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THESIS

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Smoothing PV Output Fluctuation Using Cooling Fan

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Abstract

Due to the growth of solar power and the concern regarding its effects on power system because of its intermittency and zero inertia, in this project I am trying to smooth solar power using electrical consumer. The purpose of this project is to absorb PV output fluctuation as much as possible with electrical consumer in buildings such as cooling fan, and to make the overall current draw steadily from the system (consumer + PV output), without fast intermittency. For absorbing PV output intermittency we need a consumer which we can control its usage rapidly and smoothly; a consumer which changing its consumption would not affect the functionality of the device. On this project I am making the building cooling fan to follow the PV output. There are two reason for choosing building fan; first, we can control its speed and by changing its speed we are changing its electrical usage by cubic, and second, the room temperature is not effected by making fan following PV output intermittency.

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Introduction:

One issue about renewable energy such as Wind and PV is their intermittency, since their output depends on the weather condition. More than that, PV systems have zero inertia. Those issues can cause a problem on power system, such as voltage and frequency regulation and islanding [1],[2]. One way of solving these issues is to use battery for back up [3],[4],[5],[6]. But batteries are expensive and it is not economical to use PV system with battery in many cases. Another solution is to control the load usage based on PV system output to absorb PV system intermittency. On this paper I controlling cooling fan. The reason for choosing the fan is to be able to control its speed based on the amount of energy produced by the PV system. Contrary to the PV system, the room temperature has a great inertia in a way that if we vary the fan's speed it takes some time before the room temperature changes. The main challenge for this project is to make the fan follow the PV output as fast as the latter fluctuates. Fans depending on their mechanical characteristics, have inertia and they have delays for each speed change. Moreover, they may have overshoot for speed changes.

Goal:

The goal of this project is to smooth the power fluctuation of the PV output by controlling the cooling fan's speed and maintaining the desired temperature of the building. The idea is to combine PV system with one or more electrical devices, which can be controlled based on PV system output t to reduce PV output fluctuation.

Challenges:

The main challenge for this project is to make the fan follow the PV output as fast as the latter fluctuates. Depending on their mechanical characteristics, fans have inertia and they have delays for each speed change. Moreover, they may have overshoot for speed changes.

This is graph of PV output during a cloudy day in Albuquerque, NM:

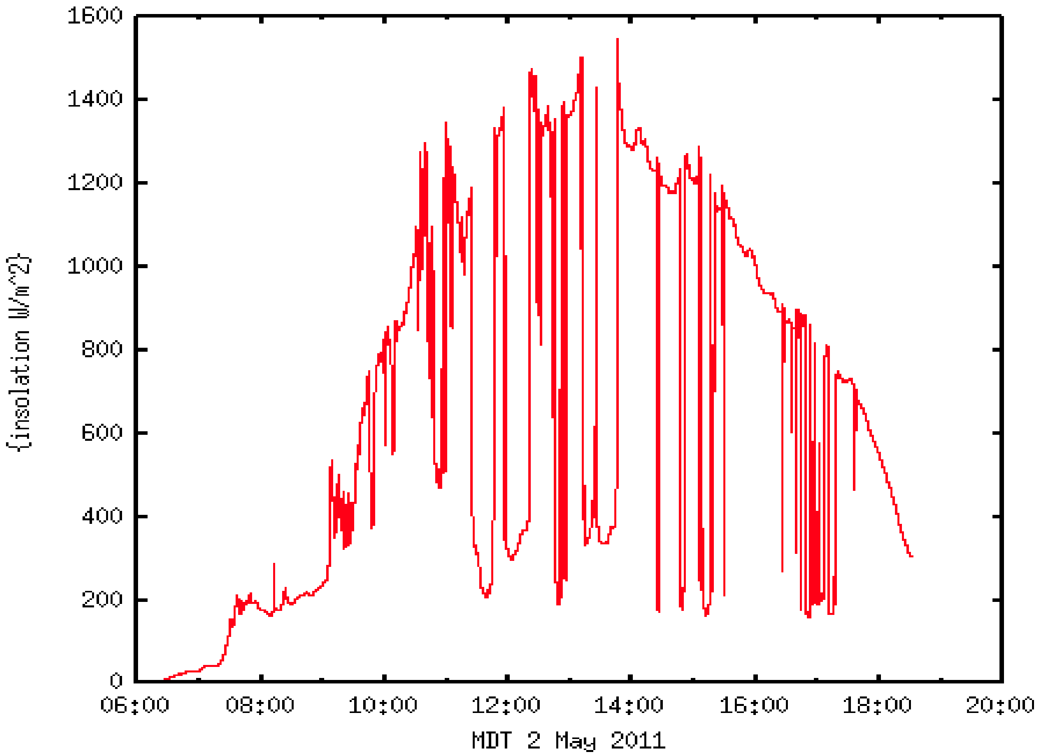

Figure 1. PV output

As we can see from Fig.1, the PV output fluctuates significantly and it is impossible for the fans to absorb all the fluctuation. Thus, there is a need to design a PID controller for the fan and simultaneously smooth the fluctuation before the fan absorbs it.

Prior work:

This project uses a 15KW PV system on the ECE rooftop. The system has been installed in a way so as to have maximum efficiency during summer time when temperatures in Albuquerque can reach more than 40^c. Hence, there is maximum electrical usage by the cooling system. There are three 5KW Sunny Boy inverters that give 3-phase 120 V from the PV system and it is fed to the building MCP panel. There is also a Current Transducers (CT) that measures current from the inverters.

Delta is a control and data management system, which provides data from the fans(speed, usage) and current from the CT every two seconds. We can also make the CT communicate with the fan's driver and send speed signals to the fan based on the PV system output via Delta.

System:

- **PV Plant:**

We need to know our PV system frequencies because we are absorbing the PV system intermittency. A study in Spain [7] that examined the relationship between PV output cut-off frequency and its size noted that the peak power and the area of the PV plant were closely related. Figure 2 plots f_C, versus the PV plant area, S, following the results from [ref]. The curve at large frequencies is well-fitted by a function of the form: $f_c = a \times S^b$

Where a=0.0204 and b=-0.4997, with f_c in Hertz and S in hectares.

