of a wound rotor synchronous machine and a permanent magnet synchronous machine, the two most common types of hydropower generators. When choosing criteria to judge variable speed generation techniques, the doubly fed induction generator was selected due to its commonplace appearance in wind power, where variable speed technology reigns supreme.

4.2 Fixed Speed Operation

Fixed speed operation of hydropower is incredibly common and is essentially the classification of all hydropower on our national electric grid today. The two generator technologies described in this section are the wound rotor synchronous machine and the permanent magnet synchronous machine, the two most common generators in hydropower. Fixed speed operation indicates that the rotor of the generator must always generate power while rotating at a given, set speed. The speed of the rotor is proportional to 60 Hz, based on how many magnetic poles the generator is composed of. For example, a fixed speed generator with 2 poles will operate at 3600 RPM, but a 10 pole machine will operate at 720 RPM. Fixed speed generators may rotate at different speeds than one another, but the current and voltage associated with the stator will have a frequency of 60 Hz.

4.2.1 Equipment Required

The equipment required for fixed speed systems is almost identical from system to system with some slight variations. The infrastructure and housing for all hydropower equipment varies from project to project based on siting constraints and we will therefore be looking only at the equipment necessary to successfully convert the mechanical energy of flowing water into the electrical power that we all use on a daily basis. The four main components of a fixed speed small scale hydropower system, as previously discussed in Chapter 2, are the governor, turbine, excitation system, and generator.

The governor is a very common part of the small scale hydropower system which can be operated similarly/identically with its large scale counterparts. Most likely, the governor will function to control both the speed and the power output of the hydroplant. This means that there will need to be active minute by minute control of the power output and speed of the turbine during transient periods of head and flow changes in a small scale run of river plant. If a customer is hoping to be able to net meter, the transient changes in head and flow will have small but present affects on the wicket gate adjustments in order to mitigate the acceleration of the hydroturbine.

The turbine, regardless of fixed speed or variable speed set-up, is always required. Based on the projected head and flow for the project site and the relationships outlined above in figure 2.3, the correct turbine can be selected. While the small scale run of river hydroplant experiences rated head and flow, the turbine will most likely always be running at it's most efficient speed. The transient changes however that the turbine may experience based on environmental changes is where the fixed speed hydroturbine will be forced to operate outside of it's most efficient points until the governor is able to correct for the transients.

The excitation system of a fixed speed hydropower plant will accomplish the same task from system to system, with the exception of the selected type. For the purpose of less maintenance and degradation over time, a static excitation system would most likely be the best choice. A DC excitation system will eventually need the replacement of brushes and a static excitation system would require batteries or some sort of independent DC supply in order to allow for black start capabilities. The AC, brushless excitation system, if used with a permanent magnet generator would also require maintenance, but could utilize the PMAC generator to drive itself, meaning that it could be more reliable in the sense of counting on the unit to really start up under black start conditions.

Finally, the generators required for a fixed speed hydropower plant are numerous. Because the hydropower industry has been fixed speed since the technology's inception, the literature on the reasoning behind different topologies and how they are to be installed is everywhere. The most common generator choices in the hydropower industry are permanent magnet synchronous machines and wound rotor synchronous machines. Permanent magnet synchronous machines are simple in their design and highly efficient but more expensive than their wound rotor counterparts scaling with rated power. Wound rotor synchronous machines are larger, could require maintenance earlier in their life cycle, and less efficient, but much cheaper than PMAC generators.

4.2.2 Developmental Considerations

The most important aspect of any new hydropower project, regardless of sizing or scope, is the upfront capital costs and projected price point. This criteria is the most influential factor when considering the design of a hydroplant, having effects on the potential infrastructure, equipment, and management considerations. Research has been conducted on small scale hydropower that indicates that small scale hydropower is subject to nonlinear economies of scale and while the average construction costs of small scale hydropower are relatively high, there are still hundreds of sites on the low end of the cost side that are still cost effective and under $5,000/kW. If a developer is looking to site the most cost effective small scale hydropower plant, there are some rules of thumb that can be followed to insure that the up front cost of the project is as low as possible. The two most influential factors affecting the cost of traditional small scale hydropower plants are the amounts of head and flow [6].

- The greater the available head, the lower the cost per kW.
- There should be enough flow to produce the power necessary for project specifications, but too high of volumetric flow can have long lasting negative effects on the machinery.
- Distance to the nearest road and/or nearest substation should be maximized.
- Penstock length

The infrastructure costs are by far the greatest hindrance to cost-effective small scale hydro and is a large factor in development regardless of fixed or variable speed system design. Dam and reservoir construction, tunnelling and canal construction, powerhouse construction, site access infrastructure, grid connection, planning, feasibility, and permitting can all be placed under the broad banner of civil works costs. The electro-mechanical equipment required for the project includes turbines, generators, transformers, cabling, and control systems, but they vary significantly less than the civil engineering costs due to their mature, well-defined technology, whose costs are not greatly influenced by site characteristics [32].

Operation and maintenance is the final developmental consideration which can have a drastic effect on the planning of a fixed speed hydropower project. Automation and robust solutions are key based on the need of the project. If the project is for a private customer on private land, net metering and automated solutions are most likely the goal of the project. Maintenance would ideally be minimal or non-existent and the proposed hydroplant would likely only turn off once a year at most to be inspected. If the project is a public project or will be coordinating with grid operators, automation would be an innovative way to cut down on staffing costs, but the maintenance and control would still need heavily monitored in order to comply with FERC regulations.

4.2.3 Energy Production Constraints

To have a successful and profitable fixed speed hydropower system, the capacity factor of the small scale run of river hydropower project should be maximized. Any downtime experienced by the system throughout the year would require not only operational costs to shut down and turn the system back on when head and flow has returned to normal, but time spent not producing energy is time that you are losing out on potential profit. The head and flow of the conduit will also vary based on seasons and yearly conditions experienced by the upstream area. Because of the fixed speed nature of the hydropower plant, rough zones must also be avoided, meaning that when head and flow are faltering below the rated values that the turbine was designed for but are still present, the plant may need to be shut down. There are minimum heads and flows required to take the machine out of motoring mode and into generating mode which also must be met during extreme cases of drought or low water flow in the fall. For this reason, the governor put in place must always be monitoring the generator and protecting it from these harmful conditions.

4.3 Variable Speed Operation

Variable speed operation of hydropower plants is a relatively new approach to hydropower, but has proved itself over recent decades in the wind power industry. It's adoption into hydropower is fairly recent and has only taken place in select projects, most notably David Brown Kinloch and Shaker Landing Hydro's adoption of a variable speed permanent magnet generator at the Weisenberger mill in midway, KY. Their fixed speed system was replaced by a permanent magnet generator connected to a VSD system to convert the voltage from whatever frequency dictated by the low head conditions to the required 60 Hz. The same result can also be accomplished by utilizing generators specifically meant to output 60 Hz electricity at variable speeds such as doubly fed induction generators.

4.3.1 Equipment Required

The equipment required for a variable speed plant is similar to that of a fixed speed system, although a bit more complicated since the standardization of parts has not yet occured for variable speed hydro. A governor is required, although if net metering is the operating condition, the wicket gates could be kept open 100% of the time thanks to the fact that speed does not need to be mechanically controlled as fixed speed hydropower. The turbine choices remain the same as fixed speed hydro, the excitation system is not utilized, but current controllers for the rotor windings is still necessary and follows the control methods outlined above in Chapter 2. The generator does not require any sort of special custom designs, a simple doubly fed induction generator is all that is needed and could be purchased from most manufacturers of wind generators.

To focus on the differences between the equipment required for a variable speed system and a fixed speed system, I will focus mostly on my descriptions of the governor, power electronics controls, and generator. The governor utilized in variable speed hydropower can serve two function depending on the relationship the project has with the grid. If the variable speed hydropower plant communicates with grid operators to provide certain amounts of power at certain times, the governor utilized in variable speed hydropower would be the same as a fixed speed hydropower governor. If, however, the variable speed hydropower plant were net metering, the wicket gates could be forced to be permanently open 100% to let all water in to the turbine at all times, allowing for the power electronics to control the speed of the turbine alone. This could allow for far more mechanical energy to enter the turbine runner than in a fixed speed system over the course of a year.

