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Dr. Hedengren,

My project focuses on a creation of a model predictive controller for thermal energy storage systems coupled to nuclear reactors. The scope includes a creation of a RELAP5-3D simulation of a small lab-scale thermal energy storage unit. That RELAP5-3D model was then used to create a reduced order model that will be used in MPC. This work will become significant as thermal energy storage technology moves forward as we will need reliable control systems to control the charging and discharging of the thermal storage units. RELAP5-3D is reliable at modeling the data needed however, being restricted access and difficult to learn, it is not ideal for preforming MPC, thus, the creation of a reduced order model will allow the generation of an MPC system much more simple and easier to manipulate.

I reached out to all the members of the team and heard back from most of them but could not get them to participate past that so the project is of my own doing. Much of my time went into the creation of the RELAP5-3D model so I did not put as much time into the MPC as I would have liked. My future plans are to continue this project to create an MPC system that will actually control our lab-scale thermal storage system when we start running the experiments.

Respectfully,

Jaron Wallace

Project Highlights

- Utilizing GEKKO to create a reduced order model of RELAP5-3D output data
- Creating an MPC that will control input for a small-scale thermal energy storge unit
- Comparison of a first-order, second-order, and ARX representations of TES data
- Development of technology that can eventually be used to control grid scale TES units

Utilizing GEKKO and RELAP5-3D to Generate a Model Predictive Controller for Thermal Energy Storage Units

Dynamic Optimization

Project Report

Jaron Wallace

April 19, 2021

Abstract

With the increase in renewable energy penetration into the grid, nuclear energy must be paired with an energy storage solution to remain viable. Thermal energy storage (TES) allows a nuclear power plant to operate constantly at full capacity while delivering the fluctuation the grid demands. Using RELAP5-3D a small-scale simulation was completed for a TES system. These simulation results were used to create a model of the system and that model was then used to create a Model Predictive Controller (MPC) to control the charging and discharging of the unit. This technique was proven throughout these experiments and can be used to develop MPC systems for nuclear power plants with integrated thermal energy storage. The MPC would take grid demand and control the TES to allow for optimum charge and discharge of the TES unit.

Introduction

Today, renewable energy sources such as wind and solar power are widely used throughout the world and are continuing to increase in usage [1]. Denholm et al. explain that with the deployment of more wind and solar power plants, the electricity supply in the middle of the day will eventually overcome the demand causing overproduction [2]. They explain that this is due to renewables handling upwards of 65% of the electricity load while other energy sources are still generating the baseload power. Denholm et al. also state that overgeneration can cause generators and motors to be damaged because of an overage of electricity. This potential for overgeneration can be seen in the California Independent System Operator (CAISO) “Duck Curve”. Figure 1 shows a plot of the electricity demand needed from sources other than wind and solar power in California versus time of day. It illustrates that solar generation during the day lowers the demand from other electricity sources. It shows that as the years progress, the demand for non-renewable electricity generation is continuing to decrease. This decrease is explained by the growing amount of electricity that is being provided by renewable energy sources, namely solar and wind. In the last eight years, the demand for non-renewable electricity generation at 1:00 PM has dropped from around 19,000 MW to about 12,000 MW. On the other hand, the non-renewable electricity demand has been increasing from 25,000 MW to 26,500 MW around 8:00 PM. In 2020, the total addition of renewable energy resources caused a ramp rate of 13,000MW in just 3 hours by the non-renewables.

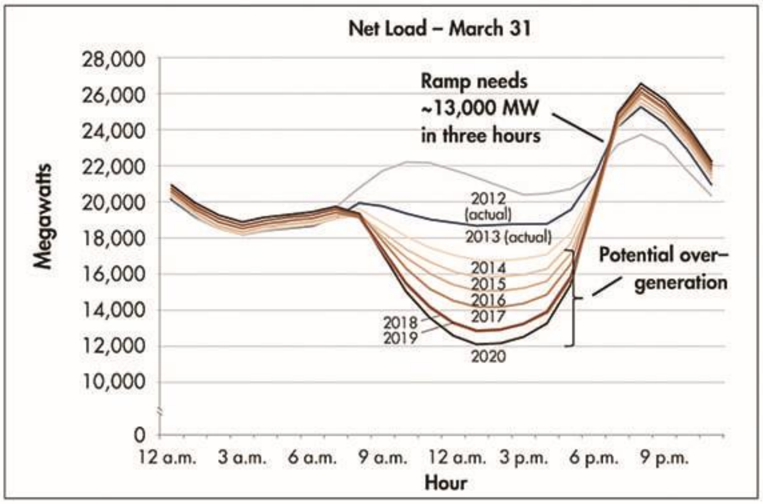

Figure 1. The California Duck Curve [3]

