International Journal of Engineering Research and Development
e-ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 10, Issue 8 (August 2014), PP.58-67

Design and Automation of a Zero Energy Model House (ZEH)*

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Abstract:- Because of the rising energy prices, green-house effects, and environmental concerns, there has been a lot of emphasis on using alternative, renewable energy sources. This paper is concerned with the use of solar energy to meet the energy needs of a scaled model house. Photovoltaic (PV) panels are used to collect solar energy and convert it to electrical energy. In this experimental study, the design of a photovoltaic system is presented for a small model house along with its associated instrumentation, real time data acquisition and automation using NI® LabVIEW. The study clearly shows that energy requirements can be met using renewable energy sources and that the goal of a zero energy house is attainable.

Keywords:- Renewable Energy Systems, Photovoltaic Systems, Instrumentation, Process Control, PID Control, Tuning

I. INTRODUCTION

Solar energy offers consumers the ability to generate electricity in a clean, quiet, and reliable manner. In the United States, solar usage is growing at the industrial level but residential usage is still staggering behind other countries in Europe and Asia. This can be attributed to the cost of producing solar energy. The initial cost for a solar energy system is usually what discourages consumers from choosing it. Because of it, the residential usage in the United States is only account for 1 percent of the world's use [1]. Countries in Europe have set incentives for residents who adopt the use of solar panels and have a fixed price for utility companies to buy back the excess electricity. The United States are gradually introducing such incentives. So in the future, the use of solar energy would be more attainable for the average american household.

A PV system [2] includes panels and hardware that are comprised of photovoltaic cells that convert solar energy directly into electrical energy. A well designed PV system allows the consumers to create and store their own reusable energy without going through big energy companies; in some cases even allow homeowners to resell this energy back to the electric provider company. Since the growth and demand for solar systems is increasing, it is believed that works like the current one will encourage readers to consider owning a PV system.

The objective of this work is to design a photovoltaic system to meet the energy requirements of a small model house. It is also within the objectives to design and implement an automation system for the distribution and use of the collected energy. The collected energy is used to primarily meet the heating and cooling requirements of the model house. A team of senior students [3] identified, designed and implemented the first version of the model house as part of their senior capstone project. The team collectively built the small model home that operates on solar energy. Since then, a number of modifications have been made which are discussed in this work. In short, the solar energy collected by the PV panels goes through a charge controller to charge the system battery. LabVIEW [4] is used to monitor battery voltage, solar voltage and desired temperature setting along with actual house temperature. LabVIEW was programmed to adjust various components within the house such as fans to maintain a desired temperature.

This paper is organized as follows. Section II describes the design of the model house and its PV system. Section III discusses the PV system automation using LabVIEW, controller design, modelling, and experimental closed loop house temperature control. Finally, Section IV presents the main conclusions of this work and is followed by references.

II. DESIGN OF THE MODEL HOUSE AND PV SYSTEM

Model House

A simple model house was constructed using commonly available building materials and was equipped with a number of speed adjustable fans, lights, and temperature sensors. Fig. 1 shows different views the model house with or without its roof. The objective is to meet the energy needs of this model house using energy generated using a PV system.

*An earlier version of this work was presented at the 2014 ASEE Conference in Indianapolis, IN.

Fig. 1: Model House

PV System requirements

The main requirements for the system are to provide sufficient energy to power the model house during the day and store enough energy to meet the demands during the night. Based on the above requirements, consideration must be given to the sizing of the solar panel system based on household needs and sizing of the battery to store enough energy for night-time consumption.

In light of this, the household daily consumption must be known or assumed. Typically, for a household of four people, the average energy consumption is 18KWh per day [5]. For the model house with dimensions of 1/200 relative to a typical house, the energy consumption is 90Wh (assuming linear energy consumption.) Thus, the solar panel should produce no less than 90Wh, and the total electronics consumption should not exceed that same amount. Also the battery should have a power rating of 7.5 Ah.

The main energy consumers in a house are heating and cooling elements such as air-conditioning, water heaters and electric stoves. The heating element for this model will not exceed the 60% of 90Wh to ensure enough energy is supplied to the other electronics and sufficient energy is stored for later use.

PV System Components

The main components of the PV system are the panels, storage battery, charge controller, heating element, ducted fan, thermocouple, signal conditioners, and the controller. Each of these components is discussed next.

Photovoltaic Panels

Such panels are comprised of a number of smaller units, called cells, arranged in series and parallel configurations, depending on the energy requirements. For the purposes of this project and in order to keep the construction cost low, individual cells were purchased and used to construct two PV modules with 36 solar cells each. Fig. 2 shows one of the two PV modules.