The electronics controls, while not off the shelf from most hydropower manufacturers, would only need slight alterations from a wind power manufacturer if given the same efficiency hill curves utilized in this research. In wind power, the speed of the turbine is controlled based on information from power curves and tip speed ratio performance. The electronics to control the rotor currents is also just as compact as a small scale hydropower excitation system, can control reactive power much like a traditional fixed speed excitation system, and must be rated for 30% of the total generator power rating.

When looking at sourcing a generator for a variable speed hydropower plant, there are many options that can be considered. For this research, a doubly fed induction generator was tested due to its availability and wide spread control documentation within the wind industry. A permanent magnet generator has been utilized in similar research for the department of energy with the stator current fed through a VFD before contributing to grid power [15] as well as the potential for the same set-up with induction machines. Many robust and uncommon generator choices could be made for practical variable speed hydropower projects that would not be viable for fixed speed cases.

4.3.2 Developmental Considerations

Variable speed hydropower faces many of the same developmental considerations as fixed speed hydropower from an infrastructure standpoint. The same details regarding the operation and maintenance of the hydroplant must be analyzed and the net metering vs grid cooperative hydropower have identical options and obstacles. However, the one area where variable speed technology shines in the project planning stage is that if there are higher variations in head and flow at a specific site, or if there are seasonal but drastic changes in water conditions, variable speed is still able to operate and respond to changes much quicker than fixed speed counterparts.

4.3.3 Energy Production Constraints

Thanks to the variable speed nature of wind power and doubly fed induction generators in general, the rough zones that must be avoided in fixed speed hydropower do not require avoidance in variable speed hydropower. To maintain synchronous speed with very little available head or flow is a difficult task to accomplish without motoring or needing to shut down until water levels return to normal. What was shown in the research by [15], during these cases when head and flow are too low for a synchronous plant, a variable speed plant can continue to operate and produce power during short and extended periods of time. This greatly increases the capacity factor of the plant and over an annual period could allow for a large increase in power production if heads and flows are variable at the project site.

4.4 Experimental Results

The experimental results of this research are presented with the preliminary simulation results obtained in Matlab/Simulink utilizing the mathematical equations for hydropower governors, generators, and Francis turbine hill curves. Separate plants were modeled for each generator choice in order to better observe independent transient reactions due to environmental changes in head and reference power conditions. The hardware results are then presented which were obtained utilizing Matlab/Simulink for control modelling, dSpace microcontroller and interface software, and a motorsolver DC brushless motor as well as a motorsolver double fed induction machine.

4.4.1 Simulation Results

During simulation testing, three hydropower plants were modeled. The first plant to be modeled during this research was a fixed speed hydropower plant utilizing a wound rotor synchronous machine. The excitation system utilized was a simple PI controller tuned for a fast response with little to no overshoot. The overall system is shown below in figure 4.1.

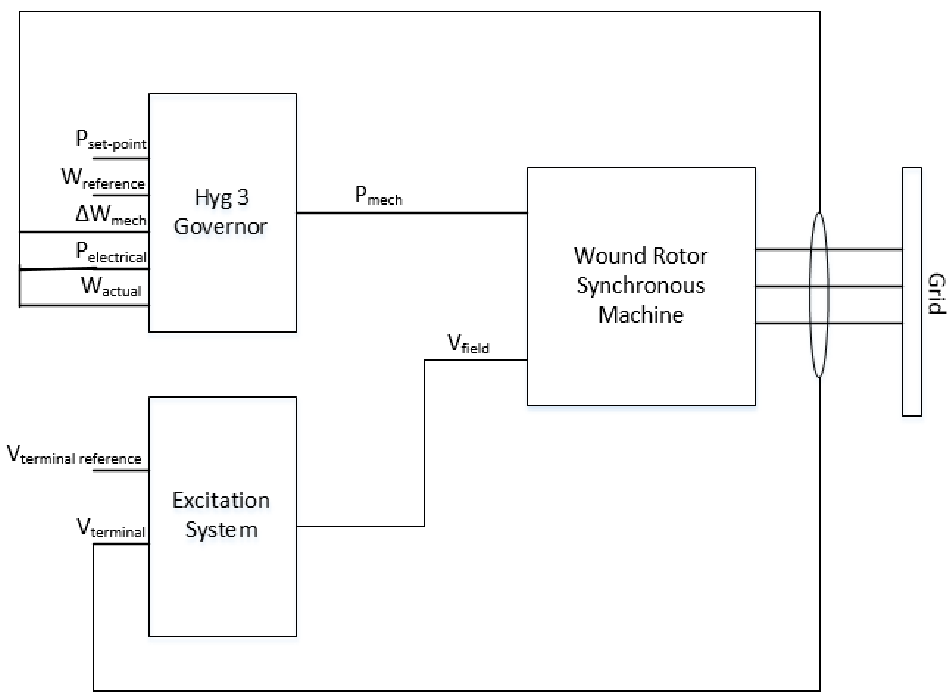

Figure 4.1: Complete model of a wound rotor synchronous machine hydropower plant used during simulation trials.

The relevant simulink models for the wound rotor synchronous machine can be found below, followed by a figure of the torque equation used to derive the speed of the machine.

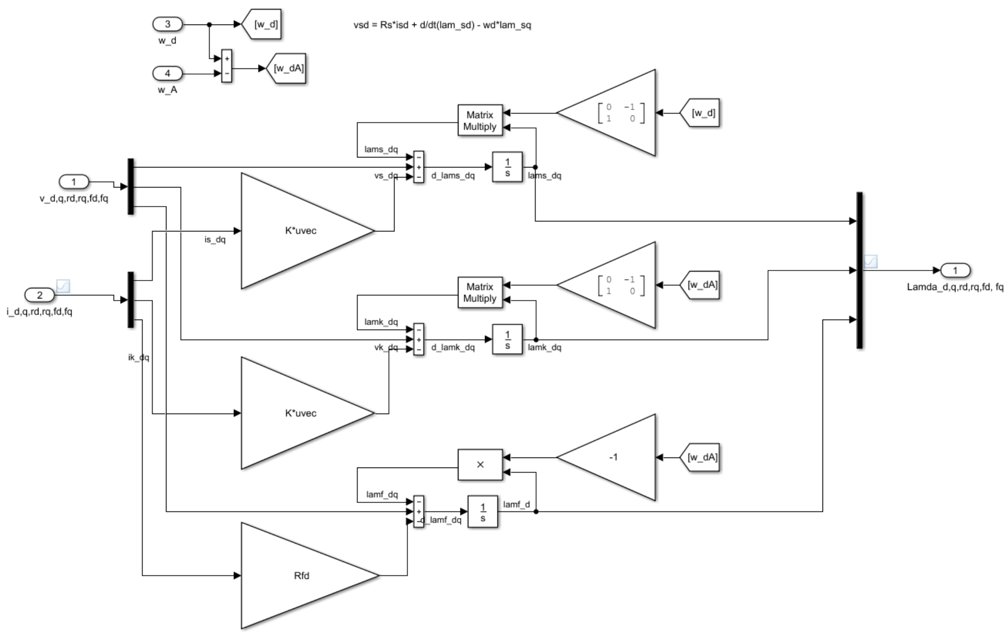

Figure 4.2: Simulink block diagram of the electrical equations used to simulate a wound rotor synchronous machine.