To solve the potential over-generation and the inability to facilitate these large ramp rates, one proposed example is to use nuclear power combined with molten-salt thermal energy storage (TES) [4, 5]. As the technology progresses, these thermal storage systems will eventually be integrated into the grid and will require some control system to operate them efficiently.

One method to control these systems is to utilize Model Predictive Control (MPC) in which a model of the system can be used to predict through timesteps in the future and to control the inputs and outputs to the thermal energy storage unit to match demand. The details of this process will be discussed further in later sections. To properly make use of MPC, a detailed an accurate model of the system must be created.

RELAP5-3D is a thermohydraulic simulation software developed by Idaho National Laboratories (INL) for modeling reactor systems and monitoring the temperature and pressure transients under different specified conditions. The main goal of the software is to analyze accident cases and transients of nuclear power plants; however, it has shown to be useful to perform design analysis as well [6]. RELAP5-3D is one of the most accurate nuclear modeling codes and its brother RELAP5 mod3 is the only code that the Nuclear Regulatory Commission (NRC) allows a nuclear power plant to be licensed with. While RELAP5-3D is incredibly accurate, it is a difficult code to learn and is restricted access. A solution around this would be to utilize RELAP5-3D to generate data for a specific setup and then use that data to create some reduced order model to describe the system that can then be used for MPC.

Theory

Before a large scale plant system can be modeled, a smaller scale model should be created that can be validated with lab-scale experiments. The purpose of this research is to create a small scale MPC system that will control a small shell and tube heat exchanger that will act as a a thermal energy storage unit. Figure 2 shows a setup of the shell and tube heat exchanger complete with heating rods and a cooling loop.

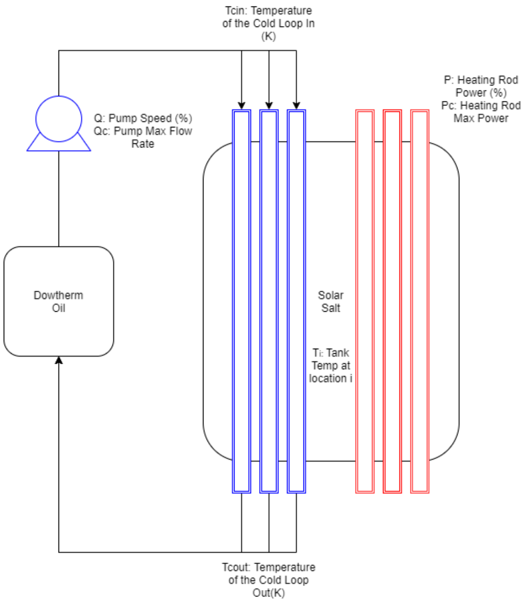

Figure 2. Lab-scale unit with variables labeled

The variables that can be controlled are the pump speed, expressed as a percentage of total pump capacity, and the heating rods, also expressed as a percentage of total heating power. The actual experimental setup is still undergoing safety alterations and actual data will not be able to be obtained for the MPC. Due to this inconvenience, RELAP5-3D was used to generate the data needed to create the model.

For the purposes of this experiment, pressurized water was used to simulate the heating rods to mimic how the system might work when hooked up to a Pressurized Water Reactor (PWR). The input deck allows for control of temperature and flow rate of the fluid. The temperature range that was used in this experiment was 5448K-588K. This range was chosen as the this is the operating temperature range of a PWR with 588K being the temperature coming out of the reactor and 548K being the temperature entering the reactor. The cooling pump was modeled as a pump with maximum capacity of 320 GPH. Both the heating rod power and cooling pump power were scaled between 0 and 1, 1 being max heating rod temperature and max cooling pump power. This scaling allows for a more accurate model to be generated. The

RELAP5-3D input deck was run for 86400 seconds and consisted of changes to the heater power and cooling pump speed. Through the use of RELAP5-3D user defined functions, the temperature difference inside the tank was calculated and a total energy stored calculation could be completed using Equation 1.