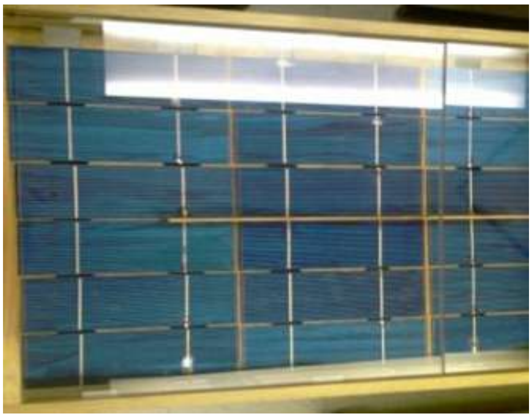

Fig. 2: PV Panel.

Evergreen Polycrystalline Class A cells were used in this work with the following specifications: 1.8Wp watts each, 3.6 max amps, rated at 0.5 volts each, thickness 0.2mm, dimensions 3.25”x6”. The PV panel open circuit voltage was 18V (36 cells in series). Fig. 3 shows the PV system wiring diagram. Solar energy is harnessed by the two photovoltaic panels and is regulated by a charge controller to charge the battery. The collected energy powers the thermocouple, and the pulse width modulation (PWM) circuit which adjusts the speed of the fan and the duty of the heating element. A NI® USB-6009 system is used for data acquisition, monitoring, and control.

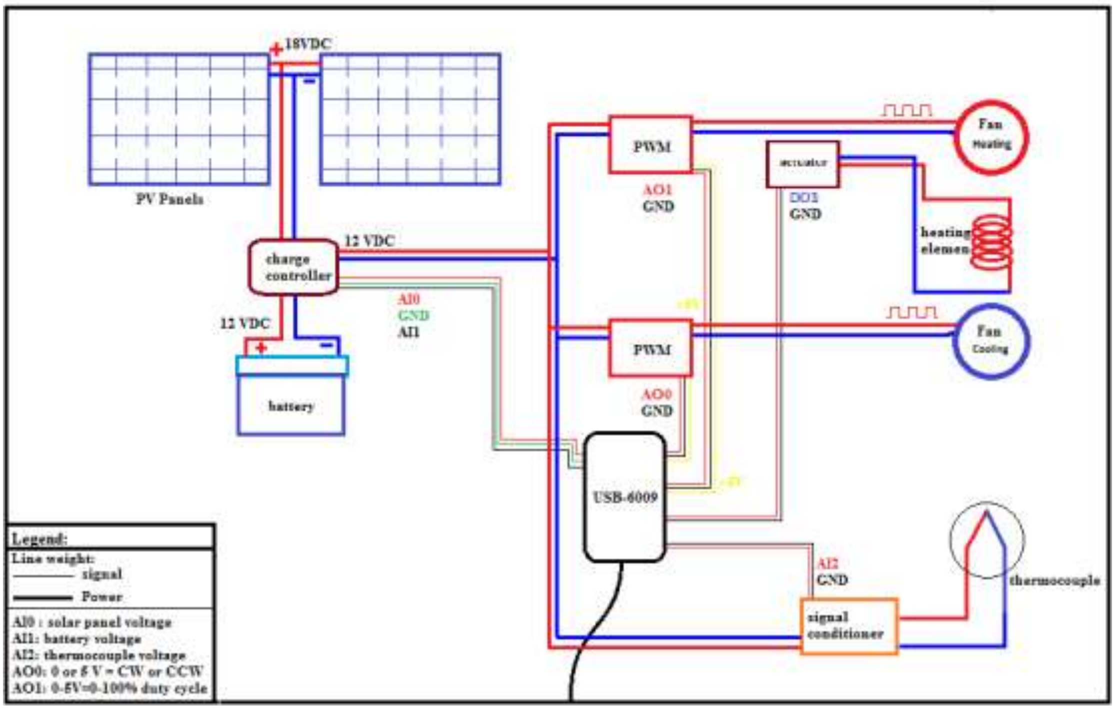

Fig 3: PV System Wiring Diagram.

Controller

The NI USB-6009 is a data acquisition system, commonly used in academia, allows for real time control monitoring through it I/O channels (Fig. 4). It can read/write both analog and digital signals.

Fig 4: Data Acquisition System [3].

Heating element:

The power source to control the model house temperature is the heating element shown in Fig. 5.