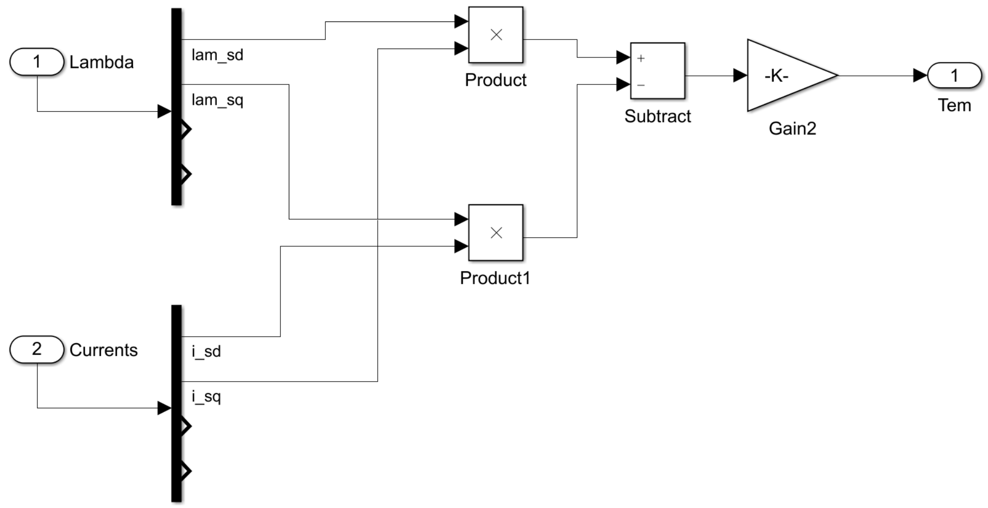

Figure 4.3: Simulink block diagram of the torque equations used to simulate a wound rotor synchronous machine.

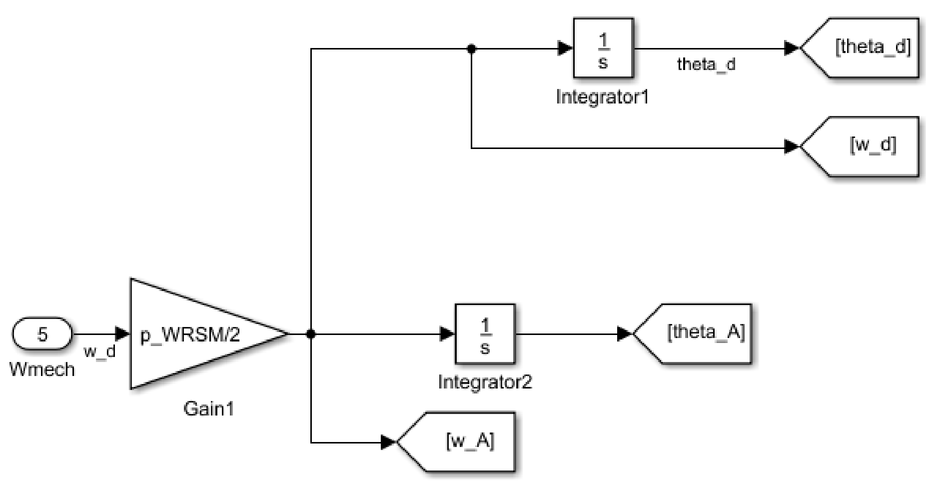

Figure 4.4: Simulink block diagram of the defining of the DQ speeds used to simulate a wound rotor synchronous machine.

Once the wound rotor synchronous machine was modeled, the fluctuations in terminal voltage caused by a connection to the grid had to be simulated which were modeled using simple grid modelling equations seen below.

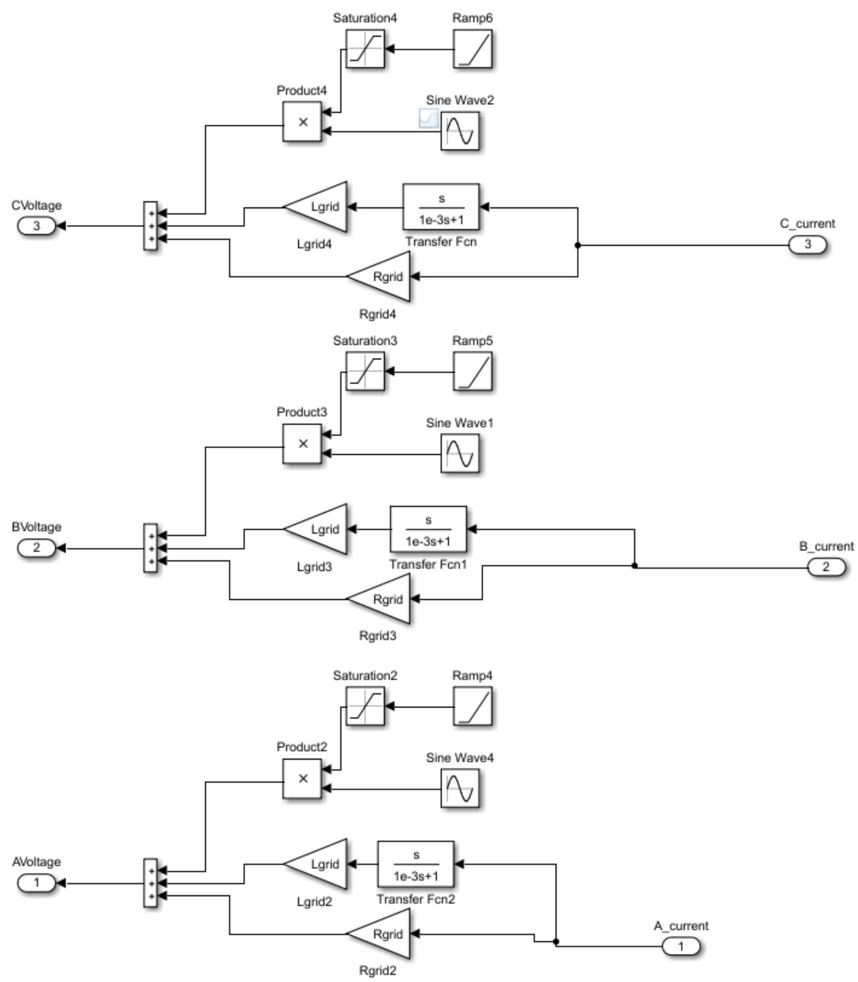

Figure 4.5: Simulink block diagram of the electric grid used to simulate the changing terminal voltage of a wound rotor synchronous machine.

The basic PID controller utilized to control the field winding of the rotor was constructed as depicted by the figure below.

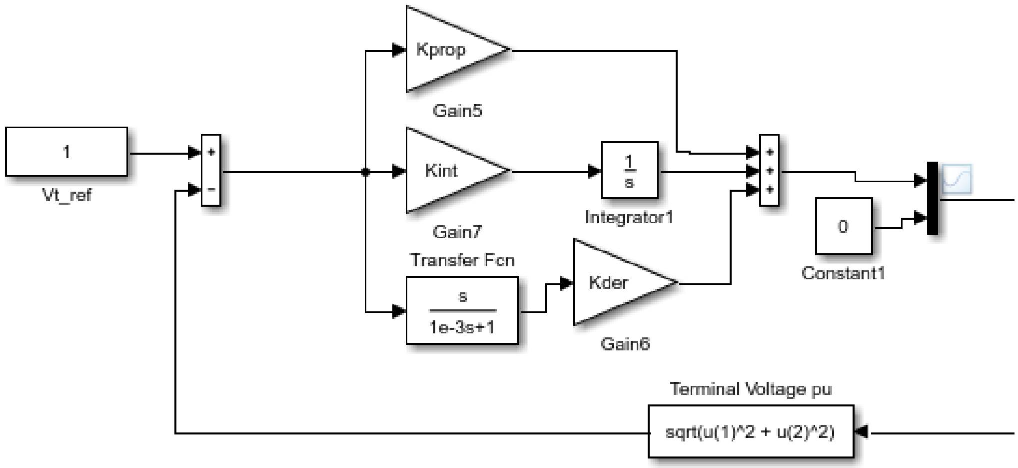

Figure 4.6: Simulink block diagram of the PID terminal voltage controller.