- $$Energy\ Stored = Cp * \rho * \Delta T_{avg} \tag{1}$$

Once the energy stored has been calculated, RELAP5-3D uses another user defined function to calculate a percent charged based on a maximum capacity of the unit of 2.238 kWh. This charged percent is expressed as a percentage between 0.0 and 1.0, 1.0 being fully charged.

Simulation Results

The RELAP5-3D input deck was run without any errors and produced realistic results. The heating rods were modeled using pressurized water and the thermal storage tank was modeled as being full of solar salt with a composition of 60% $NaNO_3$ 40% KNO_3. The fluid file for molten salt was custom created utilizing provided data for this particular molten salt [7]. Figure 3 shows the results from the 86400 second RELAP5-3D simulation.

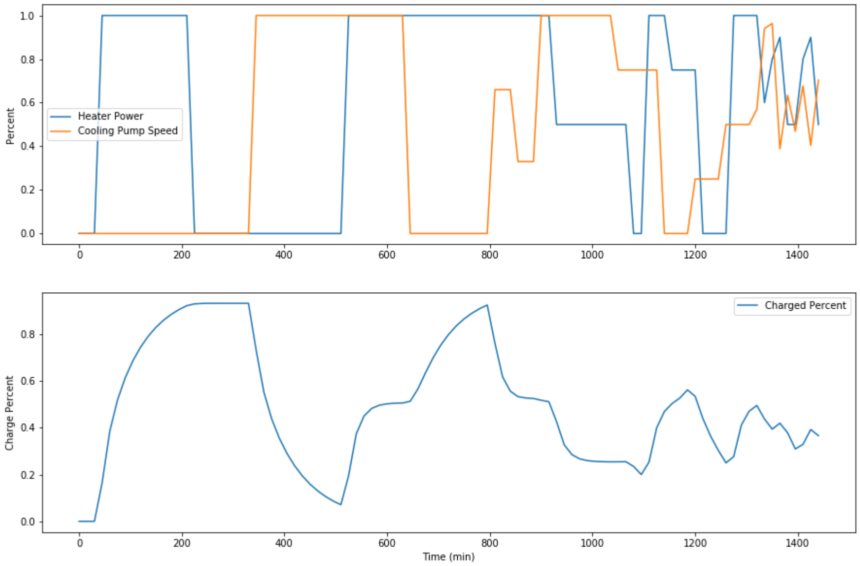

Figure 3. Initial RELAP5-3D simulation

The upper plot shows the manipulated variables of heater power and cooling pump speed. The run starts off with simple, spaced changes, while the later end of the experiment has more complex, quick changes to test the response of the system. Looking at the first 400 seconds it is found that the results match with what would be expected. For the first 30 minutes, both the heating rods and cooling pump are off which translates to no change in the charge of the thermal storage tank. At 30 minutes, the heating rods are switched to full power and the charged percentage starts to increase. As higher charged percentage values are reached the rate of charge slows down as the temperature difference between the heating rods and the tank becomes smaller and smaller. At 225 minutes the heating rods are shut off and the charged percent remains level. This is due to RELAP5-3D assuming that the tank is completely insulated. This should be adjusted in the future to give more accurate storage data. At 345 minutes the cooling pump is turned to full power and the charge percent begins to decrease, this simulates discharge of the thermal storage unit and behaves as expected.

The next step is to take the results from the RELAP simulation and create a reduced order model that can accurately represent the system. Three deferent regression methods were used to create an arcuate model of the system, first order, second order, and ARX. Each of these models will be discussed in the following section. In order to fit these models, a more simplistic RELAP5-3D simulation was used and then progressed to the more complex simulation. The simulation to be used for initial estimation is shown in Figure 4.