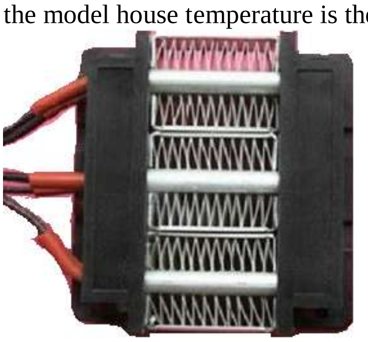

Fig 5: Heating element [6].

The above heating element is a PTC electric, ceramic, thermostatic heater that is safe for indoor use. It's a 12 V 150 W heater that consists of 3 small elements; it is capable of reaching temperatures up to 300 ° C (572 F).

Actuator Circuit Board

Fig. 6 and Fig.7 show the circuit and corresponding wiring diagram required by the heating element.

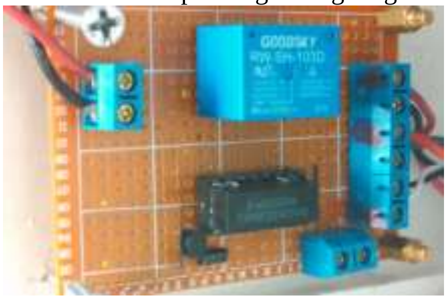

Fig 6: Actuator Circuit

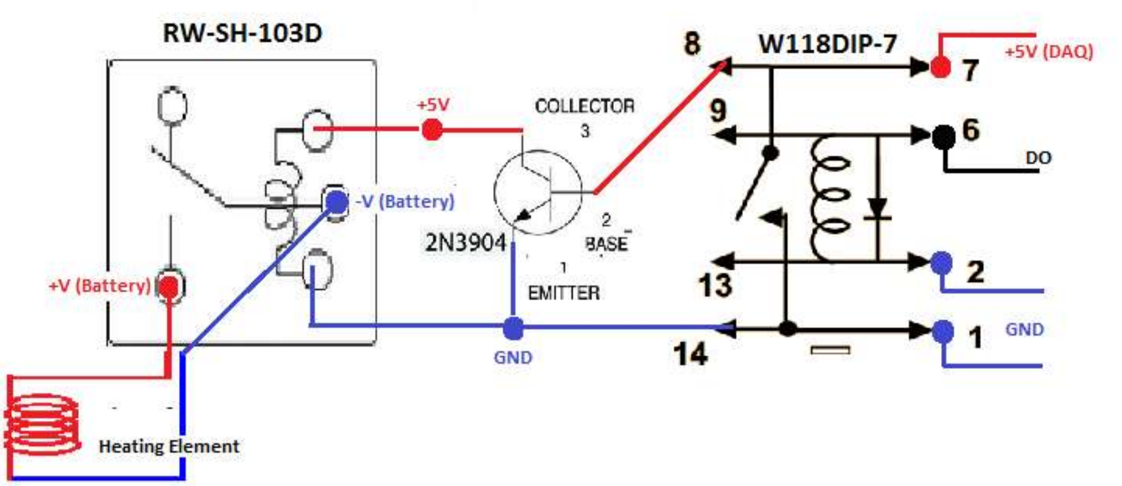

Fig 7: Relay Wiring Diagram [7]

The above circuit consists of two relays that switch the heating element on or off. The relay used is a 5 V trig, 0-120VDC mechanical relay. The model numbers are RW-SH-103D and W118DIP-7. The use of relay, model RW-SH-103D, is to sustain the high current electric load, around 3-5A 12V, for the heating element.

<u>Air Fans</u>

A system of two air fans, one for heating and another for cooling, is designed and implemented to circulate air into and out of the house in order to maintain house temperature at a desired level, see Fig. 8a and Fig. 8b.


Fig. 8a: Heating Air Blower **Fig. 8b: Cooling Air Blower**

The heating and cooling fans are 12 V 400 mA ducted blowers. The heating fan of Fig. 8a is responsible for heating the house based on the PWM duty cycle and the direction of rotation. The fan rotates counter clockwise (CCW) for the heating action. Enclosed in the duct is the heating element. As air is pulled from the outside, it flows over the heating element and thus it affects the temperature inside the house.

On the other hand, the cooling fan of Fig. 8b removes air from inside the house. This action decreases the house temperature. The cooling fan, based on the PWM duty cycle, rotates clockwise (CW).

PWM:

The pulse width modulation (PWM) circuit is shown in Fig. 9. The heating and cooling air fan motors are generated by Direct-Current (DC) voltage. In order to control the speed for such motors, PWM controller circuits are used.