In order to verify that the wound rotor synchronous hydropower plant was operating in an expected fashion, a permanent magnet synchrnous hydropower plant was modeled. The purpose of including the PMAC hydroplant was to corroborate the results of the wound rotor plant while showing an increase in efficiency. That hypothesis was proven correct during testing, so the results of both plants were utilized. The overall permanent magnet synchronous hydropower plant system is shown below in figure 4.2.

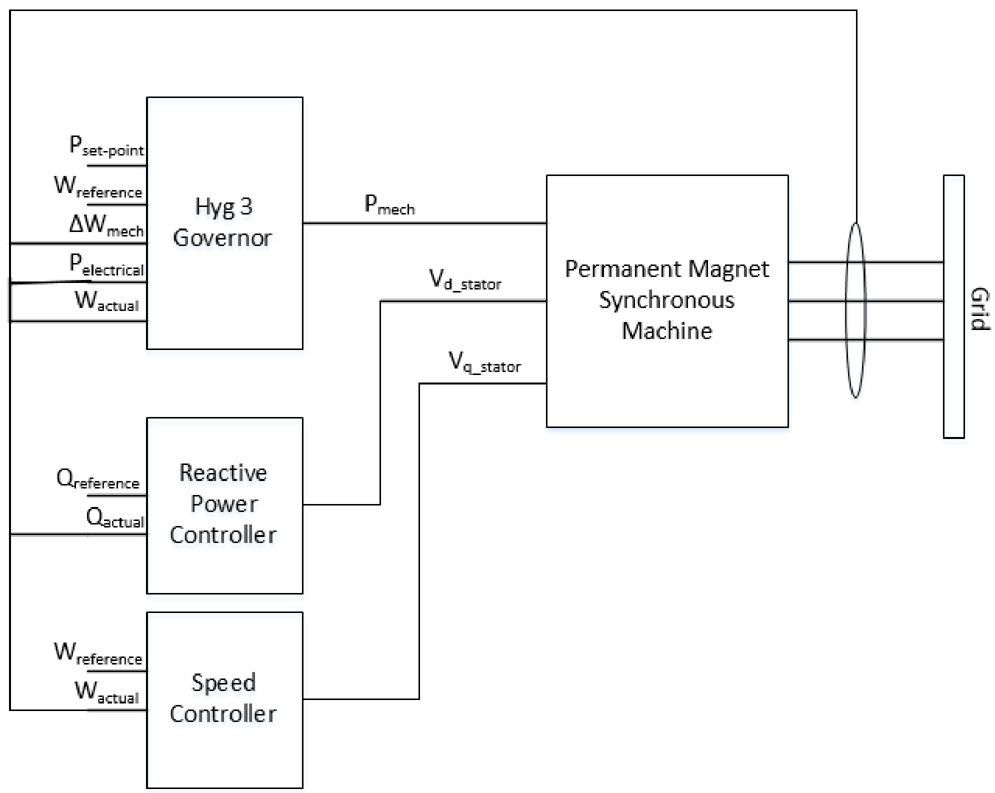

Figure 4.7: Complete model of a permanent magnet synchronous machine hydropower plant used during simulation trials.

The simulink block diagrams utilized to fully model the permanent magnet synchronous machine can be found below. The models all depict the equations mentioned earlier in this research.

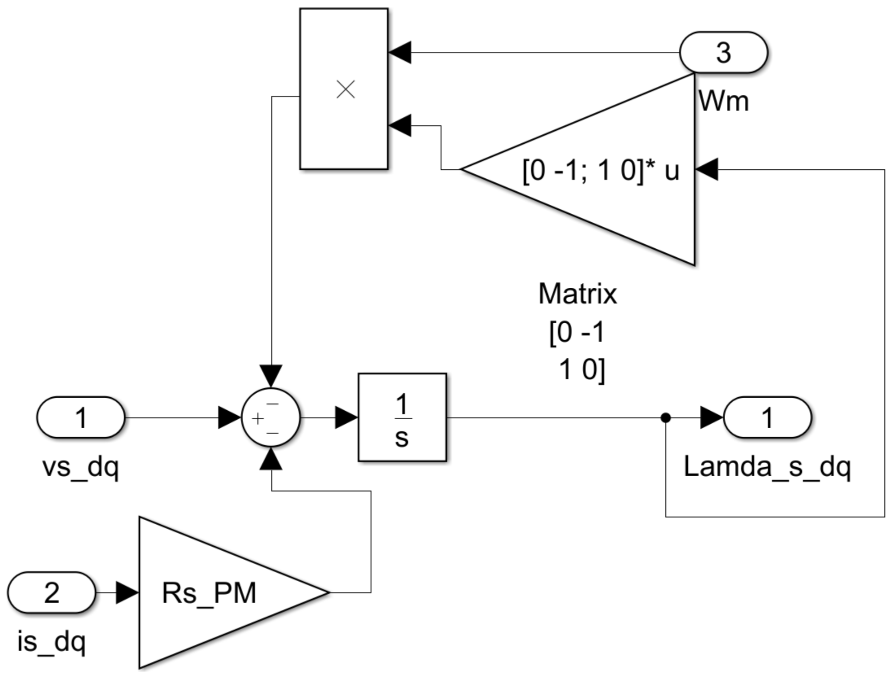

Figure 4.8: The simulink block diagram of the electrical equations of the permanent magnet synchronous machine.

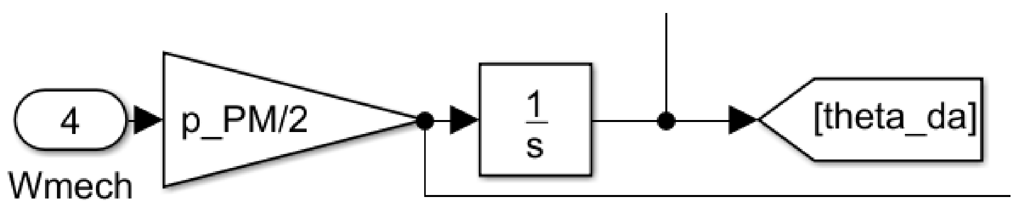

Figure 4.9: The simulink block diagram of the defining of the DQ reference speed for the permanent magnet synchronous machine.

The variable speed hydropower plant was modeled using a doubly fed induction generator, a traditional governor system utilizing power set-point droop control, and a novel adjustable speed governor created and validated by [21]. The P_{mech} portion of the model used in the research performed by [21] was implemented inside of the traditional governor much like the hyg3 governor model indicates, allowing for the control of head and flow where not possible before. The block diagram of the variable speed hydroplant model is shown below in figure 4.3.

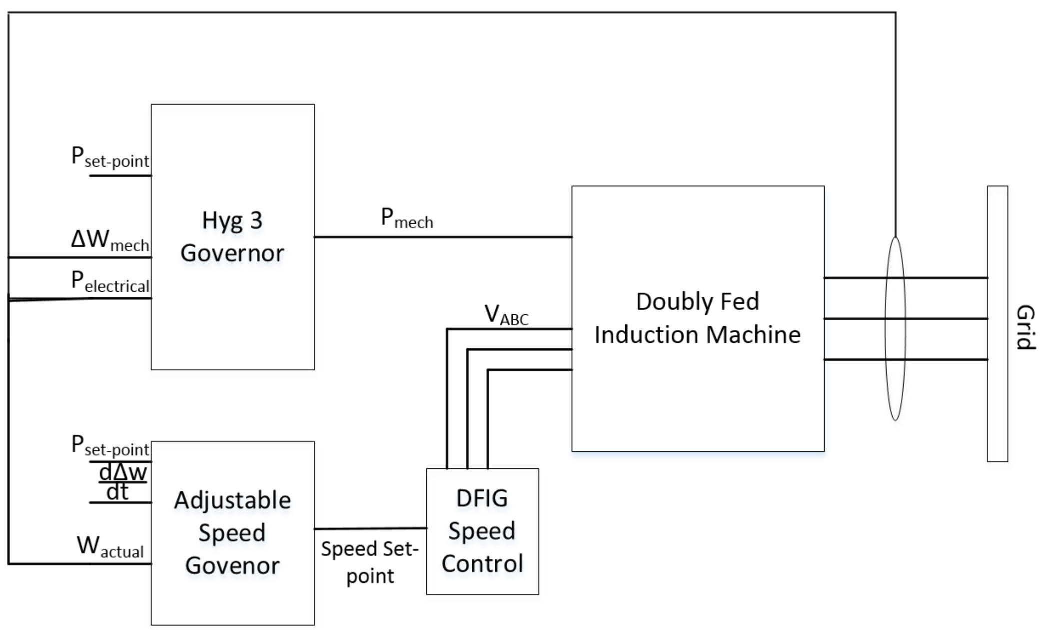

Figure 4.10: Complete model of a doubly fed induction machine variable speed hydropower plant used during simulation trials.