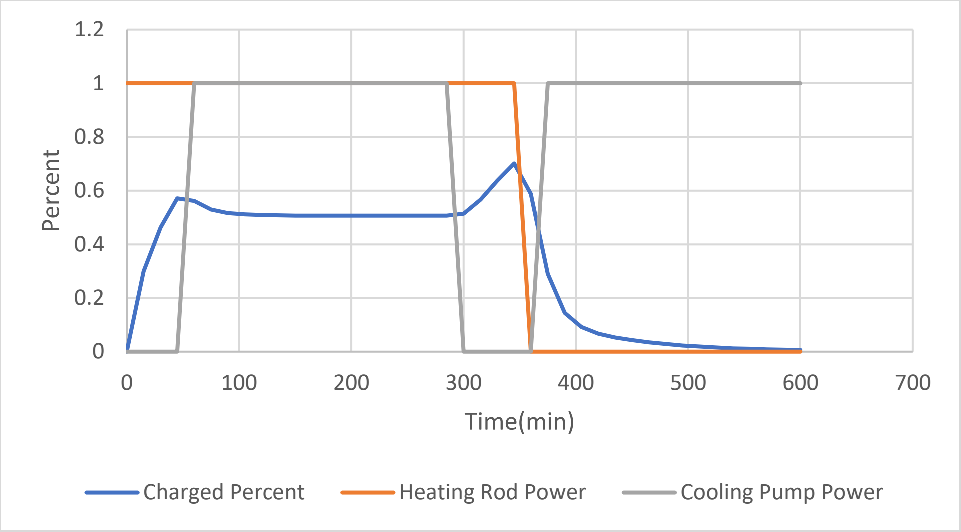

Figure 4. Simplistic RELAP5-3D simulation

Estimation and Dynamic Optimization Results

The first attempted estimation was done with a first order model. The following equation defines the first order system that was used.

$$\tau_p * \frac{dy(t)}{dt} + y(t) = K1 * u1 + K2 * u2 \tag{2}$$

where τ_p is the time constant, y is the charged percent, u1 is the heating rod power, u2 is cooling pump power, and K1 and K2 are gain parameters. GEKKO was to optimize these parameters and obtained the following result:

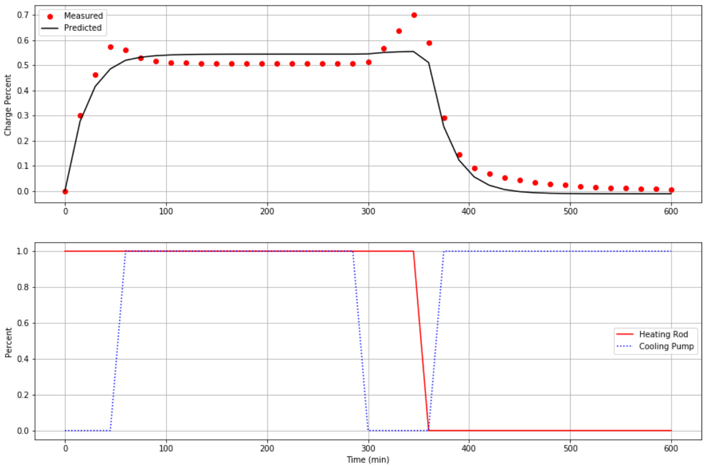

Figure 5. First Order Model

As seen from this plot, the model attempts to accurately represent the test data; however, the spikes at 50 min and 350 min are not accurately represented. The parameter guess values, collocation nodes, and bounds were manually adjusted, and the above plot was the best model representation. From here a second order model was created using the following equation:

$$\tau_s^2 * \frac{d^2y}{dt^2} + 2\zeta\tau_s\frac{dy}{dt} + y(t) = K_1u_1 + K_2u_2 \qquad (3)$$

where the parameters are the same and ζ is the damping factor. After much adjustment, the following model was obtained:

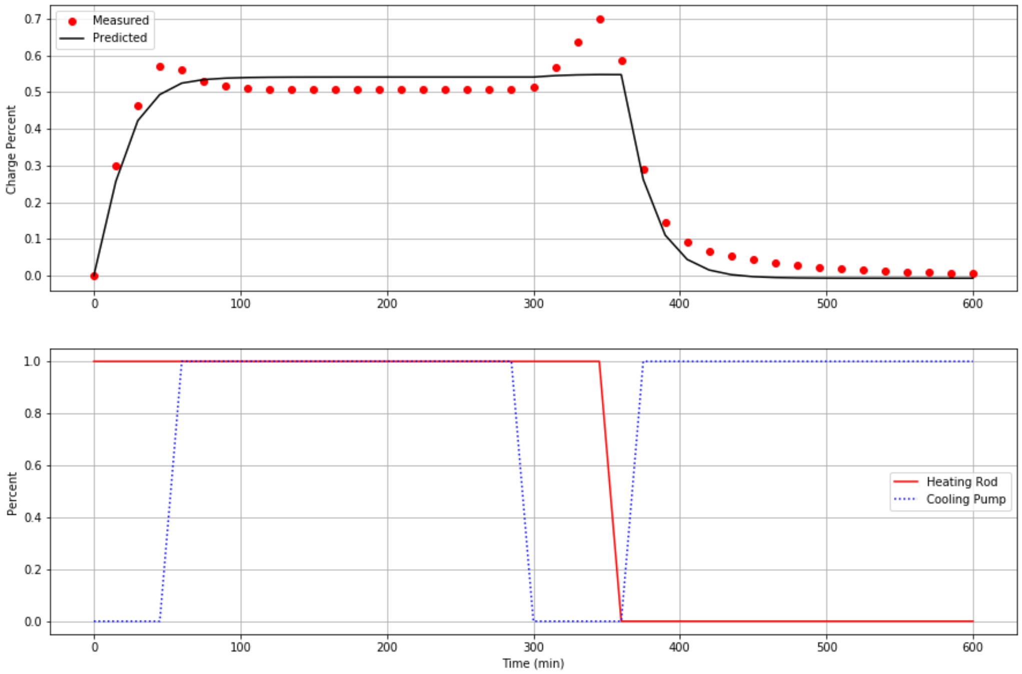

Figure 6. Second Order Model

This model does not show a much better fit than the first order model so another method was employed in an attempt to create a better model fit, ARX. An ARX model that uses 1 previous time point was used to create the following model:

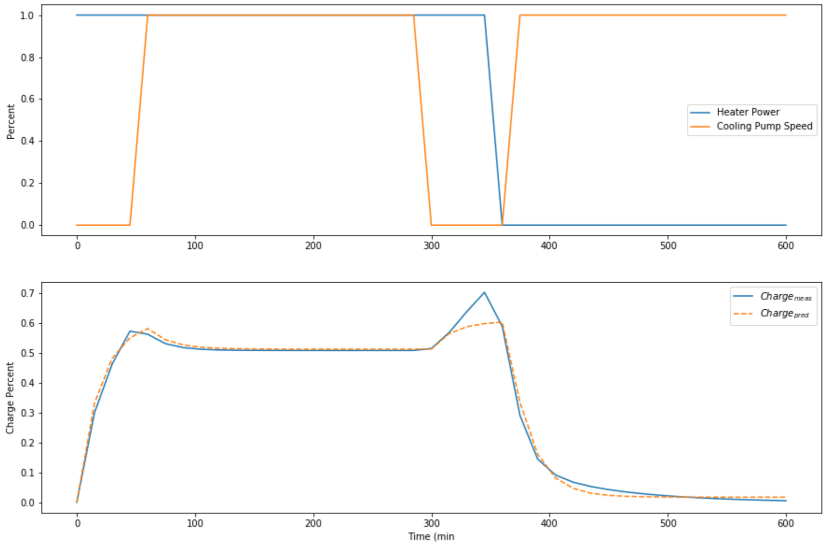

Figure 7. ARX Model with 1 input coefficient

This model is a much better fit compared to the second order model; however, it is still not accurate on the spike near 350 seconds. In order to address this issue, the number of input coefficients was adjusted until there was a perfect match between the model and simulation results. This occurred with 8 input coefficients and the plot of this ARX model is shown in Figure 8.