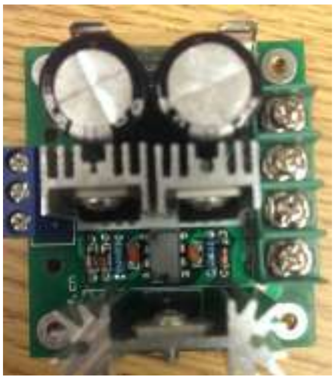

Fig 9: PWM circuit [8]

The above PWM is a 12-60 V, 0-100% duty cycle, 13.5 KHz module with a maximum discharge load of 10A. This PWM allows for greater energy savings for both the fans and the heating element. It is controlled by the NI USB-6009 with a signal of 0 to 5V corresponding to 100-0% duty cycle.

Battery

The battery used in this work (Fig. 10) is a deep cycle, solar panel purposed, 35 Ah 12 V Power Sonic. It is capable of providing sufficient energy to power all electronic components at full load.

Fig 10: Energy Storage Battery

Charge Controller

When connecting a solar panel to a rechargeable battery it is usually necessary to use a charge controller circuit to prevent the battery from overcharging. Charge control can be performed with a number of different circuit types. Fig. 11 shows the charge controller built for this work while Fig. 12 shows the wiring diagram.

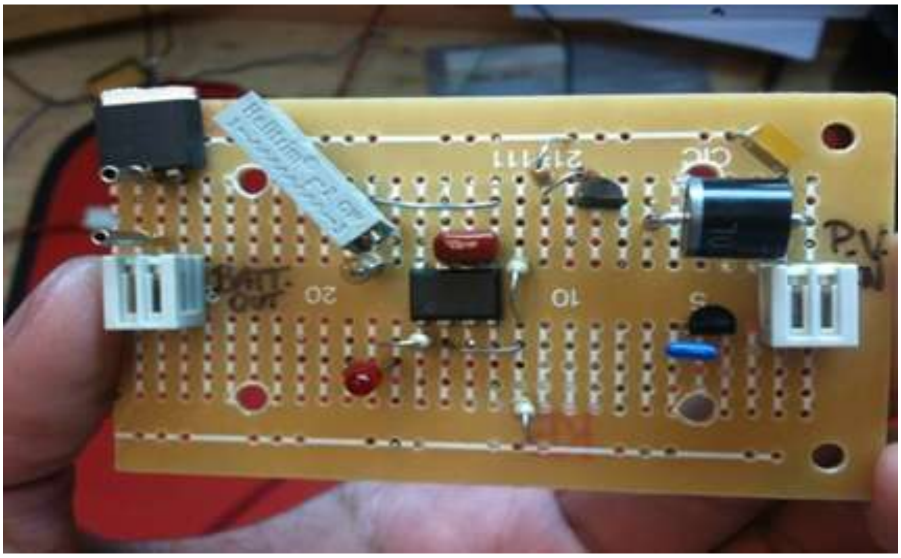

Fig. 11: PV System Charge Controller

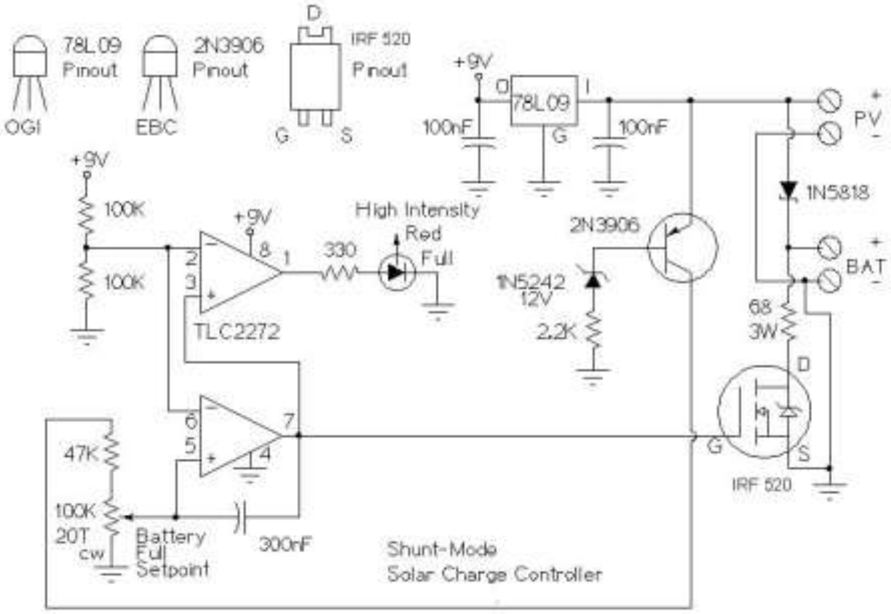

Fig 12: Charge Controller Wiring Diagram [9]