The doubly fed induction machine was then modeled similarly to the wound rotor machine and the permanent magnet machine. The block diagrams for the electrical equations and torque equations can be found below. The defining of the DQ reference speed is the same as the wound rotor synchronous machine.

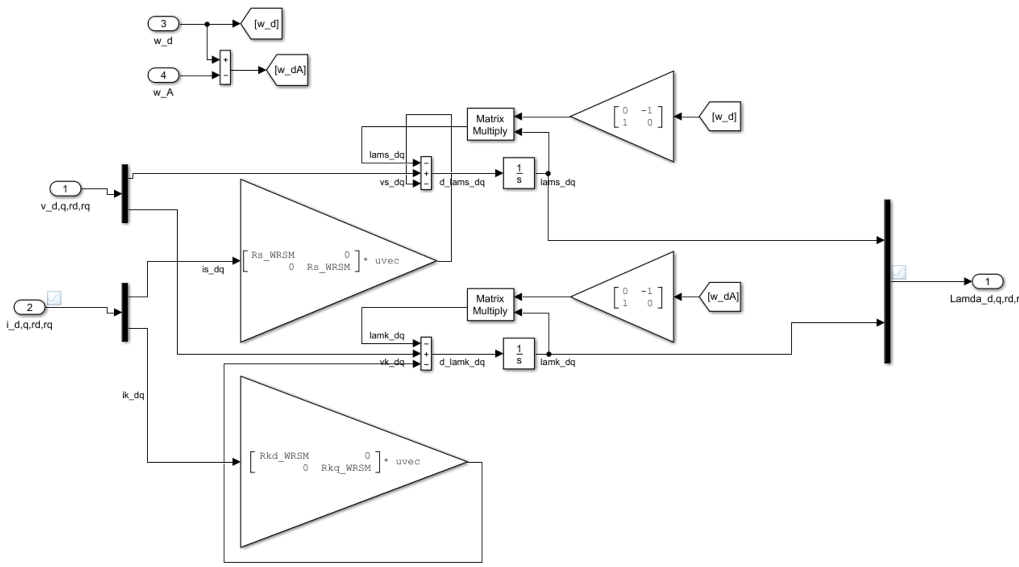

Figure 4.11: The Simulink block diagram of the electrical equations that make up the model used for the doubly fed induction machine.

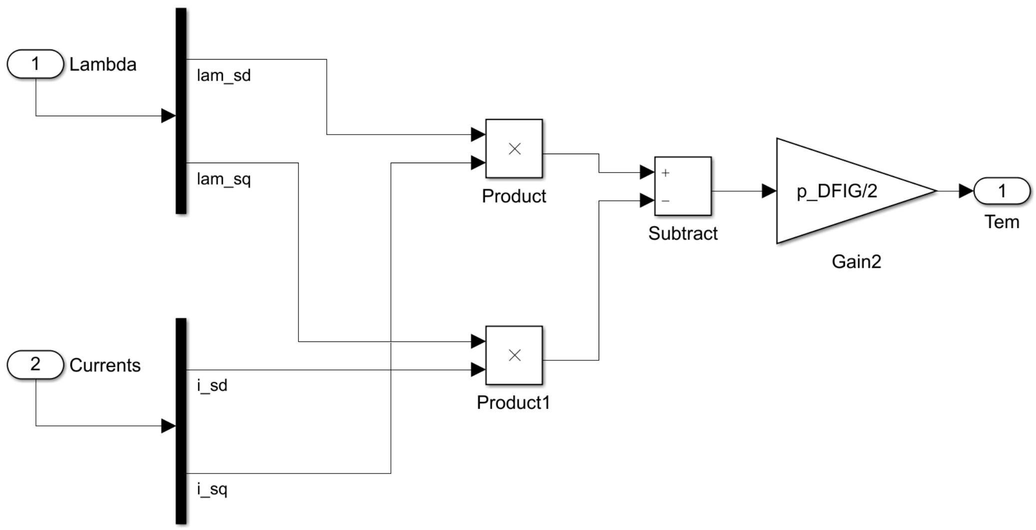

Figure 4.12: The Simulink block diagram of the electrical equations that define the electromagnetic torque on the rotor used for the doubly fed induction machine.

Utilizing the mathematical equations outlined in Chapter 2, three independant hydropower plants were modeled in Matlab/Simulink in the per-unit domain and tested with three transient cases. The first test case was a situation in which each hydropower plant achieving a steady state 0.7 per-unit (pu) total power output and experiencing a change in reference power from 0.7 to 0.75 pu. This is a common scenario in which a plant operator is instructed to produce 5% more power from the power plant to make up for a decrease in energy production at another power producing source.

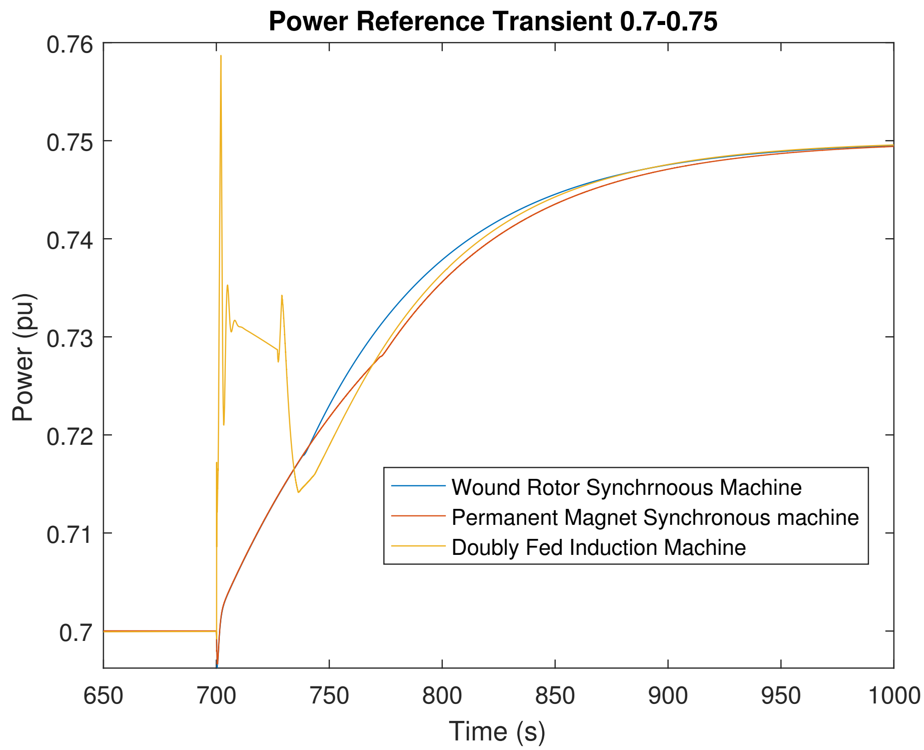

Figure 4.13: Transient response of the three tested hydroplants under the transient conditions of a step in reference power from 0.7 to 0.75 pu power output. The doubly fed induction generator is able to respond to the need for more power very quickly before following the overdamped response of a typical fixed speed hydroplant model.