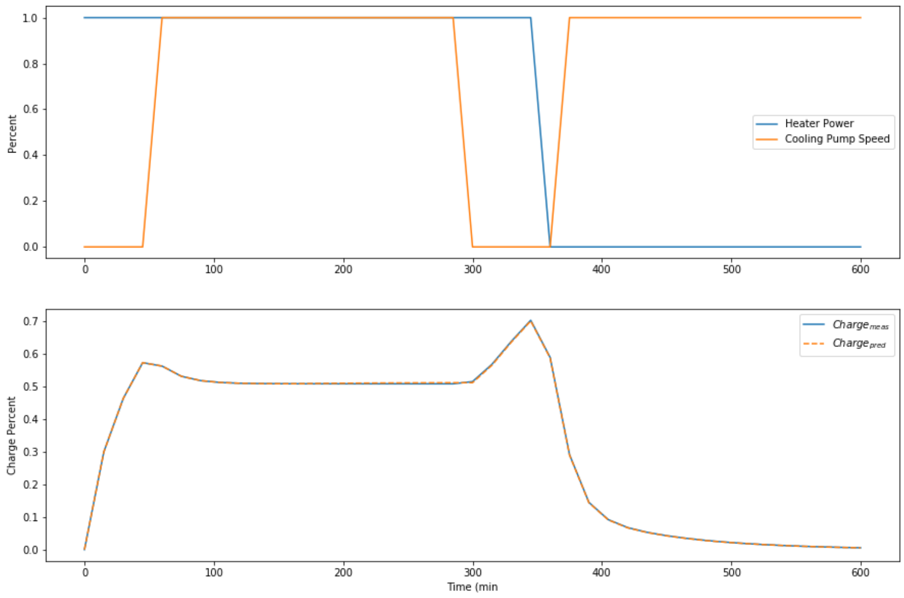

Figure 8. ARM Model with 8 input coefficients

It was determined that an ARX model was the best choice for creating a reduced order model of the RELAP5-3D results and this technique was used to create an ARX model from the complex RELAP5-3D run. The best model fit occurred at 32 input coefficients and is shown in Figure 9.

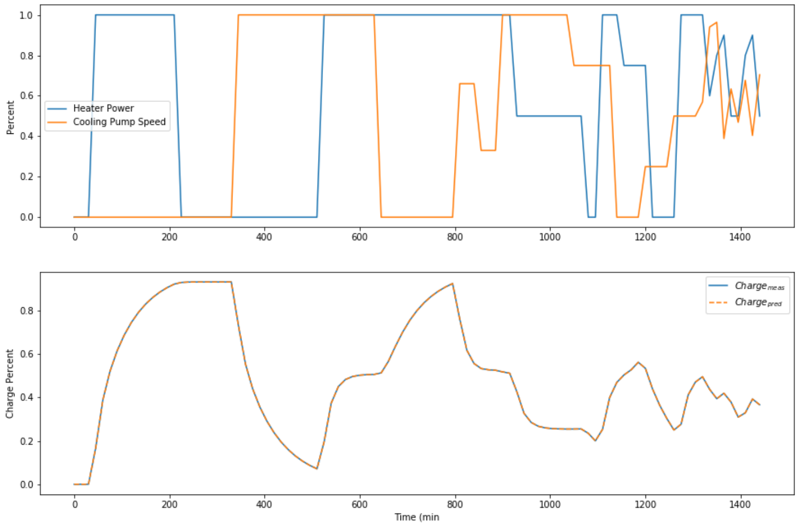

Figure 9. Complex ARX model with 32 input coefficients

Once the ARX model was defined it was used to create an MPC system with the ARX model as a steady state model and the first order equation to mimic the measured results. In the future, the experimental results would be used as the measured values but as the experimental setup is not complete, the first order model will be used. The following plot was obtained from running the MPC.

