Design of a Solar Thermal Collector Simulator

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Abstract

The rising cost of non-renewable energy resources has placed a large emphasis on alternative sources of energy to replace or augment society's increasingly large demand. For residential energy use, the average water heating load consumes approximately 14% to 25% of the total energy demand. Usually this energy is supplied by electricity or natural gas. This significant portion of a single household's energy draw, coupled with rising energy costs, provides a strong motivation for the implementation of residential solar thermal systems. The purpose of this project is to design and fabricate a simulator for a small solar thermal collector array that can be used to research improvements to solar thermal collector systems. A modified on-demand water heater in conjunction with LabVIEW control software comprises the simulator system. The heater component interfaces with a LabVIEW control panel that accepts collector geometry and specifications and then calculates the appropriate heater power to simulate array output for a given set of meteorological weather data. The heater delivers the specified amount of power to the working fluid, which is varied by power electronics using phase angle control. LabVIEW control software requests feedback from inlet and outlet thermistors in order to accurately calculate the available power to the collector and the useful energy gain. For a given set of meteorological data, the system provides the ability to repeatedly simulate the same output power conditions within 9% of theoretical calculations. The simulator will serve as a foundation to study future modifications to residential solar thermal collection systems.

Introduction

The need for research in the area of renewable energy has grown greatly in recent years due to an increase in the price of easily accessible energy sources. Renewable energy can significantly offset the amount of energy provided by consumable resources, such as fossil fuels. The Solar Thermal Collector Simulator (STCS) was created to aid in the development and progress of research in the field of solar fluid heating. The main purpose of the project is to create a computer controlled water heater that can simulate the functionality of a small solar thermal collector array in a hypothetical installation. The STCS makes it possible to test balance-of-system components (e.g. tanks, sensors, controllers, etc.) more accurately because the power output from the simulator can be repeated reliably. Repeatability removes any variability involved with using an actual solar thermal collector, due to the fact that actual weather conditions cannot be replicated from day to day.

System Apparatus

The STCS is an on-demand water heater that has been modified to allow the user to control the amount of power added to the fluid as it is pumped through the heater. An external computer with a LabVIEW software interface is used to control the power output and check the status of the simulator. Communications with the STCS are accomplished using American Standard Code for Information Interchange (ASCII) encoded strings carried by standard Ethernet Universal Datagram Protocol (UPD) packets over 10BASE-T wiring. Figure 1 shows how the different hardware systems of the STCS connect.

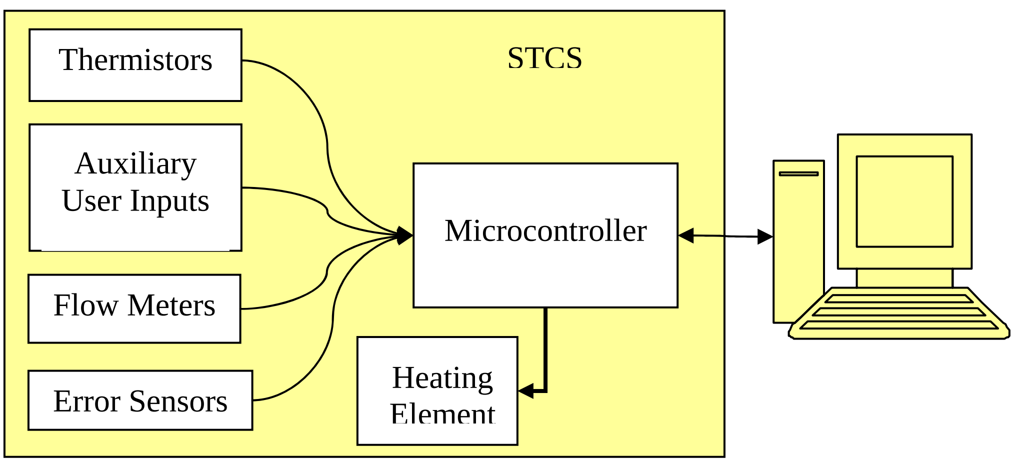

Figure 1. System Connection Overview

The STCS can report the temperatures and flow rate being measured inside the simulator as well as error codes such as a leak or an over temperature condition. Parameters of a hypothetical solar collector, including area, quantity, and efficiency are inputs to the LabVIEW controls in conjunction with simulator feedback so the performance of a specific collector can be simulated. Information about the weather conditions is provided by an external, user-supplied weather data file, using the Typical Meteorological Year 2 (TMY2) format. TMY2 files provide a specific measurement of solar insolation for each hour of each day, on a flat horizontal surface. Using the measured temperatures from the simulator, the parameters of the solar panels being modeled, and the weather data, the theoretical output power from the collector array is calculated and transmitted to the STCS. Figure 2 shows the hardware that makes up the STCS.

