Undergraduate Students Perform Successful Cogeneration Study for University

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Introduction

Energy requirements for the buildings at the University of Idaho are almost entirely met from renewable resources. The primary source is biomass for heating and cooling. The secondary sources are hydroelectric, wind, and solar, in that order. The university has a commercial natural gas delivery infrastructure, but uses it only for emergency or backup. In providing for energy needs, the steam for heating and for chilled water gets throttled down. All that energy is lost. University Facilities directors for decades have been asked about adding a turbine to replace the throttling process, capturing some energy as electrical cogeneration. In 2018, the director authorized four electrical engineering students to perform a study to determine if cogeneration could be feasible, technically and economically. This is the most recent in a sequence of designs and studies that undergraduate students have performed on several topics for university Facilities. This one is unique in that its results were so well acquired that they were adopted almost verbatim by the Board of Regents in the next fiscal year's budget authorization.

This project is a feasibility study and design for the installation of three NLine Microsteam™ turbines (MSTs) in the University of Idaho's campus steam power plant. As shown in Figure 1, there are three natural gas boilers as well as one primary wood boiler that produce the steam. Natural gas is the backup energy source, used only in emergencies. Wood chips, a completely renewable local resource, is the primary energy source. The steam exits the boilers at a pressure of about 170 psi and feeds into a common manifold. The pressure is then reduced to 35 psi for campus distribution by three pressure regulating valves (PRVs) connected in parallel. This pressure reduction method wastes a great deal of energy. In the present topology, there is no way of capturing the energy

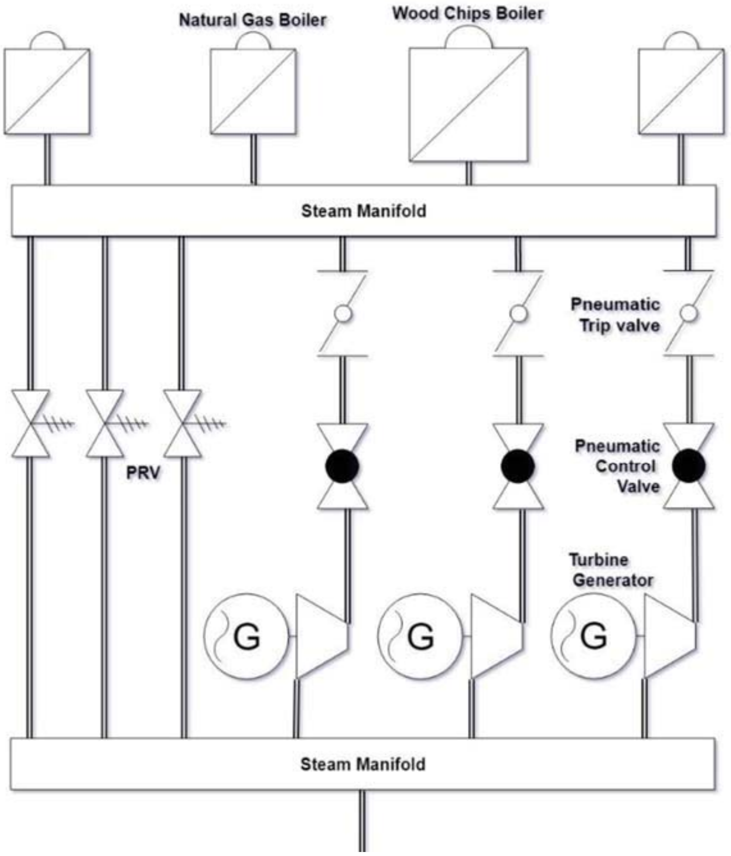

Figure 1 Steam Production Diagram

released in the process of throttling down the steam pressure.