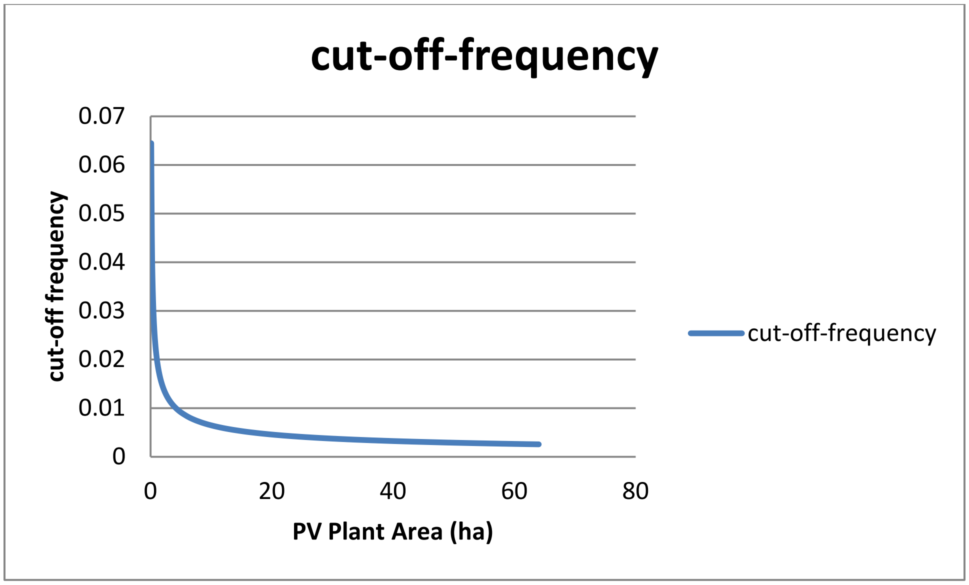

Figure 2. Cut off frequency versus PV plant area

Our PV plant area is 72 m^2 which is .0072 ha, thus the cut-off frequency is:

fc=a*s^b; (eq. editor)

fc=(.0204)*(.0072)^(-0.4997)=.24 Hz

Another way to find out the PV system frequency is by calculating Fourier transform of data that is being generated from the CT every two seconds via Delta. Our sampling frequency of the PV output is 2 seconds; thus, the cutoff frequency of the system is lower than 0.5 Hertz. Also, this frequency is different every day and is based on weather conditions.

Here is the Matlab code of getting Fourier transforms:

```
Fs = 1;                    % Sampling frequency

T = 1/Fs;                     % Sample time
L = max(size(M));                     % Length of signal
t = (0:L-1)*T;                % Time vector
figure(222)
plot(Fs*t(1:200),M(1:200))
NFFT = 2^nextpow2(L); % Next power of 2 from length of M
Y = fftshift(fft(M,NFFT))/L;
f = Fs/2*linspace(0,1,NFFT);
% Plot single-sided amplitude spectrum.
figure(333)
plot(f,2*abs(Y(1:NFFT)))
title('Single-Sided Amplitude Spectrum of y(t)')
xlabel('Frequency (Hz)')
ylabel('|M(f)|')
```

Our PV output on 11/14/2013 with 0.5 Hz sampling frequency:

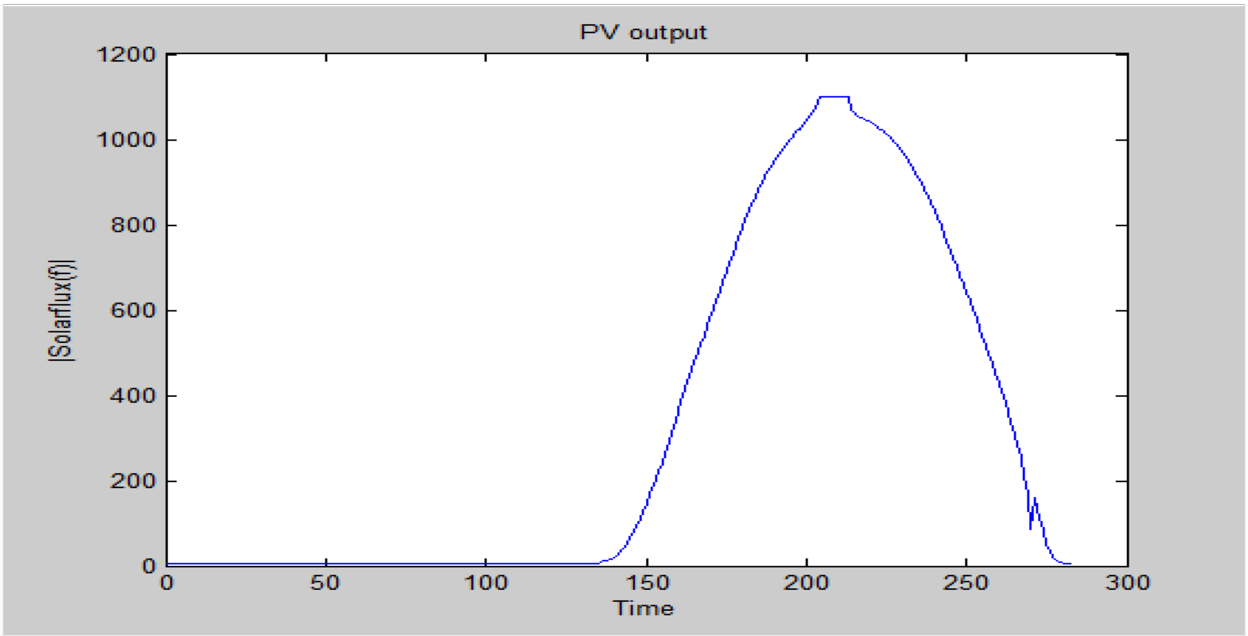

Figure 3. PV out put

This is the FFT of our PV output on 11/14/2013:

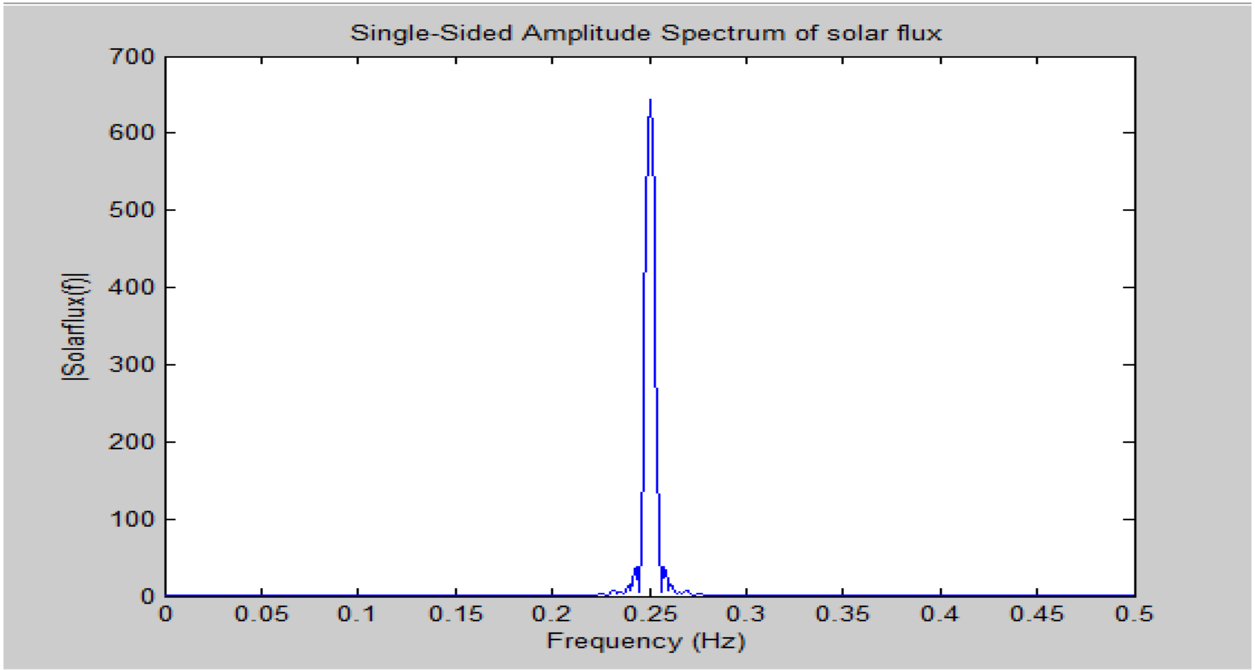

Figure 4. PV output cut-off frequency

Which shows our dominant frequency is .25 Hz.

- **Fans:**

In This project I am working with a fan at ECE building. The fan is 100-hp motor on 208 V 3-phase service. It is a beltless aluminum fan, and the blades are approximately 5 ft in diameter and 1/2" thick. The full speed of fan is 1800 RPM, and 72,000 CFM. Since the fan is beltless the most of the inertia is due to the motor itself and it respond to speed changes relatively fast and it doesn't have over-shoot.

Based on those information we could find the fan characteristics such as damping ratio and inertia.

- **Building Temperature:**

There are three different transfer heats in every building. To maintain constant temperature, we need to make sure that the sum of those heat transfers is zero.

Transfer heats are:

1. Internal: produced by different machines we have in a building and by humans.
2. External: This is the amount of energy that a building absorbs from the sun through walls and windows. And heat transfers through walls and windows. Each wall and window has its own heat conductivity. Fourier's Law expresses conductive heat transfer as:

$q = k\,A\,dT\,/ds$ [8] Where

q = heat transfer (W, J/s, Btu/s)

A = heat transfer area (m^2, ft^2)

k = thermal conductivity of material (W/m.K or W/m ^oC, Btu/(hr ^oF ft^2/ft))

dT = temperature difference across the material (K or ^oC, ^oF)

s = material thickness (m, ft)

3.The amount of energy absorbed by cooling and heating systems depends on the amount of air mass generated by the fan and the temperature of the air being generated.

$Q = \alpha\omega C_P(T - T_s)$ Where:

α = is constant to convert fans speed to air mass flow

ω = is fan speed (rpm)

$T_S =$ Air supply temperature throw

T = internal temperature

This project assumes that it is summer time and the goal is to reduce the building temperature.

Thus, the second transfer heat is positive and the third one is negative.

Model:

In this project I develop two models: the first model calculates fan behavior and the second one measures building temperature. The combination of the two models tells us how smoothly the fan is working and following PV fluctuations, the temperature of the building and the rate of room temperature change.

Fan Model:

The model have been used for controlling the fan is HSSPFC (Hamiltonian Surface Shaping and Power Flow Control)[9]. In this model, the Hamiltonian of the system is defined as the total energy of the system, and its derivative is the power flow of the system. A system is stable if the Hamiltonian of system is positive definite and its derivative is negative, which means the system is going to lower energy levels.

The energy equation for the fan is: $I\dot{\omega} = \tau - \gamma\omega^2 - D\omega$ where:

I is motor inertia,

ω is circular speed (rpm),

τ is our controller which is PII

D is air damping and

ɣ is our motor damping.

Fans don't have potential energy; but only kinetic energy. Thus, we define our Hamiltonian to be: $H = \frac{1}{2}I\omega^2$ which is positive definite for I>0.

$H = \frac{1}{2}I\omega^2 + \frac{1}{2}\ K_I(\int \omega)\text{^}2dt$ as kinetic energy and controller. As I am trying to make the model track PV output, I am using the tracking controller:

$\widetilde{\omega} = \omega_R - \omega\ \tilde{\tau} = \tau_{R-}\tau$

$H = \frac{1}{2}I\widetilde{\omega}^2 + \frac{1}{2}\ K_I(\int \widetilde{\omega})^2$ Which is Positive definite for $K_I > 0$

$\dot{H} = \left[I\dot{\widetilde{\omega}} + K_I(\int \widetilde{\omega}\,dt)^2\right]\widetilde{\omega} = [I(\dot{\omega_R} - \dot{\omega}) + K_I \int \widetilde{\omega}\ \ dt]\widetilde{\omega}$ =

$[\tau_R -\ \gamma{\omega_R}^2 -\ D\omega_R - \tau +\ \gamma\omega^2 +\ D\omega + K_I \int \widetilde{\omega}\ \ dt]\widetilde{\omega}$=

$[\tilde{\tau} -\ \gamma({\omega_R}^2\text{-}\omega) -\ D\omega_R + K_I \int \widetilde{\omega}\ \ dt]\widetilde{\omega}$, $\tilde{\tau} =\ -K_P\widetilde{\omega} - K_I \int \widetilde{\omega}\ \ dt$

$= -(D\text{+}K_P)\ \widetilde{\omega}^2 -\ \gamma(\omega_R + \omega)\widetilde{\omega}^2 < 0$ for $\omega_R, \omega, K_P > 0$

Figure 3 demonstrates the model in Simulink.