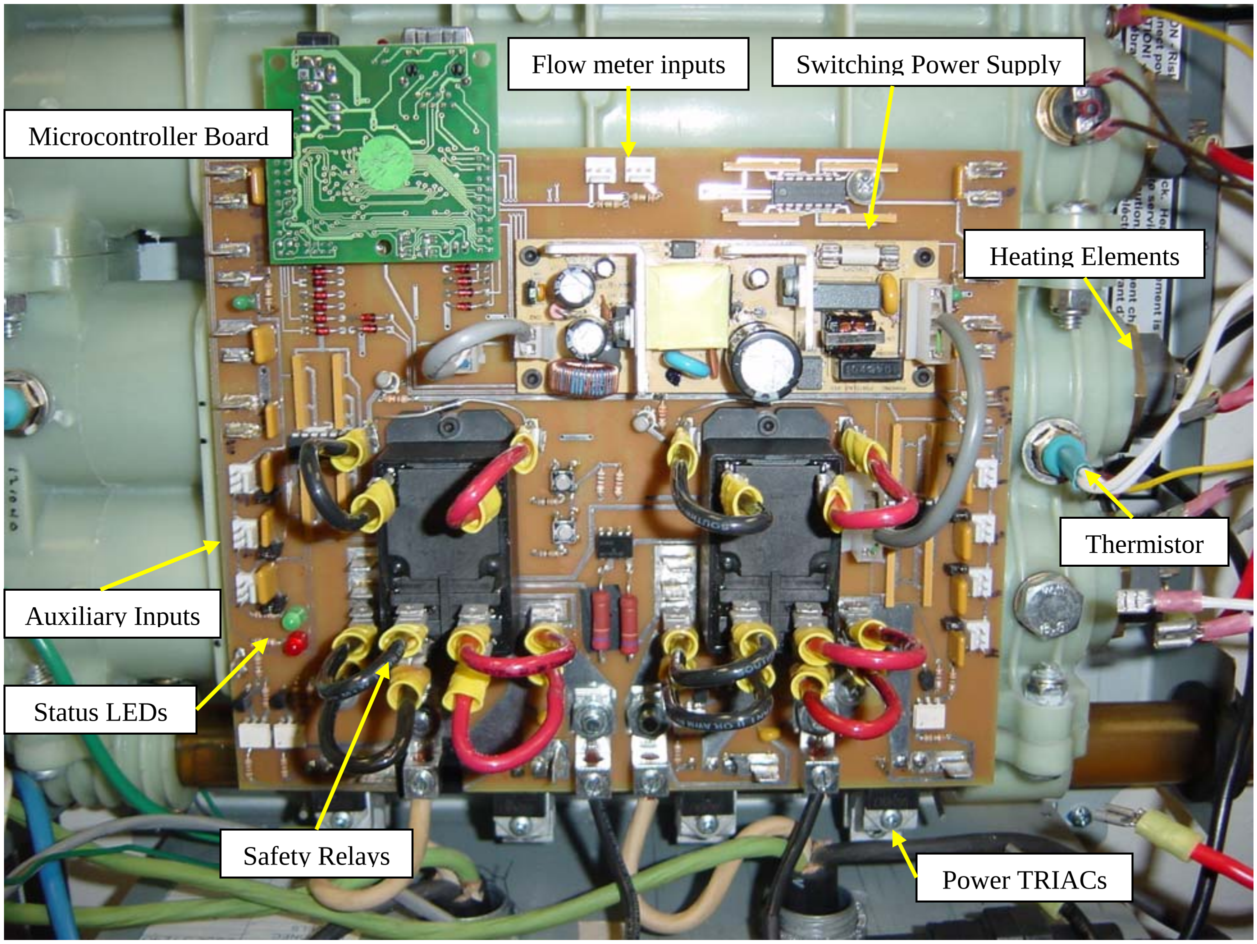

Figure 2. STCS controller board with main hardware components labeled.