Cogeneration concept

University Facilities wants to capture that wasted energy by placing MSTs developed by NLine Energy in parallel with the existing Pressure Reducing Valves (PRVs), again as shown in Figure 1. The turbines are each a revolutionary high-speed Euler turbine with a titanium composition that allows them to operate on saturated steam, unlike traditional turbines that are highly susceptible to corrosion in these conditions. Each MST includes a turbine that is coupled by a gear reduction box to a 480 Volt, three phase, generator that converts mechanical energy into electrical energy. That electrical energy is metered and tied into the nearest 480 V electrical panel, where it reaches the bulk electrical grid and can be delivered and consumed. Each MST comes with its own Programmable Logic Controller (PLC) as well as associated control equipment such as pneumatic valves, breakers, and meters.

During blackout conditions, the Steam Plant currently relies on a 208 V diesel backup generator that ties into the 208 V panel and supplies power to critical loads in the event of a loss of utility power. The primary boiler’s housekeeping supply is powered from the nearby 480 V panel, but because of the voltage difference, the boiler cannot currently be powered in blackout conditions. This diesel generator is aging, noisy, and inefficient. Because of this, University Facilities has a strong desire to eventually replace the generator with a reliable power source that can operate the steam plant during a blackout condition. The replacement system should operate without the lapse in power that is currently the case with the diesel generator. Further, any design and recommendations should fit into a future microgrid consisting of critical steam plant loads and the MSTs as a primary generation source.

Feasibility Study and Narrowing the Approach

University Facilities requested a recommendation of the optimal number of MSTs to be implemented in the campus power plant. This analysis began with the consideration of between one and four MSTs. Analysis determined that current steam production levels would enable full utilization of a single turbine and 90% utilization of two turbines. Both the one and two turbine options would have similar payback periods, yet the two turbine option would produce nearly double the power generation. A four turbine installation allowed for the largest increase in future steam production, but it was accompanied by a drastically longer payback than any other option as well as only minimal utilization of the fourth turbine. The analysis was then narrowed to either two or three turbines as these were identified as the superior options.

Option A: Two MSTs	
Initial Cost	$ 1,115,900.00
20 Year Total Maintenance Cost	$ (280,000.00)
20 Year Net Gain	$ 4,729,296.65
Buy Back Period (Years)	4.33

Option B: Three MSTs	
Initial Cost	$ 1,559,000.00
20 Year Total Maintenance Cost	$ (420,000.00)
20 Year Net Gain	$ 5,863,023.77
Buy Back Period (Years)	5.57

Figure 2. Cost Comparison

Comparing the two- and three-turbine options

Figure 2 shows a cost comparison between the two-turbine option and the three-turbine option. The two-turbine option has the more obvious benefits of a cheaper installation cost and a faster payback time, making it the more attractive option in the immediate future. However, looking out 20 years, this option has a severe limitation: By the year 2035, it will be 100% utilized as shown in Figure 3. At first this sounds like a good thing, but it overlooks a lot of available electrical energy. This is where the three turbine option has an important advantage.

The three turbine option does have a higher installation cost, a slightly longer payback period, and a much lower utilization rate at the time of the installation. The additional power generated during peak steam demand season, as well as long term capacity, makes it a better choice. The three-turbine option has the additional benefit that yearly maintenance may be scheduled during steam production troughs when one turbine is already off-line or lightly loaded. This usually means that needed maintenance may be planned while sacrificing little overall energy generation capability.

Campus steam load projections

University Facilities provided six years' worth of steam production data. Using this data, steam production was extrapolated out to 20 years. This required some error mitigation, correcting for clearly erroneous manual data entries, such as obvious stray values of zero or clear numerical saturation. Making error mitigation from manual entries was the most tedious and painstaking part of the project. After normalizing the data, a nearly uniform average rate of growth was calculated to be approximately 1.7% annually over the past six years. The University Facilities director projects closer to 3% annual growth despite the uniformity of the statistical trend. In order to make projections as accurate as possible, a weighted average of these two rates produced a projected annual growth rate of 2.27%. This rate should take into account any new buildings that will be built on campus as well as updates to current buildings that make them more energy efficient. The twenty-year steam projection provided in Figure 3 shows the historical steam use