Other Instrumentation

As mentioned earlier, several other instruments have been included in this project. Thermocouples are used to measure house temperature. Thus, thermocouple signal conditioning must be addressed. The thermocouple signal conditioning circuit AD595 is used. Since the AD595 circuit needs an external power source of 5V DC at pin11 to operate, it was decided to use a 0-30V DC to 5V DC voltage regulator to power the AD595. This on board voltage regulator draws its power from the battery and converts it to a constant 5V DC output. This design eliminates the need for a dedicated 5V DC power supply and saves precious space in the junction box. Both the V DC Power and the thermocouple are installed on quick disconnect WAGO connectors for ease of installation and removal.

Fig. 13 shows the thermocouple signal conditioning board. This board contains the AD 595 thermocouple signal conditioner with ice point compensation. It also has a built in 0-30V DC Input to 5 V DC Regulated Output. Fig. 14 shows the wiring diagram and pin outs of the AD 595 conditioner.

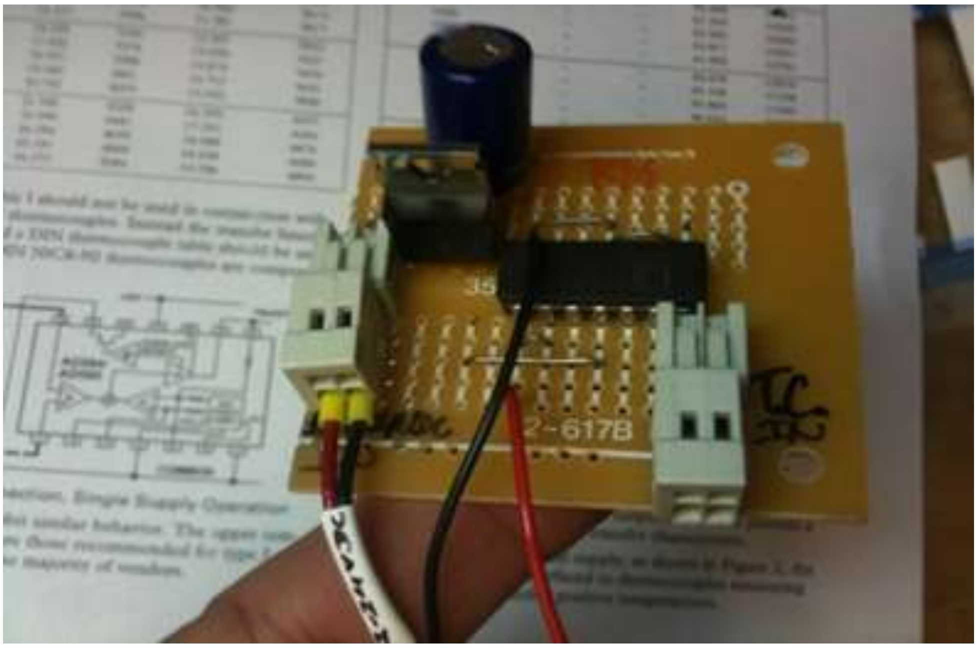

Fig. 13: Thermocouple Signal Conditioning Board

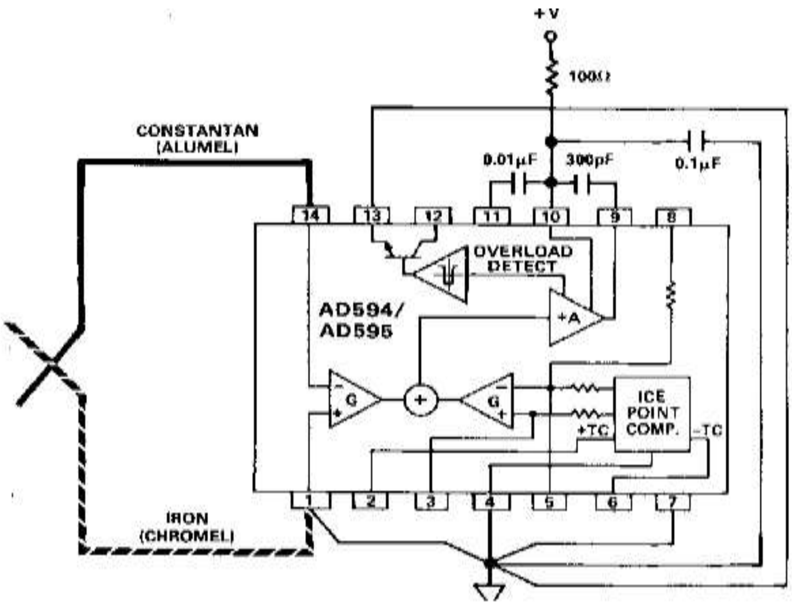

Fig 14: AD595 Thermocouple Signal Conditioner Wiring Diagram [10]