Test Procedure

When simulating the output of a small array of flat plate solar thermal collectors, the two functions of the STCS are to provide power that is accurate and repeatable. For both the accuracy and the repeatability of the system to be verified there had to be a precise and reliable source of data for comparison. The Transient Energy System Simulation Tool (TRNSYS) was used to provide the data for comparing the performance of the STCS to theoretical results. For each test, a user enters the collector parameters, test period in hours, location of the TMY2 weather file, and properties of the working fluid into the LabView interface. Available irradiance is updated once an hour, while the collector output power is recalculated once every thirty seconds using the feedback temperatures from the STCS.

The output power of the STCS is modulated by power electronics that use random phase angle controlled triodes for alternating current (TRIACs). A TRIAC is a device that allows alternating current to pass through when its gate pin has a high signal. The power is controlled by changing the point in the wave cycle when power is allowed to flow through the TRIAC. Figure 3 shows a half-wave of the mains input voltage. The TRIAC phase angle is the delay from the point when previous voltage crosses zero. By setting this delay value, the percentage of the total power that is allowed to pass through the TRIAC is controllable. This delay value is calculated by the LabVIEW controls after the required output power has been calculated.

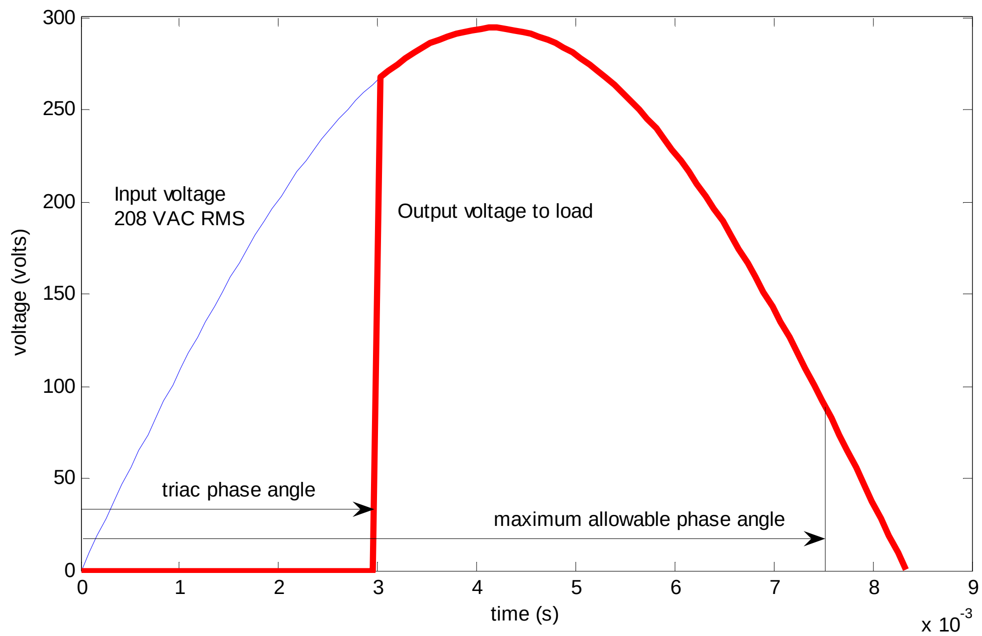

Figure 3. TRIAC phase angle delay.

For initial testing, the STCS was operated in an open loop system configuration, with the cold water inlet coming from city mains, and the hot water outlet emptying to a drain. Future configurations will involve a circulation pump and storage tanks. To test the accuracy of the output, the output power uncertainty was calculated, accounting for each variable in the system, including: thermistors, flow meter, and analog-to-digital converter (ADC) sampling. The output from the accuracy test had to fall within the uncertainty bounds calculated in order to be considered accurate. To show the system was repeatable, five trials were recorded with the same input parameters over the same two hour period of a theoretical day. The output power profile from each trial was compared to the other four trials to confirm the STCS's repeatability. An Alternative Energy Technologies AE-40 flat plat solar thermal collector was modeled in Waco, Texas on June 2 using TMY2 data. This date was chosen, because it is a sunny day and would provide clear results.