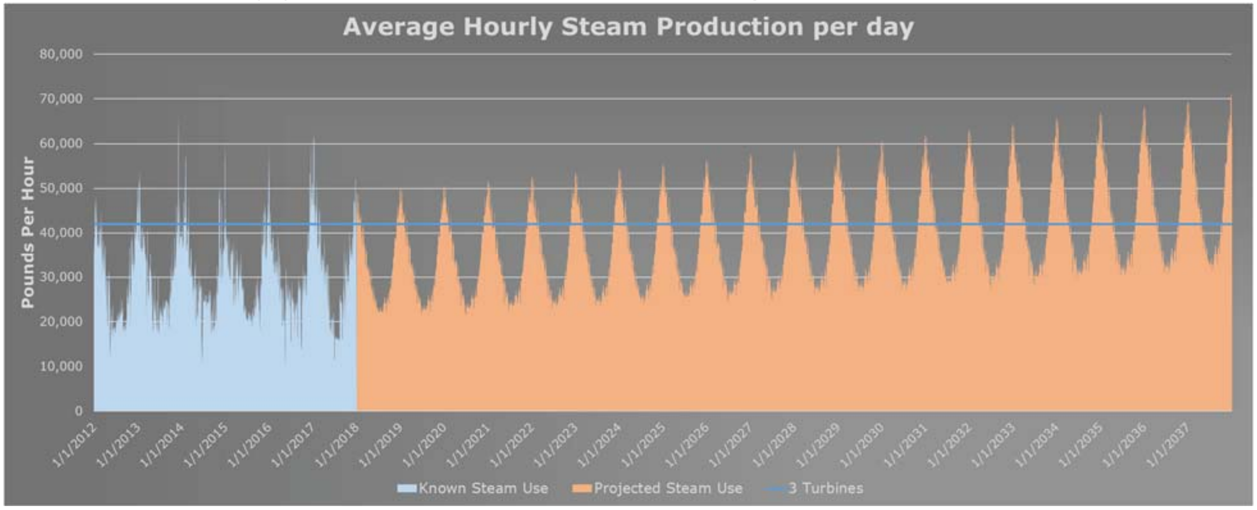

Figure 3. Average Projected Turbine Generation

in light blue, projected steam use in orange, and the maximum steam capacity of the three-turbine option (14,000 PPH per MST, 42,000 PPH total) in dark blue.

Projected steam use is then compared to how MST energy generation. An initial assumption of a linear efficiency curve for the units is made for both options. This enables calculation of a simple payback period in each case. However, this ignores the fact that the turbines do not produce any electrical power unless steam flow through a turbine exceeds 5,000 PPH. Parallel operation of the turbines and a linear efficiency curve was otherwise assumed. The corrected efficiency curve projected for twenty-year life produces projected generation for both the two-turbine option and the three turbine option as shown in Figure 4. The efficiency curve itself, with further explanation, appears in this paper's Appendix. Generation from the MSTs plateaus as each turbine comes online and after twenty years, indicates that two of the three turbines will be completely utilized, giving the university optimized energy generation for the entire time period.

Twenty-year economic analysis

The utility offers a tabulated set of energy conservation incentives to commercial customers who improve the efficiency of their energy system. Installing cogeneration fits into one category of such incentives, projects that have less than 15 years' payback. The students' economic analysis estimates an incentive of 20 cents per kWh saved in the first year up to 70% of program cost.