III. PV SYSTEM AUTOMATION USING LABVIEW

Data Acquisition, Control and Programming

LabVIEW provides an easy to use platform for real time data acquisition and control. It extensively has been used in academia and has been available for this work. Programming of the different control functions proved a time consuming process. However, online references such as the National Instrument [3] forum proved very useful.

Temperature control is achieved using a PI control algorithm in a split range control structure. The manipulated variable is the fan speed (i.e. air flow to or from the house.) Based on the output of the PI controller, which ranges from -50% to 50%, one of the two air fans is on. If the PI output is between 0 and 50%, the hot air fan is on. Otherwise, the cool air fan is on. To minimize turning the air fans on or off when the PI output is around 0%, a dead-band has been implemented. This dead-band is based on the proximity of the temperature to its desired setpoint value. The block diagrams shown in Fig. 15a and 15b display the programming of the temperature control loop. Data acquisition, signal conversion, control, and display functions are included in the program shown in Fig. 15a while Fig. 15b indicates the spilt range control structure used in this system.

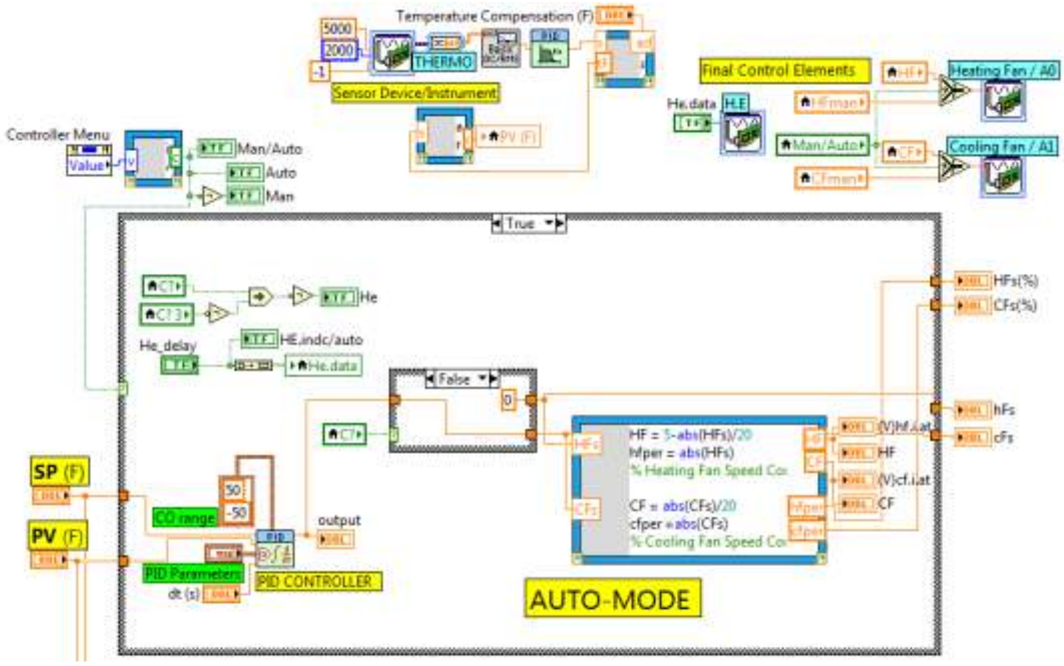

Fig. 15a: Temperature Control Using LabVIEW

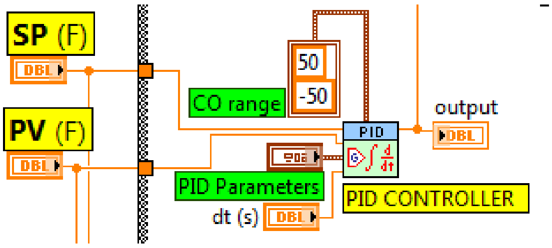

Fig. 15b: Split Range Control Structure

Human Machine Interface (HMI)

Fig. 16 shows the LabVIEW HMI for power monitoring and house temperature control. The top chart shows the house temperature and its setpoint. The bottom chart shows the speed of the air fans on a percent basis. The control panel includes capabilities for controller mode, setpoint, and tuning parameters adjustment.