Test Results

After calibration of each measurement device, several tests were conducted to prove the repeatability and accuracy of the hardware and software. The first test was five trials of a two hour period during the sunniest part of the day, which happened between the hours of 1:00pm and 2:00pm. Figure 4, shows the output from one trial of the repeatability test, with results falling within uncertainty bounds and very close to theoretical calculations. Four additional tests were recorded with the same parameters to determine repeatability.

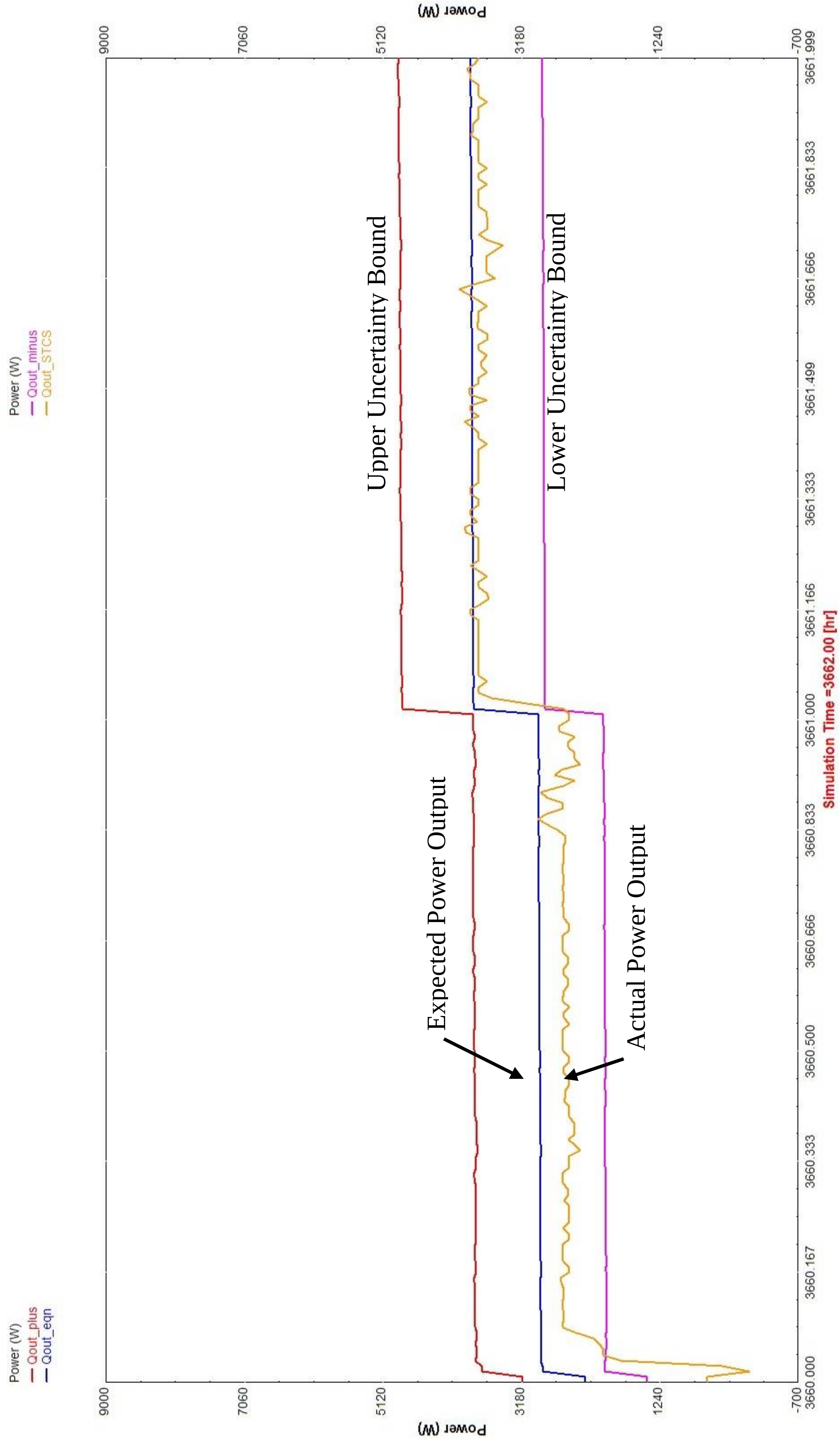

Figure 4. Output from a trial of the repeatability tests.