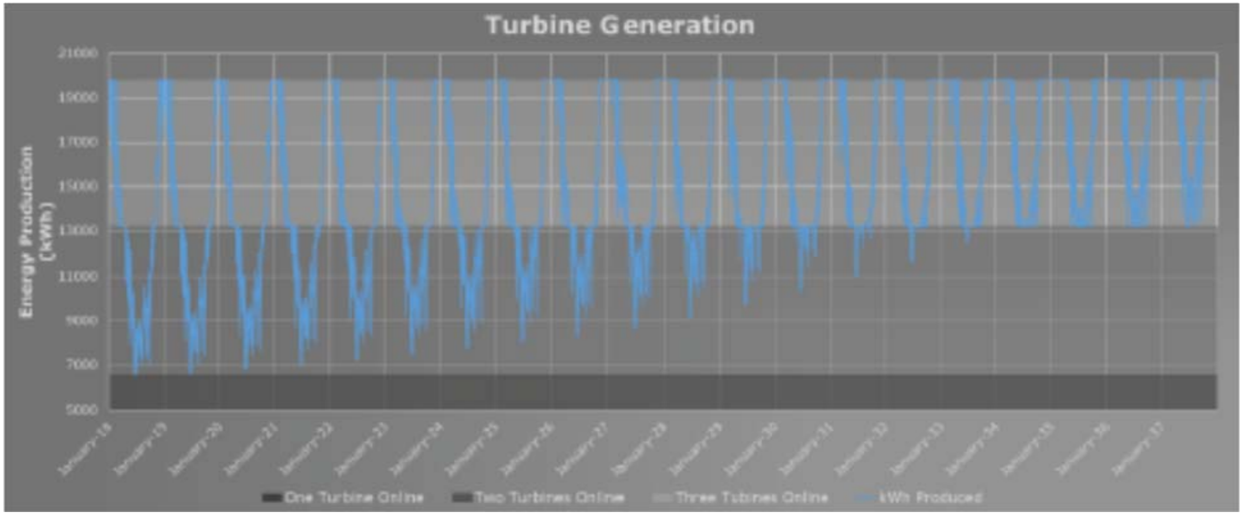

Figure 4. Twenty Year MST Energy Generation

As the initial analysis appears to be promising, the students performed detailed calculations using the utility's published rate schedule for the university. They also investigated whether the university could expect some demand shaving. The analysis resulted in a slightly longer payback period and little advantage in demand shaving. However, this was still well below the eligibility period of 15 years, qualifying for the utility's Schedule 90 Incentive Program. Projected first year generation was 4.697 MWh. With a 4% interest rate, this yielded a US$939,436.47 incentive from the utility's incentive program. Altogether, this leaves the University with a twenty-year net gain of US$5.94 million.

The university took the students' calculations into the budgeting process. With little change or correction to their numbers, a budget line was inserted in the FY20 university budget request to the Board of Regents and the legislature. Approval was granted at the Regents' February 2019 meeting with construction beginning in July. The legislature approved the budget in March.

Other less tangible benefits

Apart from the economic benefit that is the focal point of the project, additional less tangible benefits, although harder to quantify make this project even more appealing. We have researched similar projects to discover effects on the electrical systems in the vicinity of the proposed generation installation.[1]

Due to the nature of the steam generation process, the proposed turbine application would exhibit a great deal of inertia. The steam is produced in large boilers using wood chips that burn at a steady, controllable rate. Because of this, the steam flow changes only gradually and can be regulated accurately with automated control valves. The turbines, which spin at about 28,000 rpm, have a large amount of inertia as well. The maximum output of three MSTs is 825 kW with a nominal Power Factor of 0.92 lagging. This is about 15% of the average campus power consumption and matches a proportional percentage of reactive power demand. However, it is a significant enough portion that it will have a steadying effect on the campus grid. It is enough to mitigate a wide range of power grid transients and power quality problems, taking advantage of the university's remote location within the utility's grid. This is consistent with US DoE data that documents others universities' experiences in installing turbine generator systems of similar size and in similarly isolated locations. [1]

The steam plant will reap the same benefits as the rest of the campus system. It will experience these effects to a greater extent because its physical proximity to the turbines. Better phase balancing, improved power quality, and greater reliability of backup generation will all benefit the operation of the campus steam plant.