The second test case was a situation in which each hydropower plant achieves a steady state 0.7 pu total power output and experiencing a change in reference power from 0.7 to 0.65 pu. This is a common scenario in which a plant operator is instructed to produce 5% less power from the power plant to make up for a increase in energy production at another power producing source.

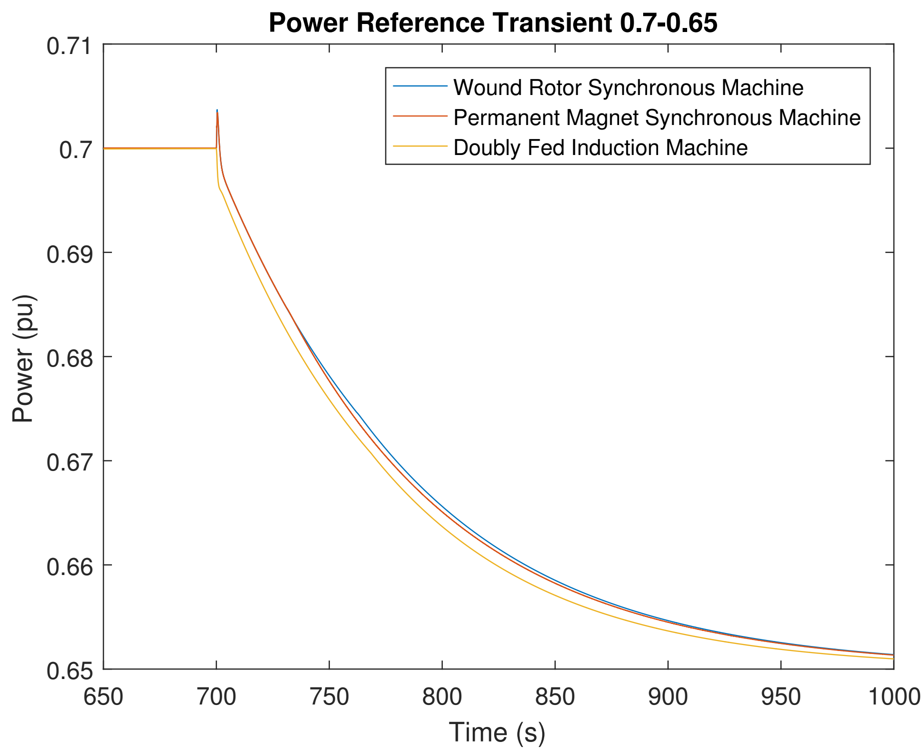

Figure 4.14: Transient response of the three tested hydroplants under the transient conditions of a step in reference power from 0.7 to 0.65 pu power output. The doubly fed induction generator responds to the command for less power in the same predictable decline as a fixed speed hydroplant, indicating stability when ramping down power production.

The third test case was a situation in which all three hydroplants are producing a steady state 0.7 pu power output and suddenly there is a 5% deficit in the amount of available static head. This response in a fixed speed hydropower plant would require the governor to detect the change in power and force the gates to open to allow more water into the turbine runner to make up for the 5% change. In the variable speed hydropower plant model, the same effect on the governor occurs, but the power electronics also sense the change in flow and are able to adjust the speed of the turbine to allow for a faster and more profitable return to the commanded 0.7 pu power output.

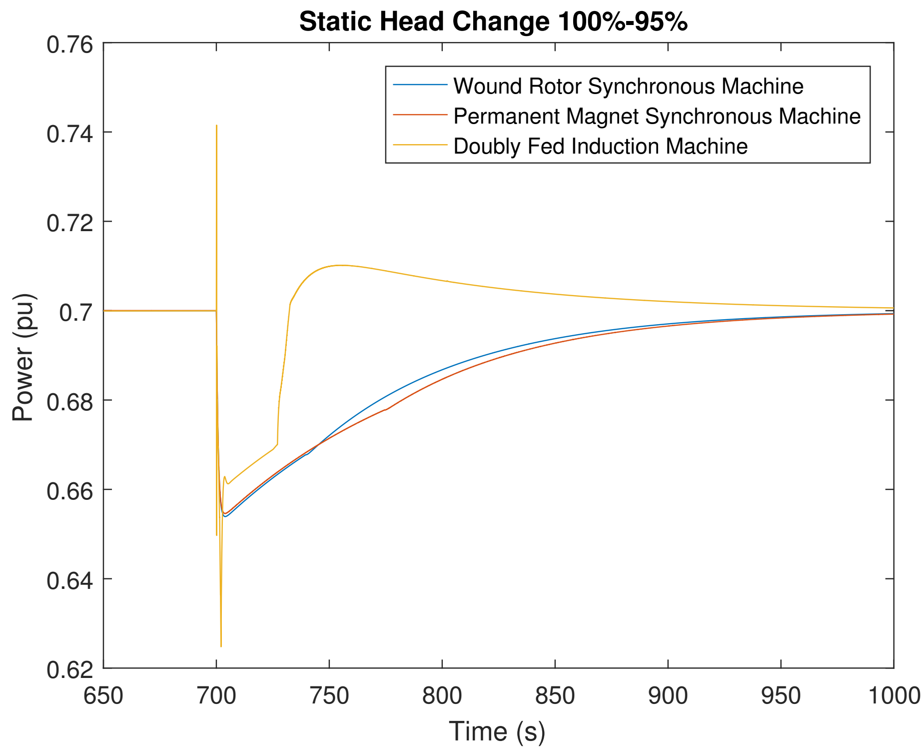

Figure 4.15: Transient response of the three tested hydroplants under the transient conditions of a negative step change in available static head from 99.7% to 0.95%. The doubly fed induction generator responds to the change in head similarly to the fixed speed hydroplant, but is then able to correct for the change in head significantly faster than the fixed speed plants, indicating a more robust solution to quick environmental changes.

4.4.2 Hardware Results

The results gathered from simulations in Matlab/Simulink were then compared with results from real electric machines to test for accuracy. The hardware utilized still used Matlab/Simulink for modelling, but where then broken down and built in C code which was fed to ControlDesk v3.7 and controlled using a dSpace microcontroller setup. The C instructions where then used by the controller to send signals to a power electronics board with inverters and other power electronics to drive the chosen electric machines under the 3 different test conditions. A photograph of the hardware setup can be seen below in figure 4.16.

The electric machines under test were the same as in the simulation portion of this research, but the mechanical power delivery of the governor was created in hardware by driving a torque controlled DC motor. The choice of using a DC motor for this purpose was due to the simplicity of control. Controlling the torque output of the DC motor can be accomplished independant of the speed of the rotor. By controlling the current of the DC motor, you can directly control the torque output by simply multiplying the current being commanded and the K_e value of the motor.