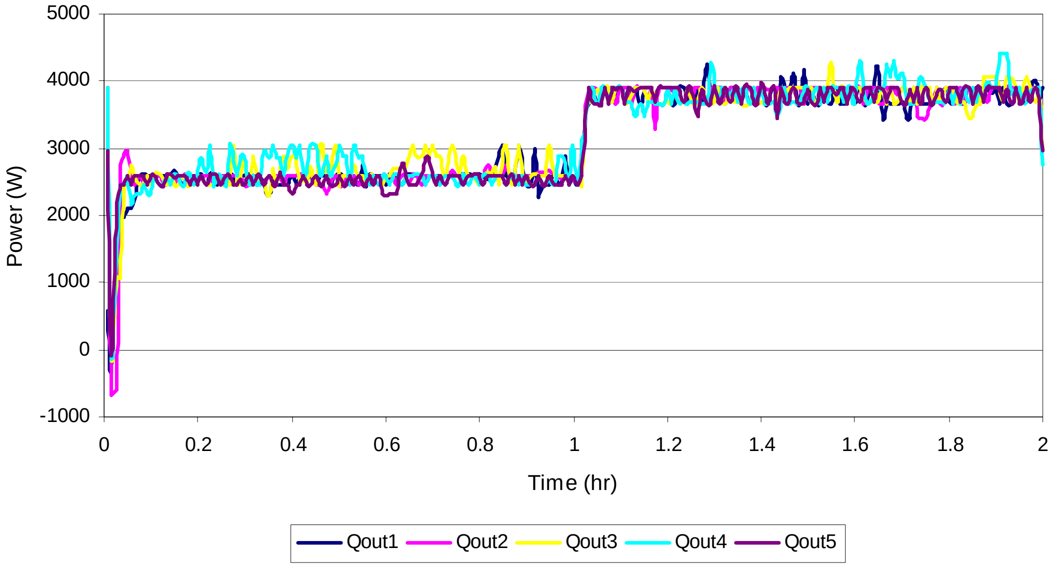

Figure 5. Output from the five repeatability test trials overlaid.

The power output from the five tests are overlapped in Figure 5 and show all five tests resulting in very similar power output profiles. The dip that is seen near the beginning of the trials is due to the filtering that is used on the flow rate input. The system needs to have five input values before the output power calculations will be accurate. To quantify repeatability, (1) was used to show how close a given trial was to the other four. The norms shown are standard square-integral norms. The average of these differences was then taken to find the overall difference of the STCS output. The output from the five trials was found to vary on average by only 8.5%.

$$\frac{\left\| Q_{out_i} - Q_{out_j} \right\|}{\left\| Q_{out_{\min(i,j)}} \right\|} \qquad (1)$$

In all of the experimental data, there were slight fluctuations in the output power, which were attributable to small changes in flow rate and variations in the inlet temperature. The mains temperature at the Rogers Engineering Building at Baylor University ranged from 24ºC to 31ºC, making accurate measurements of the temperature essential to the calculation of the output power.

A thirteen hour test was conducted to simulate long term accuracy of the STCS. The time from sunrise to sunset on June 2 was chosen as the model period in order to stay consistent with previous tests. The results, shown in Figure 6, were satisfactory given the calculated uncertainty bounds and modeled the theoretical data very well.