The addition of three MSTs at the Steam Plant fits into plans for a future campus microgrid. As a microgrid, the Steam Plant, or at least a portion of it, would be able to disconnect from the main grid and operate in a self-sufficient islanded state. Black start capability likewise comes with these MSTs. Two subsequent student projects are currently in progress as the next steps toward this eventual campus microgrid. Those projects will provide improved metering and protection of the interface to the public utility and an ability to shed load at will among several buildings or groups of buildings on campus. Student projects to design a microgrid in the largest city within the utility's territory serve as a model for these ongoing improvements. [2]

Assessment

As presented in this paper, this project produced results that saved the university a projected US$5.94 million. The students' design and economic analysis was presented to the university Facilities leadership in December 2019. The projected economics were validated by Facilities' engineers and financial specialists. A proposal to perform this project was written into the university's FY20 budget. As approved by the Board of Regents in February 2019 and subsequently by the legislature in March, it will be installed beginning in July. Those who teach senior capstone design know from experience how rare taking a project to production really is. It definitely proves the most significant education outcome sought in this project: To bring several elements of the students' education and experience to bear on a complicated, open-ended problem to achieve a useful solution. Results are presented in a wikipage and supporting links to documents and reports.[4]

This success, unprecedented in an undergraduate capstone design project at this university, obviously gave the students a great deal of confidence and credibility in their job interviews. Of the four students, one has accepted a position as an engineer with Washington State University at a rank above entry level. He has since moved to a public utility in Coeur d'Alene, Idaho. One has begun work for Power Engineers of Hailey, Idaho, a leading nationwide power system consulting company. A third student went to work with the electric power division of Raytheon. The fourth student returned to her native country of China and accepted a position as a power generation engineer there.

The university is currently arranging to showcase the students' success in its recruiting materials for the next annual recruiting cycle. Clearly, the Dean of Engineering, his Vice Dean for Development, and the university's Vice President for Advancement believe (and verify in their next budget) that this is a highly successful project. So does the Director of Facilities, who immediately commissioned two follow-on capstone projects: one to instrument internally the two electrical gateways to the university, making the data available in real time for a subsequent project to activate and control a university microgrid. The data will also appear in a graphic on the university's website. The other new project is a microgrid itself using these microturbines as three of its four sources of generation. A solar array atop the university's newest building is the other source. Four buildings electrically closest to the MSTs are the microgrid's load.

This project has, to a small degree, a diversity component that is new to this university. One of the students is a native of China, finishing the final year of her baccalaureate degree in the USA. She is part of a "3+1" program wherein students complete three years in China in an English-language engineering college, then come to the USA for their final year. She is part of the first class to do this in coordination with the University of Idaho. The other three students were US citizens. The team worked quite well together. Of five capstone design teams in this year's capstone course sequence, this team performed best by far. The mix of talent, two students with extensive power plant and paper mill experience and the Chinese student with power plant experience in an international setting, contributed to an obviously successful project.

Though turbine installations between a university and an industry partner as described in this paper are by no means novel, the degree of student involvement is rare. This installation as part of a longer term all-renewable microgrid project designed almost completely by undergraduate students, is a daring and novel educational initiative, both this piece and the overall concept. As few student projects of this nature anywhere are taken all the way into production, this is a remarkably successful one as well. Its international component indicates that education of engineering students can be quite successful, integrating skills learned here and elsewhere while overcoming language and cultural barriers. None of these components taken individually is by itself unique or novel, but the overall combination as an educational experience in practical engineering design and its success is rather unusual. This paper proves that it can be done and, to a lesser degree, illustrates how to do it.