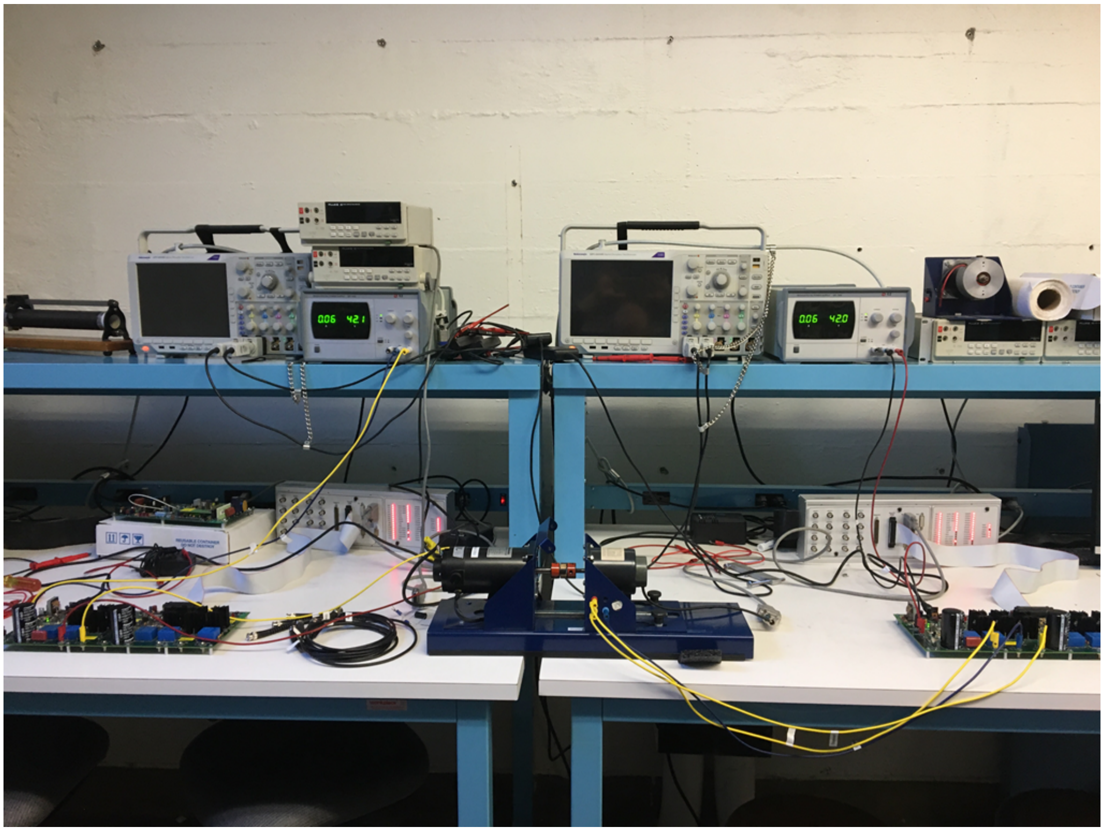

Figure 4.16: The hardware testbed that was utilized in the hardware portion of this research. The white board with LEDS that can be seen is the microcontroller that utilizes dSpace commands. The power electornics board connected to the electric machines can be seen on either side. This setup in particular is depicting the permanent magnet machine testing that occured.

Test case one was tested using the set-up described above. The responses observed match the behaviors of the simulation results and the transient response to the power reference being increased by a step input value is identical. In both the simulation and hardware results, when the reference power is increased instantaneously, there is a slight decrease in power output followed by a overdamped increase in power output over time towards the new reference power in the fixed speed hydropower systems. The hardware results are complete for the fixed speed systems but the variable speed system utilizing the doubly fed induction generator is still in development due to a hardware malfunction that will be completed by the writing of the final draft of this thesis.

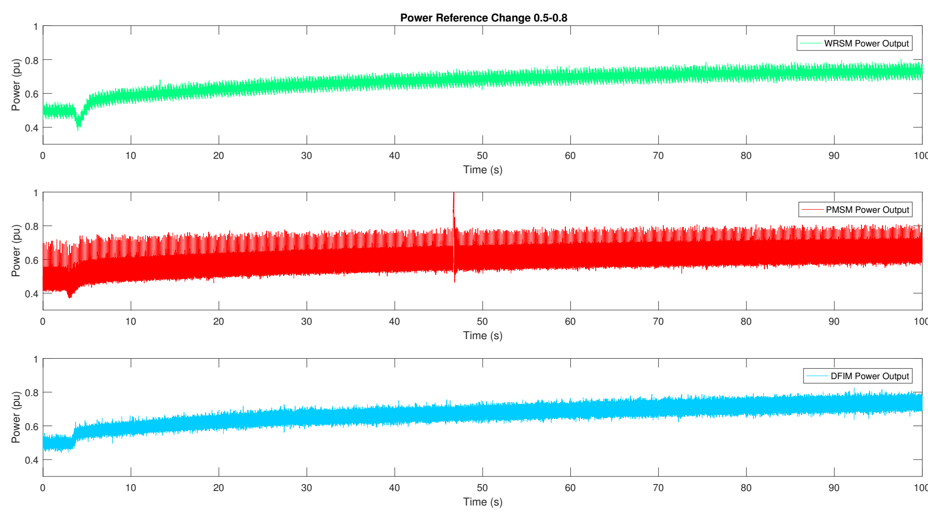

Figure 4.17: Transient response of the three tested hydroplants under the transient conditions of a step in reference power from 0.5 to 0.8 pu power output. The wound rotor synchronous generator and permanent magnet synchronous generator are able to respond to the need for more power very slowly, following the overdamped response of a typical fixed speed hydroplant model.

Test case two was then tested on the same criteria as test case one. The responses observed match the results of the simulation results and the transient response to the power reference being decreased by a step input value is again identical. In both the simulation and hardware results, when the reference power is decreased instantaneously, there is a slight increase in power output followed by a overdamped decrease in power output over time towards the new reference power.

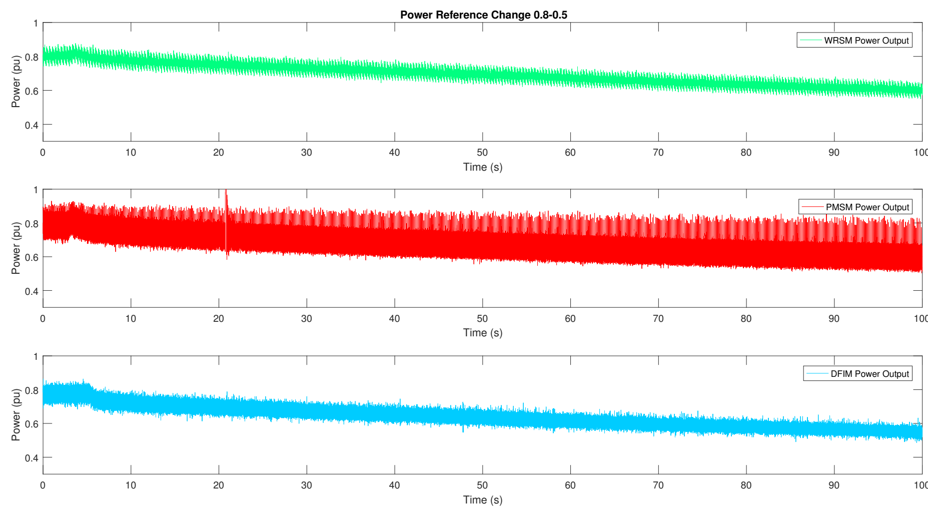

Figure 4.18: Transient response of the three tested hydroplants under the transient conditions of a step in reference power from 0.8 to 0.5 pu power output. The wound rotor synchronous generator and permanent magnet synchronous generator are able to respond to the need for more power very quickly before following the overdamped response of a typical fixed speed hydroplant model.

Test case three was then tested, creating an instantaneous drop in available static head entering the Francis turbine. The responses observed match the results of the simulation results and the transient response to the available head decreasing remains identical. In both the simulation and hardware results, when the available static head is decreased instantaneously, there is a large drop in power output followed by a overdamped decrease in power output over time towards the original reference power.

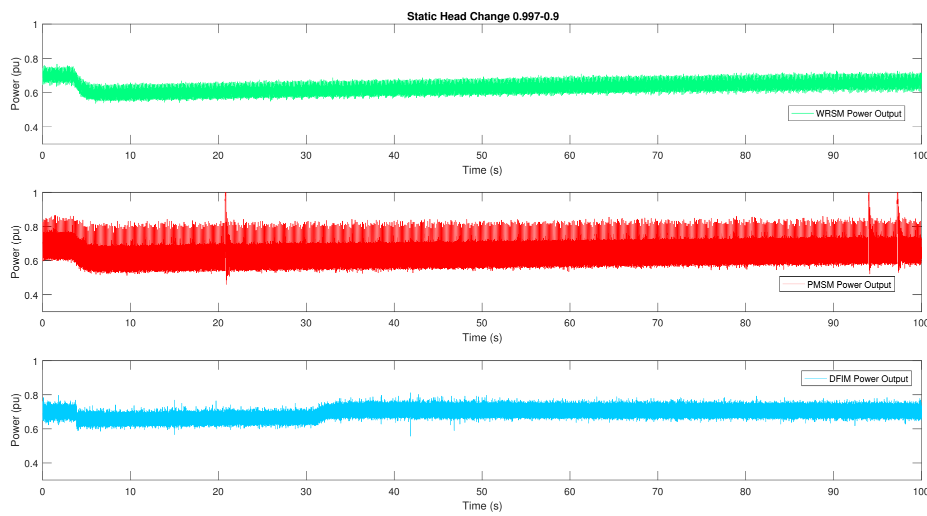

Figure 4.19: Transient response of the three tested hydroplants under the transient conditions of a step change in available static head from 0.997 to 0.9 pu. The wound rotor synchronous generator and permanent magnet synchronous generator all experience a large drop in power output and then slowly return to the previously set power point.