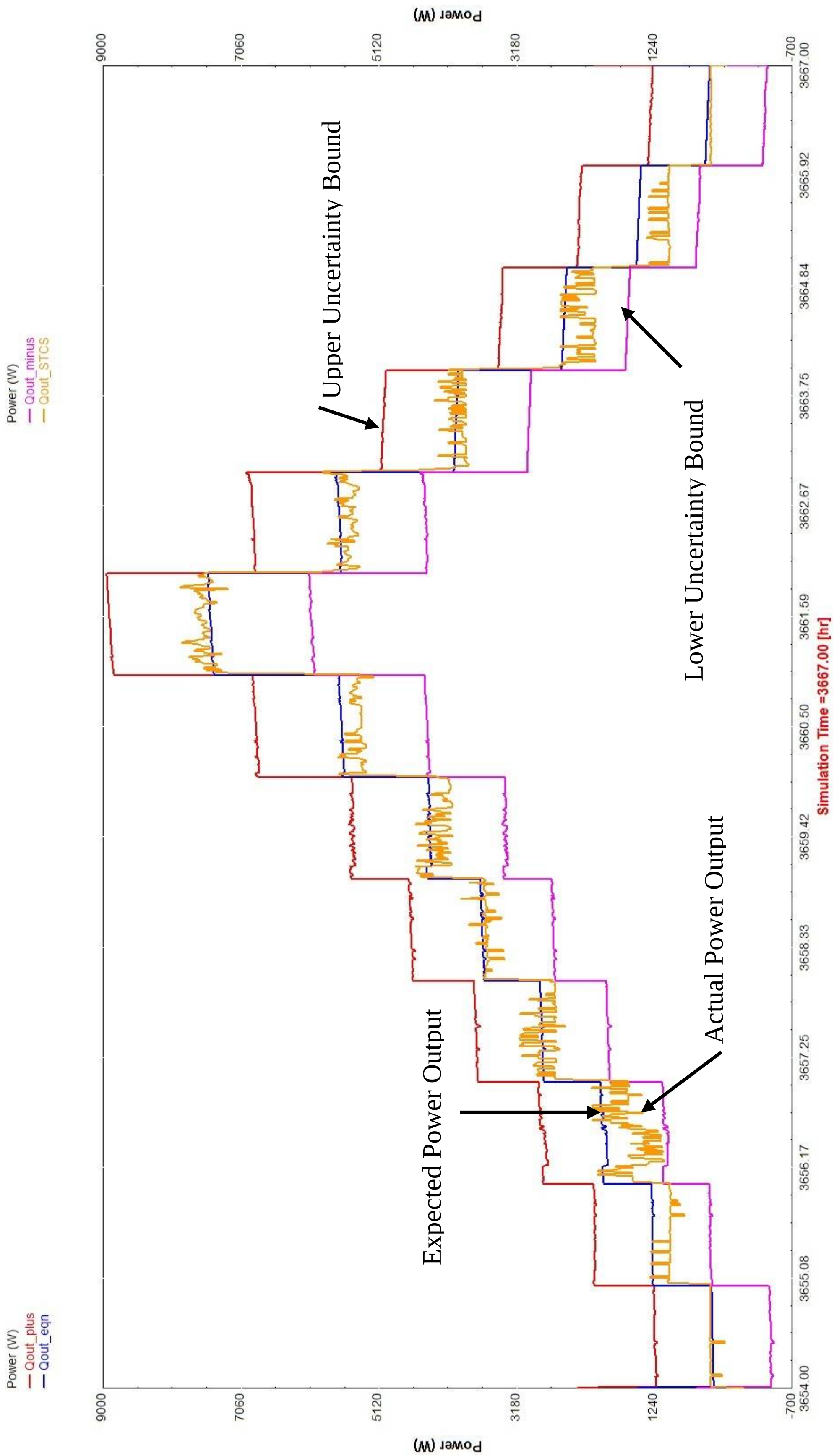

Figure 5. Output from the accuracy test.

The third hour shows a drop in power due to an unexpected rise in the inlet temperature, thus decreasing the temperature difference between inlet and outlet. A metric, given by (2), was used to quantify the accuracy of the results. The output from the STCS was found to vary from the expect output by 7.8%.

$$\frac{\|Q_u - Q_{out}\|}{\|Q_u\|} \qquad (2)$$

Conclusions

The results of the testing of the STCS were very encouraging and satisfactory for the desired output. The results of the tests show that a typical day can be modeled accurately within 7.8% and repeated within 8.5%, making it possible to test the balance of a solar thermal collector system over many days or months without the variability of actual weather conditions. The current configuration utilizes five thermistors for system monitoring, two or which are used for data collection, and has seven available auxiliary inputs. These available inputs allow for additional model features to be added in the future. Implementation of a storage tank with a wrap around heat exchanger, circulation pump, and additional storage tanks are planned for future experiments.

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