Conclusions

The university's director of facilities commissioned a study to design and evaluate a MST-based cogeneration project at the university's steam power plant. The only product of that steam power plant had been energy for heating and cooling, produced almost 100% by renewable energy. As shown in this paper, the students built technical and economic models for the cogeneration facility. They proposed two options: a two-turbine and a three turbine installation. The two turbine option had a shorter payback but it did not produce as much energy as the three-turbine option did. A three-turbine solution was chosen. Over twenty years, the students' design is projected to save the university US$5.94 million. This turbine system was then prepared for inclusion in the university's FY20 budget for construction beginning in July 2019. The turbine system has power quality and system stability benefits as well.

This project as a whole is unusual in that it is an undergraduate capstone project that integrates economics, policy, and technical aspects of engineering into a successful renewable energy project that goes to production. Taking such a project to production alone is rare indeed. Addressing successfully this integrated set of educational outcomes is also quite unusual and encouraging. Its place in a longer sequence of projects to obtain a microgrid based wholly on renewable energy generation shows that such projects are actually obtainable. They can be and are completed as an educational experience by undergraduates.

All four students found positions in the public electrical utilities, in power production for manufacturing, or in technical consulting for the electric power industry. Though this paper contains a great deal of technical material, all of it was researched, designed, modeled, and tested by these four students. This project had a successful diversity component in that one member of the student team was an international student who contributed well to a strong team effort. Students from the team found entry level positions in both cultures.

Appendix

Efficiency Curve

In the course of this project, the students created a model of the turbines to examine steady state and transient behavior under changing electrical load and steam input conditions. This model was used for preliminary design, for construction, and also for a microgrid analysis if changes are made to allow islanding and microgrid control. Additionally, power output based on steam input data is necessary for an accurate economic analysis and an appropriate behavioral model. The resulting efficiency curve shown in this Appendix is for a three-turbine installation.

The MSTs are comprised of several components, each having power losses of a different nature. In order to create an accurate economic analysis, the students created an efficiency curve based on this understanding of the MST's losses. Within the behavioral model of the turbines, the efficiency curve easily and accurately converts a steam input to power output from the turbines.

Because of the complexity of the MST, the most accurate way to find power output given steam input is to use MST performance curve data generated by the manufacturer. [3] A satisfactory number of data points from this curve were extracted by adapting a software program provided by the manufacturer. To predict the most efficient steam sharing scheme, the students created an iterative program that compared every possible sharing configuration, interpolated, and limited for the step size of the data points, for steam inputs from zero pounds per hour to the maximum capability of three turbines. The results of this were then plotted to create the efficiency curve shown in Figure 5. The results were verified by an unpublished LaGrange optimization analysis performed by a student, a mathematics minor, from another senior capstone design team.