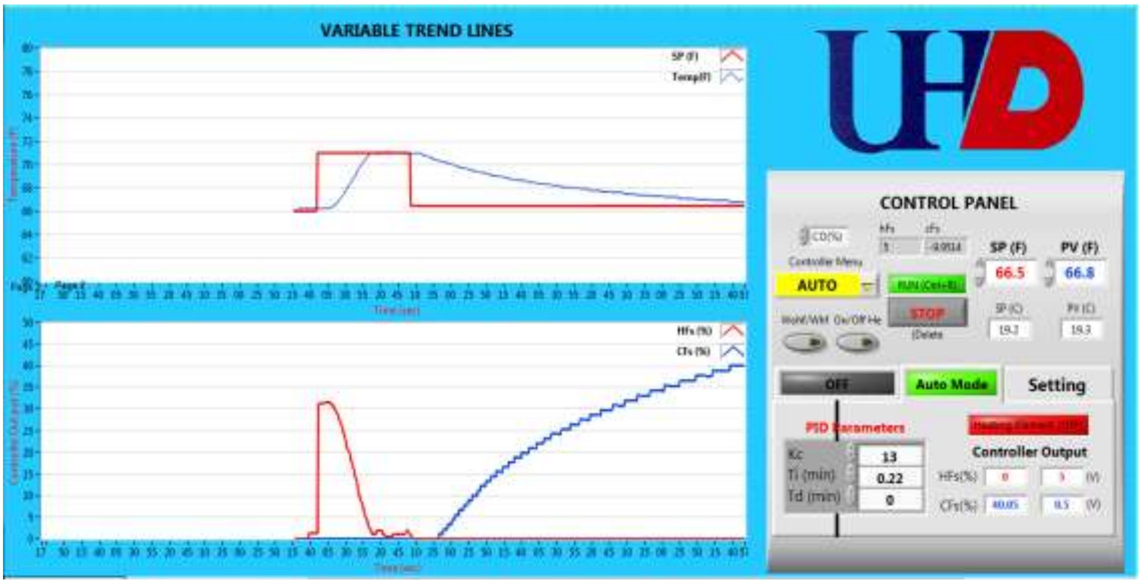

Fig. 16: PV System Human Machine Interface

Empirical Modeling and Controller Tuning

Empirical models between the controlled (house temperature) and manipulated variables (hot or cool air fan speed) were developed by analyzing process data gathered under controlled, open loop conditions by step changing the manipulated variable (air fan speed). Using such models, initial tuning parameters for the temperature PI controller were calculated for the heating and cooling processes. Finally, the closed loop performance of the PI controller was tested for temperature setpoint tracking.

Model developed has been done using TuneWizard [11]. TuneWizard allows for data acquisition and analysis, model development, controller tuning, and closed loop controller performance evaluation. Table 1 shows the process model and the tuning parameters for the heating and cooling phases. The models are of the first order plus time delay form. Figures 17 and 18 show how well the models fit process data for the heating and cooling phases. It appears that the models developed fit the process data reasonably well.

Table 1: Modeling and Tuning Results using TuneWizard

	Heating Process	Cooling Process
Modeling		
Process Gain (deg F/%)	0.083	-0.326
Time Delay (min)	0.106	0.053
Time Constant (min)	0.224	0.671
Tuning		
Proportional Gain (%/deg F)	13.2	19
Integral Time (min)	0.22	0.4