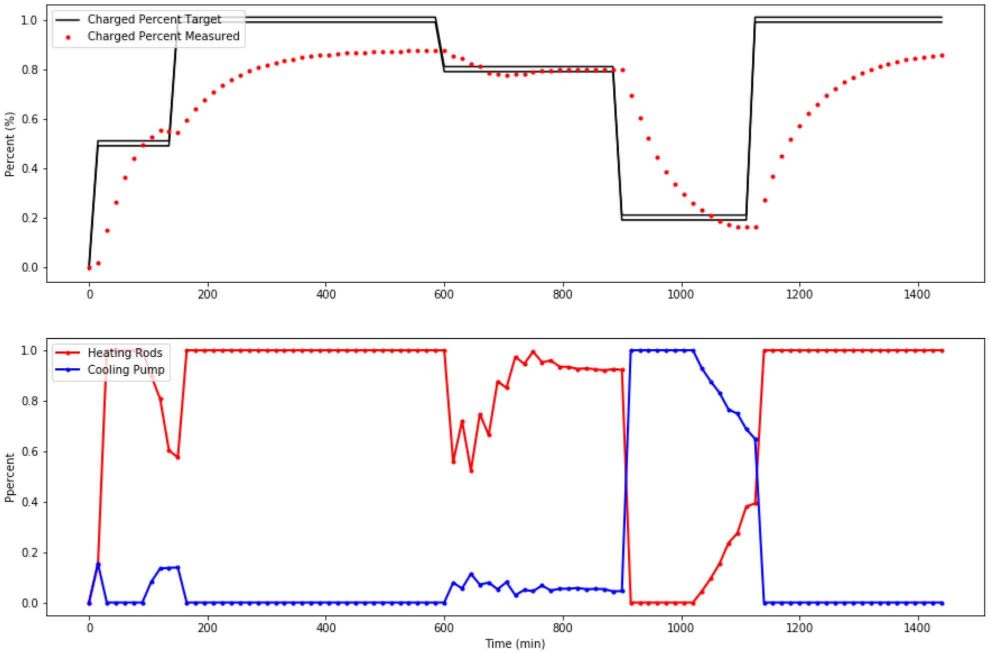

Figure 10. MPC Results

From the top graph the set points are shown in between the black lines, the black lines showing a dead band of ±0.01. The red dots show the actual values as calculated by the first order equation. The bottom plot shows the response of the heating rod power and cooling pump power in order to drive the charged percent to the target values. As shown above, the controller is able to drive the charged percent to the desired values except for when the target charged value is 1.0. This is due to the fact that as a higher charge is obtained the temperature difference between the heating rods and the tank becomes smaller and smaller which results in a lower charge derivative. The other set points are all reached but do have a small amount of overshoot. If the setpoint is extended, such as the setpoint at 600 min, the controller will overshoot but then stabilize inside the dead band.

Discussion

The first main issue that was discovered was that no model fit very well. It was not much surprise that the first-order model did not fit as it is not expected that a complex system such as this would behave in a linear fashion. When the second-order model was created it acted just as the first-order model did. This was an interesting result and even with manual changing of the parameters a better solution could not be found. This eventually led to the creation of the ARX model. The ARX model with 1 input coefficient was much more accurate than the previous 2 models but still not completely accurate. It was found that by adjusting the number of input parameters, the fit would get better. Finally landing on 32 input coefficients the plan was to use that model for the MPC. Unfortunately, even with tuning, GEKKO could not find a solution to the MPC with 32 input coefficients. In order to have GEKKO find a solution, 2 input coefficients has to be used.

The use of 2 input coefficients leads to inaccuracies in the model, the use of the first-order model to obtain the measured values also leads to inaccuracies. However, this experiment allowed for a proof of concept to show the ability of GEKKO to handle MPC of a model created by RELAP5-3D data for control of a thermal energy storage system.

Future work with this technology would include further development of the MPC to allow the system to take in grid-scale electricity demand as well as what the output ability of the nuclear reactor is. Using a well-defined model, the MPC could then change the amount of energy that is redirected to the TES unit for charging. It would also be able to predict how to turn valves and direct flow to discharge the TES unit when higher demand is experienced.

Conclusions

The purpose of the work was to utilize RELAP5-3D to create a simulation of a lab-scale thermal energy storage unit and use those simulation results to create an MPC capable of controlling the system. The work was successful and an ARX model of the RELAP5-3D simulation was regressed and matches the simulation results quite well. This ARX model was then used to generate an MPC system which fairly accurately controlled the charging and discharging of the system to meet a target charge value.

While issues were uncovered throughout the process, these issues will be focused on in future work to make the system more reliable. These issues include the MPC being unable to accept the more accurate ARX model and only being able to find a solution to the simplistic ARX model that is less accurate. Another issue that will addressed is the overshoot during the MPC. While this is not a large issue it should be addressed it this is to be used on a grid-scale. As part of future work a machine learning model will be explored for its accuracy and determining its competitiveness against the ARX model when paired with MPC.

Once an accurate small-scale method is finalized a full grid-scale model will be created allowing to take in current demand as an input and be able to control the TES system automatically. This will allow for the most efficient usage of a TES combined with a nuclear power plant and will eventually lead to a balancing of the grid with the increase of renewable penetration.

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