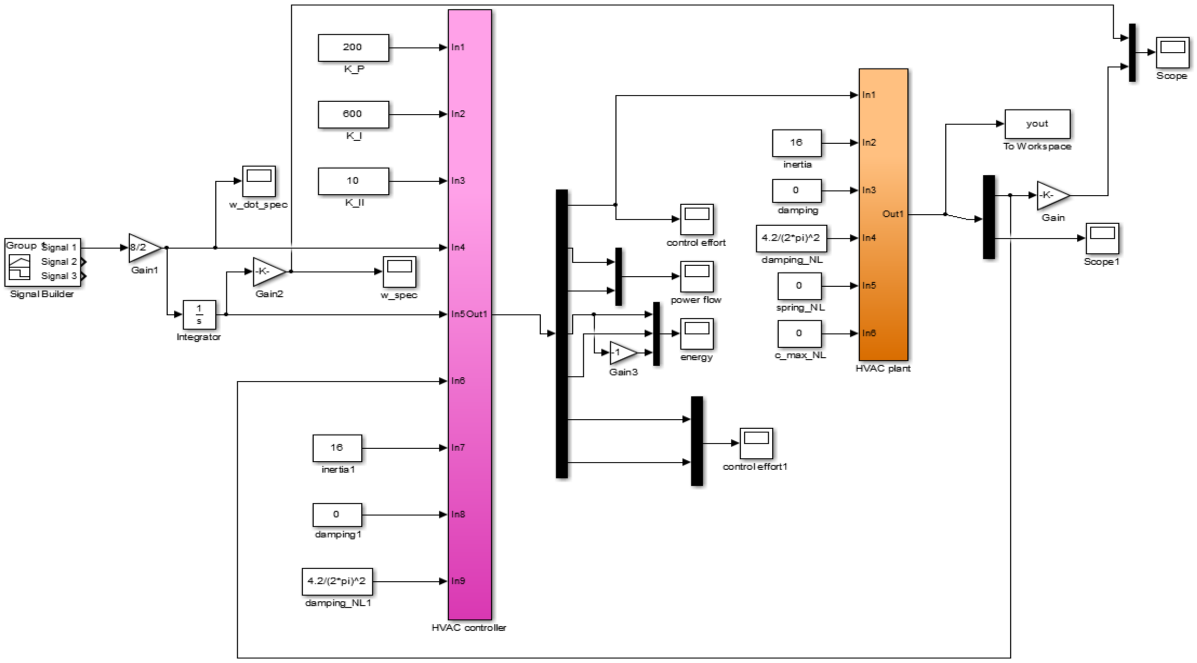

Figure 5. Fan Model

On the HVAC controller, I defined mechanical and controller parameters such as inertia, damping, and PID proportional and setting the required fan speed. On the HVAC plant, I calculated the fan speed and acceleration. There is feedback from HVAC plant to HVAC controller to measure error (desired speed - actual speed). Based on this error, I calculated these signals on the HVAC controller:

Control signal: $\gamma {\omega_R}^2 + D\omega_R + K_I \int \tilde{\omega}\ dt + K_P\tilde{\omega}$

Power dissipater: $-(D + K_P)\,\tilde{\omega}^2 - \gamma(\omega_R + \omega)\tilde{\omega}^2$

Power generator: $K_{II} * \iint \tilde{\omega}\ dt * \tilde{\omega}$

By getting integrator of power flow we are getting energy of system.

Temperature Controller:

While trying to control the fan, we must maintain room temperature at the desired point. In this part I am modeling room temperature.

There are several heat transfers in every building such as:

1. Internal heat, produced by humans and different machines in the building, which is positive. I call it: $\dot{Q}_{int}$

2. The amount of heat that the building absorbs from the sun, which is positive, and heat transfer through walls. This could be positive or negative depending on the temperatures inside and outside of the building. I call it: $\dot{Q}_{ext}$

3. Heating or cooling provided by the fan.

The sum of these heat transfers makes our room temperature model. In this project, I am not primarily concerned with deep temperature modeling. Hence, I make several assumptions:

1. I assume a uniform temperature for the whole building.

2. The heat transfer through the walls is proportional to the temperature difference inside and outside of the building. But, I linearize it.

For maintaining the desired temperature, the sum of those heat transfers should equal to zero.

The only heat transfer we can control is heating or cooling provided by the fan. There are three ways to do so:

1. Controlling the air temperature of the fan

2. Controlling the fan speed

3. Controlling both

As we are trying to control the fan's speed in this project, I chose the second option.

Room Temperature Model:

This is the room energy equation:

$$\rho V C_P \dot{T} = -\alpha \omega C_P (T - T_s) + \dot{Q}_{ext} + \dot{Q}_{int}$$

$$M\dot{T} = V_1 + V_2 - R u_1 (T - u_2)$$

$$M = \rho V C_P \,, V_1 = \dot{Q}_{ext} \,, V_2 = \dot{Q}_{int} \,, R = \alpha C_P \,, u_1 = \omega, u_2 = T_s$$

M is the total mass of air in the building

V is volume of our building

ρ is air density

C_P is air heat capacity on constant pressure

$\dot{T}$ is temperature difference of our building

α is constant to convert fans speed to air mass flow

ω is fan speed (rpm)

T_S air supply temperature throw

T internal temperature

Q_{ext} the amount of heat, building absorb from sun plus heat transfer through walls

Q_{int} the amount of internal heat produce by people and other facility in the building

u_1 is fan speed

u_2 is air temperature which fan is providing

M	$M = \rho * V = 1.18 * 9000 = 10800$
V	9000
ρ	1.18
C_P	1 (KJ/Kg K)
α	.01
K	.2
A	1500
T_S	15

Table 1. Building characteristic

In this model $\dot{Q}_{ext}$ and $\dot{Q}_{int}$ are generators and $\alpha\omega C_P(T - T_s)$ is dissipative. For maintaining room temperature, the sum of generators and dissipative should become zero.

Again, I am using HSSPF to track the desired temperature. I defined our Hamiltonian to be:

$H = \frac{1}{2}M\widetilde{T^2} + 1/2K_{I2}(\int \tilde{T}\,dt)$^2 Which is positive definite for $K_I > 0$

$\tilde{T} = T_R - T; \widetilde{u_1} = u_{1R} - u$

$\widetilde{u_1} = \left[k_{p2}\tilde{T} + k_{I2}\int \tilde{T}\,dt\,\right]/R(T - u_{2R})$

$\dot{H} = \left[M\left(\dot{T}_R - \dot{T}\right) + K_{I2}\int \tilde{T}\,dt\right]\tilde{T} = [M\dot{T}_R - V_1 - V_2 + Ru_1(T - u_{2R}) + K_{I2}\int \tilde{T}\,dt]\tilde{T}$=

$$= \left[\, M\dot{T}_R - V_1 - V_2 + \left(M\dot{T}_R - V_1 - V_2 - k_{p2}\tilde{T} - K_{I2}\int \tilde{T}\,dt\right) + K_{I2}\int \tilde{T}\,dt\right]\tilde{T} =$$

$= -k_{p2}\tilde{T} < 0$ Thus $k_{p2} > 0$

System: $M\dot{\tilde{T}} = V_1 + V_2 + \left(M\dot{T}_R - V_1 - V_2 - k_{p2}\tilde{T} - K_{I2}\int \tilde{T}\,dt\right)$

$\rightarrow M\dot{\tilde{T}} + k_{p2}\tilde{T} + K_{I2}\int \tilde{T}\,dt = 0$

$u_1 = u_{1R} - \widetilde{u_1} = -\left[\, M\dot{T}_R - V_1 - V_2 + k_{p2}\tilde{T} + K_{I2}\int \tilde{T}\,dt\right]/\, R(T - u_{2R})$

Temperature model in Simulink:

In the temperature model, I defined building and air parameters such as building volume, air density, and air heat capacity on constant pressure, and the fan's speed is connected to the model. From the energy equation of the building $\rho V C_P \dot{T} = -\alpha\omega C_P (T - T_s) + \dot{Q}_{ext} + \dot{Q}_{int}$, I calculated the temperature (T) and the rate of temperature change $(\dot{T})$. I need to make sure the room temperature reaches the desired point and does not vary while making the fan follow the PV output.