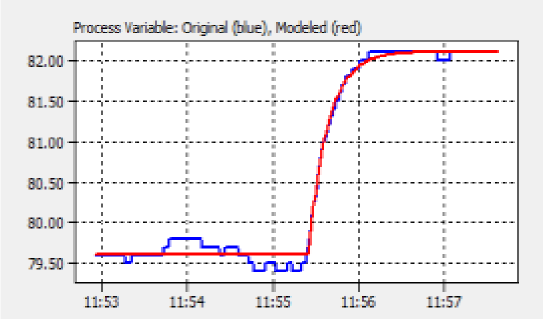

Fig. 17: Modeling for Heating Process

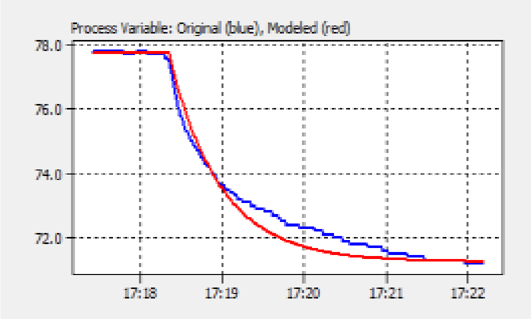

Fig. 18: Modeling for Cooling Process

Experimental Evaluation of Temperature Controller Performance

Since the tuning parameters between the heating and cooling processes are not significantly different, the tuning parameters of the heating process (Table 1) are used in the experimental verification of the controller performance. Fig. 19 refers to the heating process and shows the closed loop performance for a step change in the temperature setpoint. The controller achieves and maintains the temperature at the new setpoint value. Similarly, Fig. 20 shows the controller performance for the cooling process.

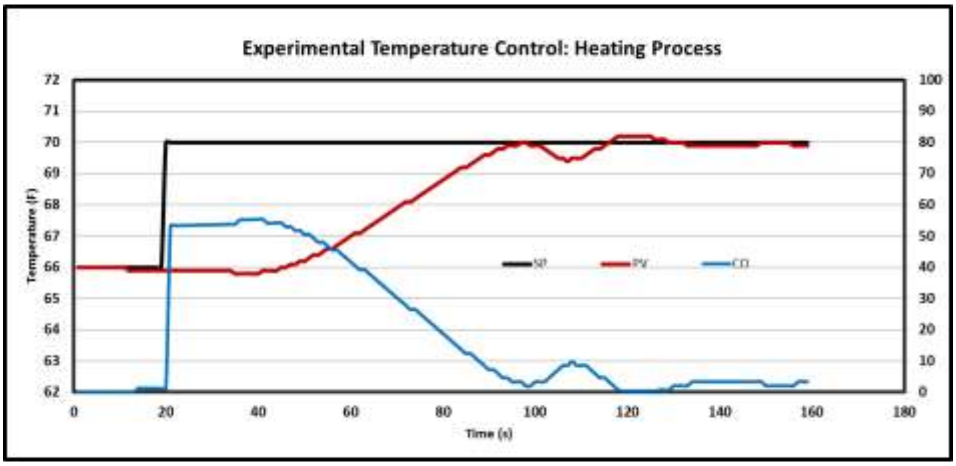

Fig. 19: Temperature Control (Heating Process)

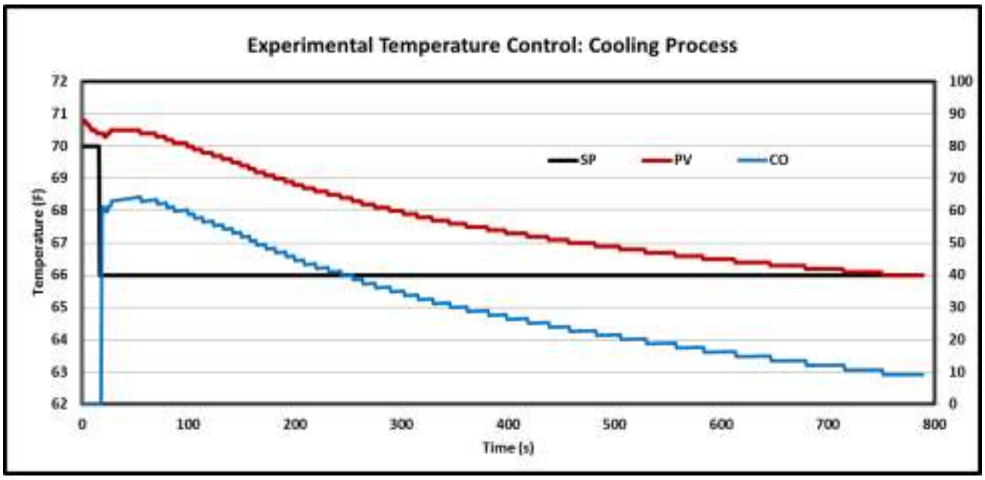

Fig. 20: Temperature Control (Heating Process)

IV. CONCLUSIONS

This paper was concerned with the use of solar energy to meet the energy needs of a small model house along with the needed automation for the distribution and use of the generated electrical energy. This experimental study discussed the design of the photovoltaic system, for the small scale model house, along with its associated instrumentation, real time data acquisition and automation using LabVIEW. The study showed that the house energy requirements can be met using renewable energy sources.

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