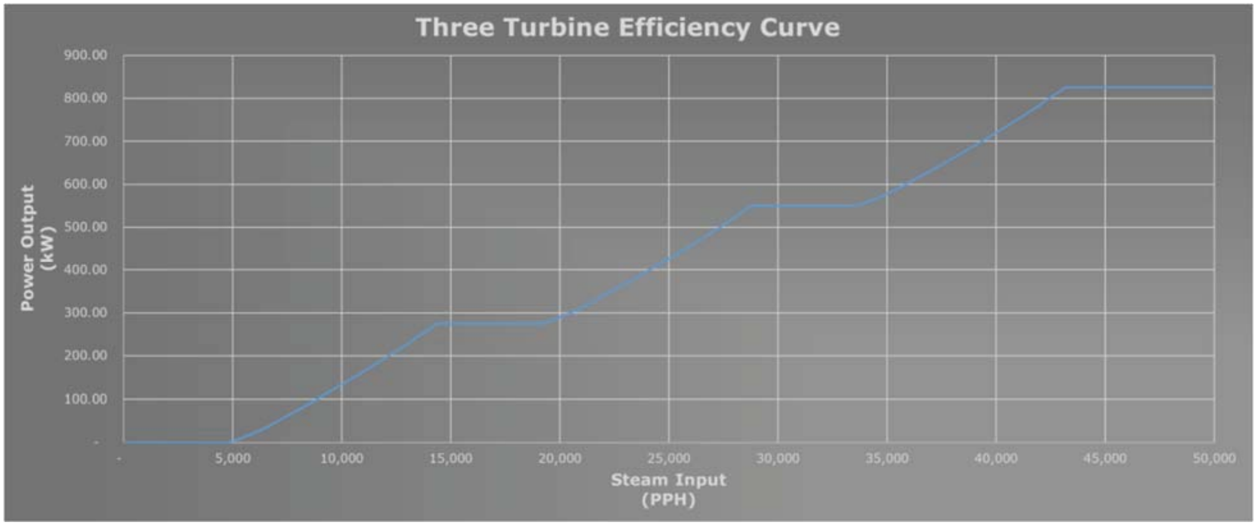

Figure 5. Efficiency Curve for Committing Turbines in Sequence

A sequential input sharing scheme proved to be the most efficient solution because of the rapidly increasing efficiency of each turbine as steam input is increased. This means that one MST will be fully loaded before the next receives any steam. Gaps or flat regions on the curve are the result of a minimum level of steam flow necessary before a given turbine can begin generation.

The overall system was modeled in MATLAB / Simulink to support and verify the efficiency curve and to substantiate the claims of improved power quality presented in the paper. The Simulink diagram of this model is show in Figure 6.

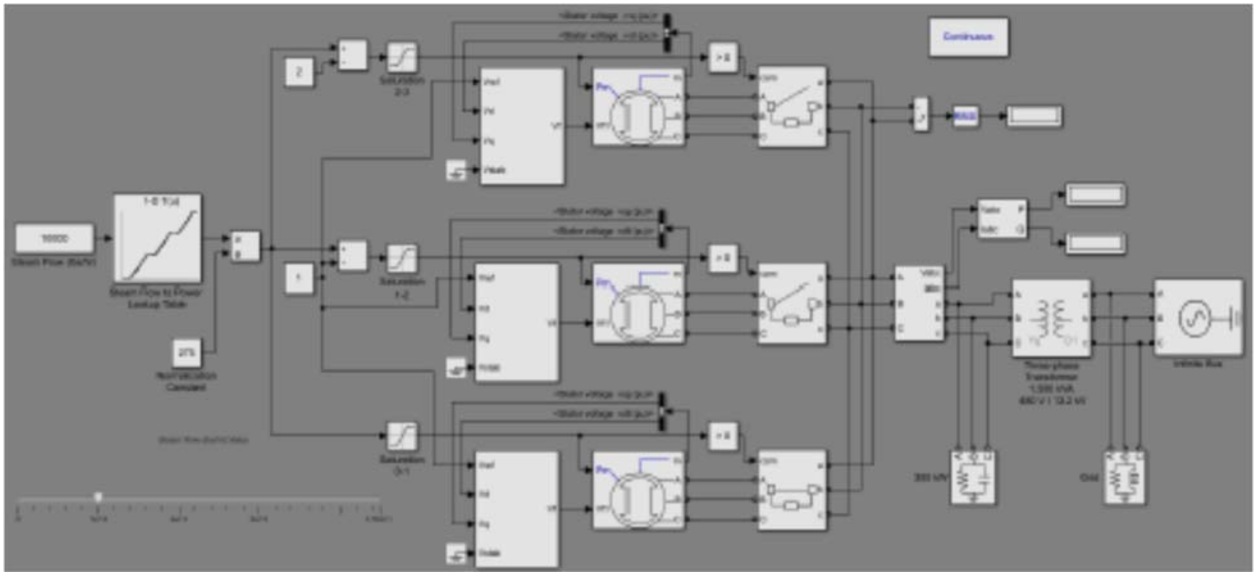

Figure 6. Simulink Diagram of Three-Turbine Cogeneration System

Acknowledgements

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