The variable that makes $\dot{T}$ sensitive to the fan speed fluctuation is building volume. Based on this equation: $\dot{T} = \left[-\alpha\omega C_P (T - T_s) + \dot{Q}_{ext} + \dot{Q}_{int}\right] / \rho V C_P$, all the parameters on the denominator are constant (air density and air heat capacity on constant pressure), except building volume. Thus, as the building volume increases, $\dot{T}$ becomes smaller. And since we are modeling this system for commercial buildings, their volume is big enough to make $\dot{T}$ small.

MOVING AVERAGE:

On one hand, since the PV output intermittency can be more than the fan can absorb, there is a need to smooth the command signal as much as the fan can follow the PV output fluctuation without any overshoot. On the other hand, the fan must be fast enough to absorb the PV output fluctuation. One way to smooth the command signal is by calculating the moving average of raw data from the PV output. Additionally, we need to set the reference fan speed signal based on the PV output fluctuation. We need to create a moving-average of the PV output and subtract it from the raw data of the PV output. Then, we should convert this amount of energy to the fan speed and add it to the fan speed reference command. From Fans law we know that a fan's power consumption is related to its speed: $\frac{P_1}{P_2} = (\frac{N_1}{N_2})^3$ [10]. Based on this equation, we can figure out how much we need to change the fan's speed for absorbing the amount of fluctuation. For instance, for saving 33% energy, we need to decrease fan's speed by 10%.

Current:

Graphs of PV output data for the same day every 5 minutes and the smooth version of the data obtained by calculating the moving-average are shown in Figure 6. below .

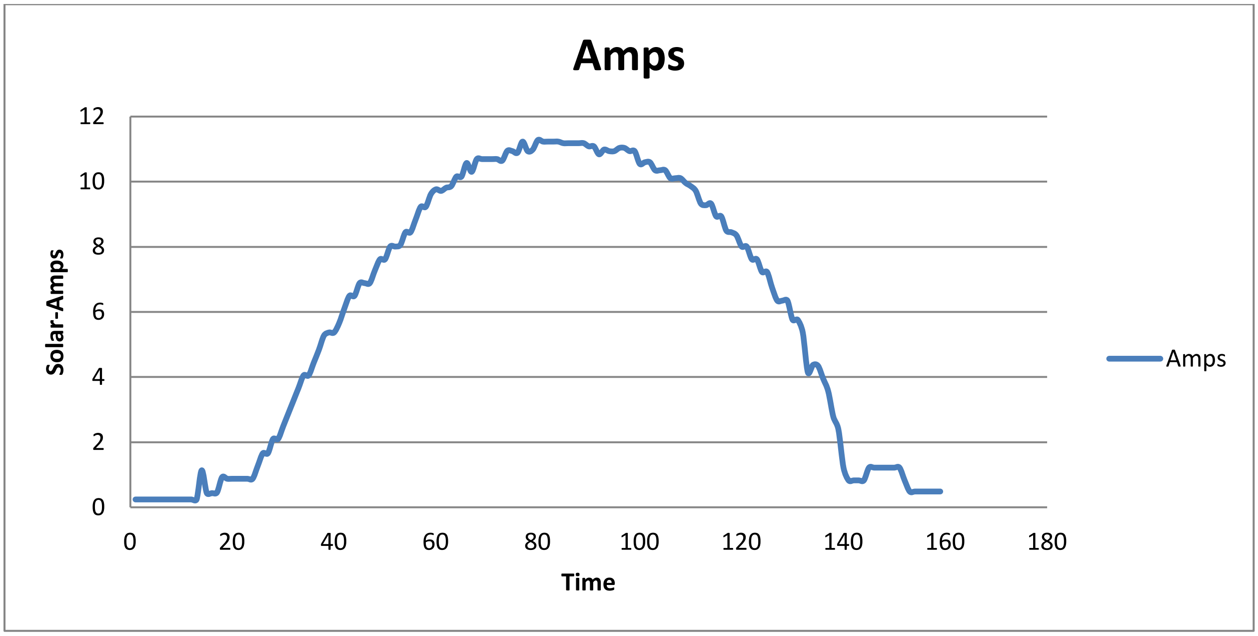

Figure 6. PV output in Ampere

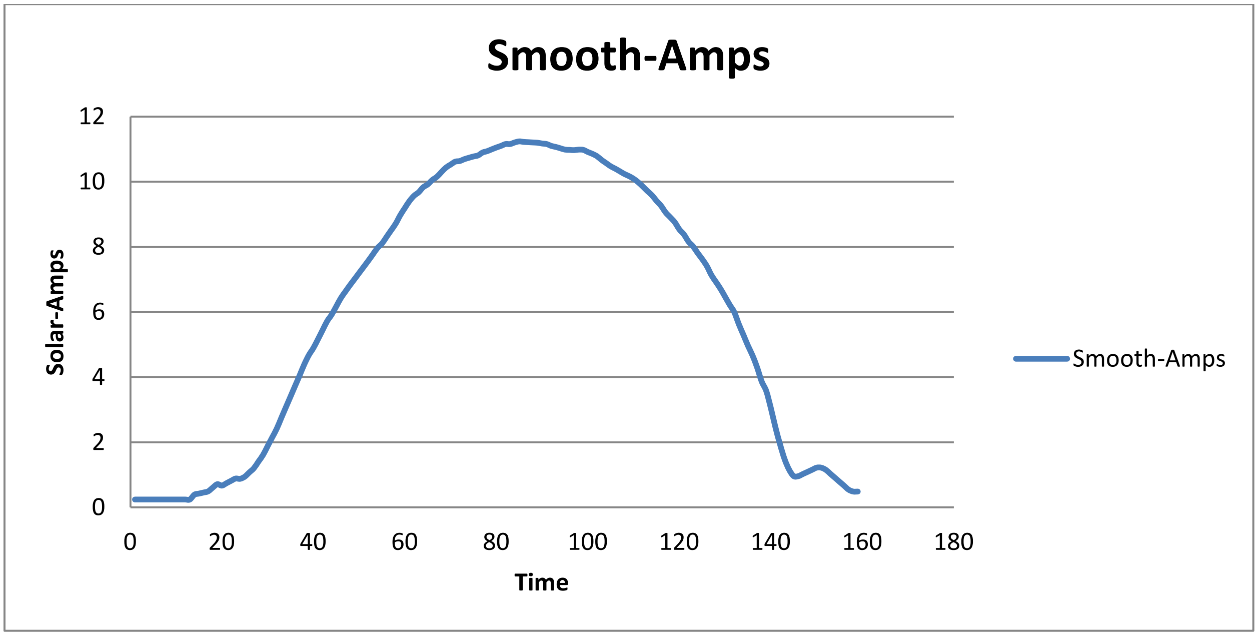

Figure 7. Smooth PV output in Ampere

Current Fluctuation:

Amps fluctuation obtained by subtracting new data from the previous one:

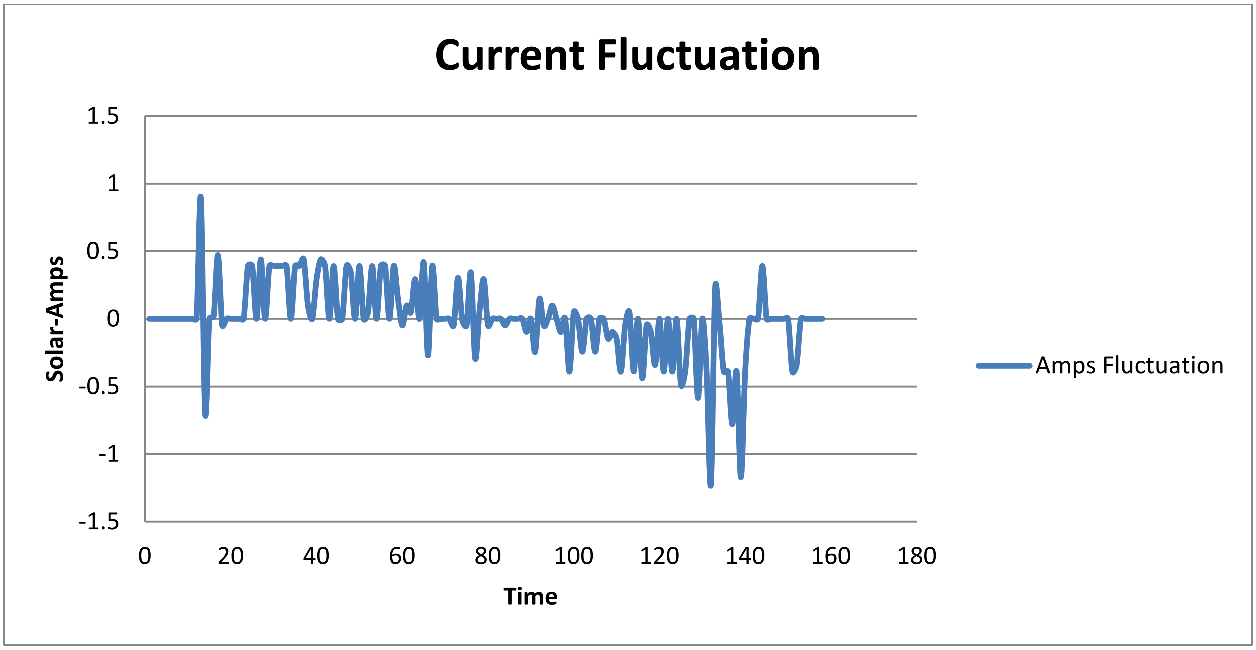

Figure 8. Current fluctuation

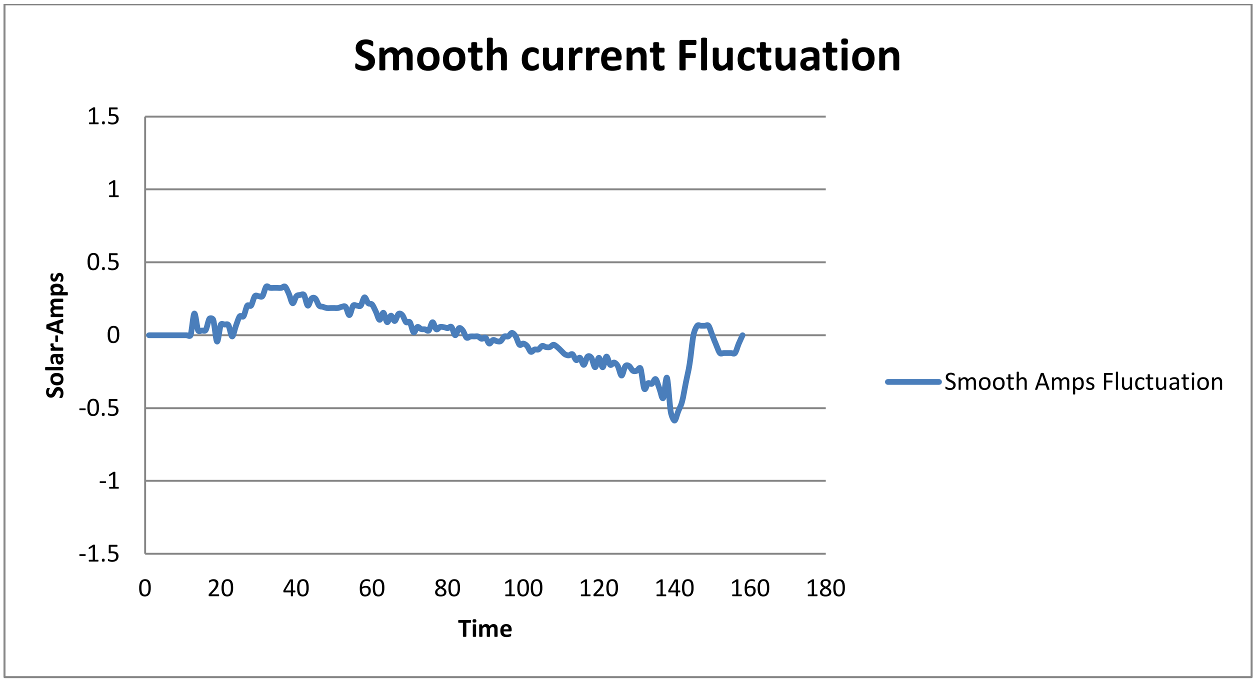

Figure 9. Smooth Current fluctuation

Energy Fluctuation:

We need to find the amount of power fluctuation: $P = I \times V \times p_f$, $P = I \times 120 \times 1$