Chapter 5: Conclusions and Future Work

After analyzing the simulation and hardware results of this research, there are several conclusions that have been made. While hydropower has been primarily of a synchronous nature throughout the history of the technology, variable speed has a place in hydropower's future if adopted by developers. A problem faced by some developers today is that some understand the benefits of variable speed and wish to implement the technology, but must choose synchronous hydropower options due to the wait time on equipment. The wait time on variable speed equipment is due in large part however to the lack of adoption throughout industry. This research could help ease this catch-22 by creating awareness for the technology within the hydropower industry.

The simplicity of fixed speed hydropower was certainly recognized and appreciated throughout this research and the attractiveness of the abundance of literature has been recognized. While variable speed is new/nonexistent within hydropower, simulations and hardware have shown that for small scale run-of-river systems where head and flow can fluctuate, not only is variable speed technology more responsive to environmental changes, but has the potential to allow for greater power density and higher capacity factors.

This research could be greatly aided by expanding the breadth of variable speed technologies that could potentially be used in hydropower. Single phase generation and the use of VFDs could also be of great interest.

Bibliography

[1] E. K. Courtney Krause and M. Merrill, "Incorporating Small-Scale Hydropower Projects Into Our Energy Future," *Natural Resources & Environment*, 2016.

[2] R. J. Campbell, "Small hydro and low-head hydro power technologies and prospects," *Congressional Research Center*, 2010.

[3] "Hydropower (small-scale) — sswm," http://www.sswm.info/content/hydropower-small-scale, (Accessed on 04/26/2017).

[4] *Hydropower Vision - U.S. Department of Energy.* United States. Dept. of Energy., 2016.

[5] K. Johnson and B. Hadjerioua, "Small hydropower in the united states," 2015.

[6] L. Kosnik, "The potential for small scale hydropower development in the us," *Energy Policy*, vol. 38, no. 10, pp. 5512–5519, 2010.

[7] T. N. Manders, J. I. Höffken, and E. B. van der Vleuten, "Small-scale hydropower in the netherlands: Problems and strategies of system builders," *Renewable and Sustainable Energy Reviews*, vol. 59, pp. 1493–1503, 2016.

[8] "State of oregon: Energy in oregon - electricity mix in oregon," https://www.oregon.gov/energy/energy-oregon/Pages/Electricity-Mix-in-Oregon.aspx, (Accessed on 05/11/2017).

[9] "The price of electricity in your state : Planet money : Npr," http://www.npr.org/sections/money/2011/10/27/141766341/the-price-of-electricity-in-your-state, (Accessed on 05/16/2017).

[10] "Rm11-7-000 frequency regulation compensation in the," https://www.ferc.gov/whats-new/comm-meet/2011/102011/E-28.pdf, (Accessed on 05/16/2017).

[11] A. Majzoobi and A. Khodaei, "Application of microgrids in addressing distribution network net-load ramping," in *2016 IEEE Power Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, Sept 2016, pp. 1–5.

[12] "Endangered species act and columbia river salmon and steelhead," https://www.nwcouncil.org/history/EndangeredSpeciesAct, (Accessed on 04/26/2017).

[13] "The columbia river system inside story," (Accessed on 05/16/2017).

[14] O. Paish, "Small hydro power: technology and current status," *Renewable and sustainable energy reviews*, vol. 6, no. 6, pp. 537–556, 2002.

[15] D. B. Kinloch, "Demonstration of variable speed permanent magnet generator at small low-head hydro site," Nov 2015. [Online]. Available: https://www.osti.gov/scitech/servlets/purl/1230014

[16] M. F. K. Pasha, D. Yeasmin, S.-C. Kao, B. Hadjerioua, Y. Wei, and B. T. Smith, "Stream-reach identification for new run-of-river hydropower development through a merit matrix–based geospatial algorithm," *Journal of Water Resources Planning and Management*, vol. 140, no. 8, p. 04014016, 2013.

[17] "2.3 turbine selection." [Online]. Available: http://rivers.bee.oregonstate.edu/book/export/html/35

[18] J. Zhao, L. Wang, D. Liu, J. Wang, Y. Zhao, T. Liu, and H. Wang, "Dynamic model of kaplan turbine regulating system suitable for power system analysis," *Mathematical Problems in Engineering*, vol. 2015, 2015.

[19] E. De Jaeger, N. Janssens, B. Malfliet, and F. Van De Meulebroeke, "Hydro turbine model for system dynamic studies," *IEEE Transactions on Power Systems*, vol. 9, no. 4, pp. 1709–1715, 1994.

[20] "Test case." [Online]. Available: https://www.ntnu.edu/nvks/experimental-study

[21] M. Starrett, "Development and experimental hardware validation of novel variable speed hydropower control schemes for emerging applications and water resource paradigms," http://www.hydrofoundation.org/uploads/3/7/6/1/37618667/dissertation_-_mike_starrett.pdf, 6 2016, (Accessed on 05/21/2017).

[22] J. Fraile-Ardanuy, J. Wilhelmi, J. Fraile-Mora, J. Pérez, and I. Sarasua, "A dynamic model of adjustable speed hydro plants," in *Proceedings of the 9th Congreso Hispano Luso de Ingeniería Eléctrica, Marbella, Spain*, vol. 30, 2005.

[23] J. Fraile-Ardanuy, J. R. Wilhelmi, J. J. Fraile-Mora, and J. I. Pérez, "Variable-speed hydro generation: operational aspects and control," *IEEE Transactions on energy conversion*, vol. 21, no. 2, pp. 569–574, 2006.

[24] "Governor model: Hyg3," (Accessed on 05/17/2017). [Online]. Available: https://www.powerworld.com/WebHelp/Content/TransientModels_HTML /Governor%20HYG3.htm

[25] G. Laliberte, "A comparison of generator excitation systems," 2014.

[26] "What is excitation system? definition & types of excitation system," Mar 2017. [Online]. Available: http://circuitglobe.com/excitation-system.html

[27] "Ieee recommended practice for excitation system models for power system stability studies," *IEEE Std 421.5-2005 (Revision of IEEE Std 421.5-1992)*, pp. 1–93, April 2006.

[28] N. Mohan, *Advanced electric drives: analysis, control, and modeling using MATLAB/Simulink*. Wiley, 2014.

[29] "Importance of reactive power for system," Jun 2013. [Online]. Available: https://electricalnotes.wordpress.com/2011/03/21/importance-of-reactive-power-for-system/

[30] T. K. Brekken, "A novel control scheme for a doubly-fed induction wind generator under unbalanced grid voltage conditions," 6 2016, (Accessed on 05/21/2017).

[31] "Causes & effects of cavitation. what is cavitation in hydraulic turbines?" http://www.brighthubengineering.com/fluid-mechanics-hydraulics/27427-cavitation-in-hydraulic-turbines-causes-and-effects/, (Accessed on 05/19/2017).

[32] "Renewable energy cost analysis: Hydropower," https://www.irena.org/documentdownloads/publications/re_technologies _cost_analysis-hydropower.pdf, (Accessed on 05/20/2017).