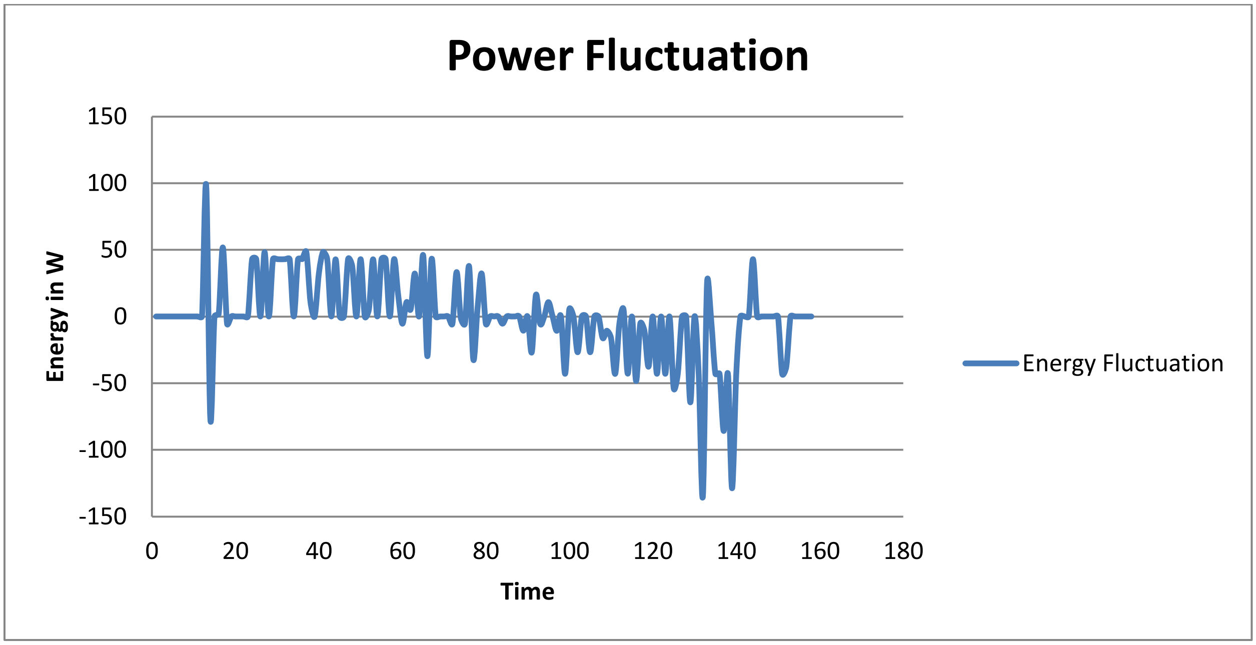

Figure 10. Energy fluctuation

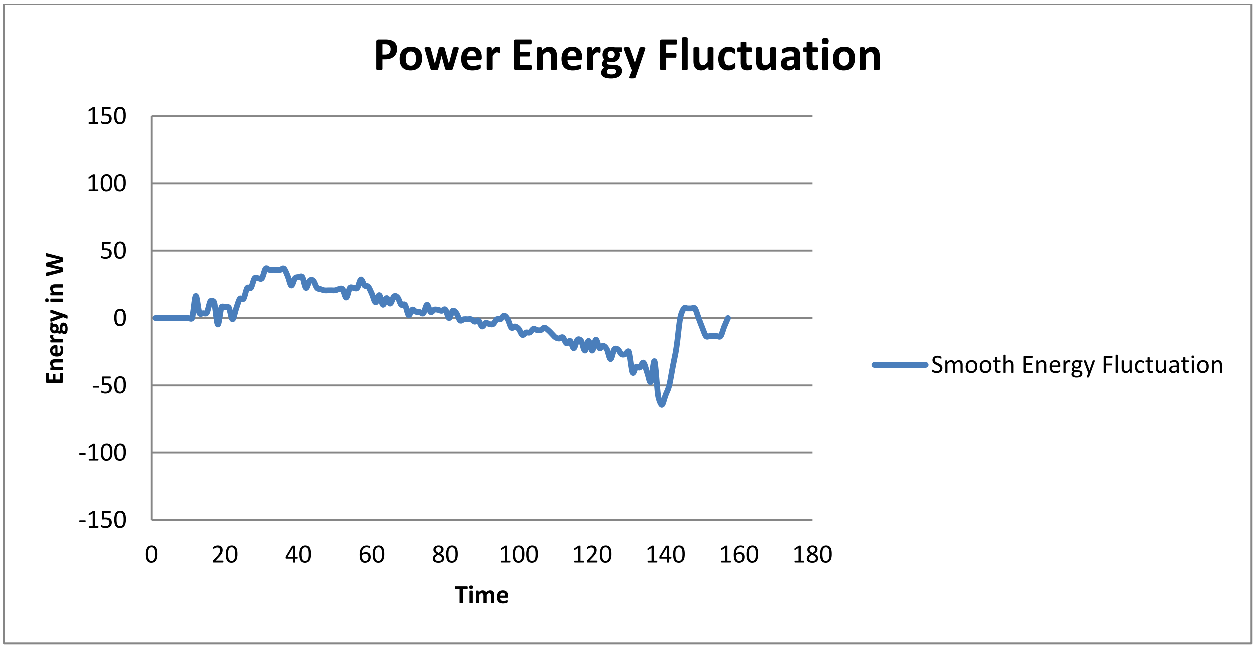

Figure 11. Smooth energy fluctuation

Fan’s Speed:

Fan’s speed calculated based on fan’s law: $\frac{P_1}{P_2} = (\frac{N_1}{N_2})^3$:

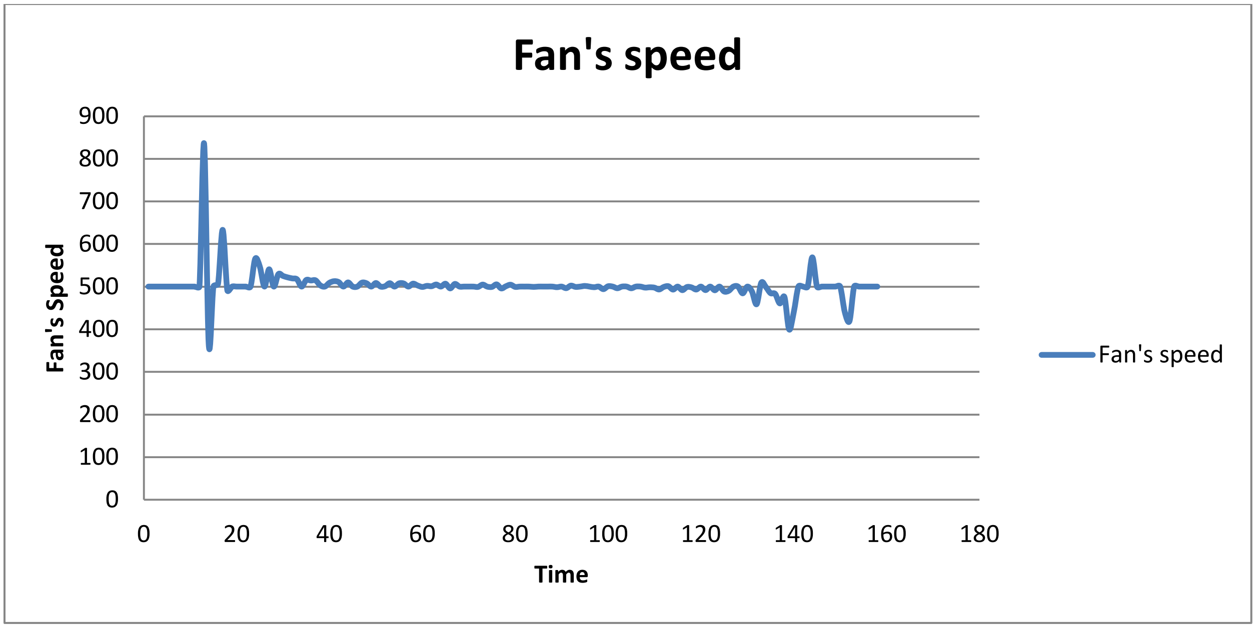

Figure 12. Fan's speed

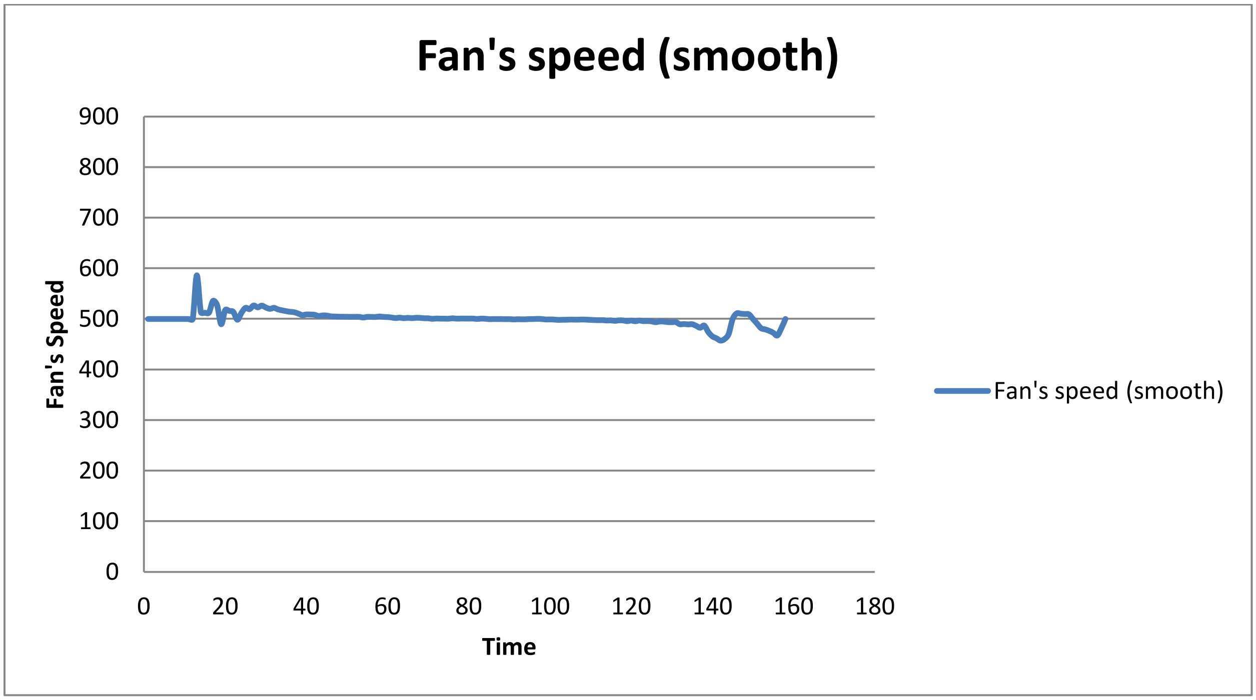

Figure 13. Smooth fan's speed

Fan's Fluctuation:

The fan's speed fluctuation obtained by subtracting the data from the previous one:

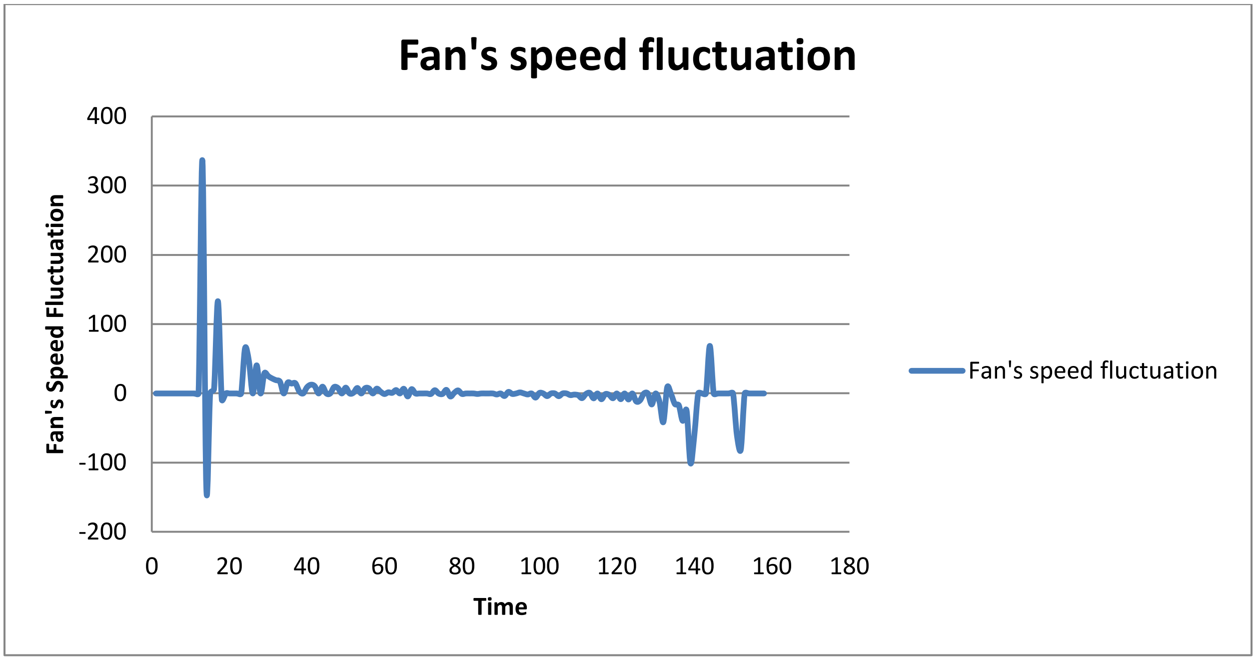

Figure 14. Fan's speed fluctuation

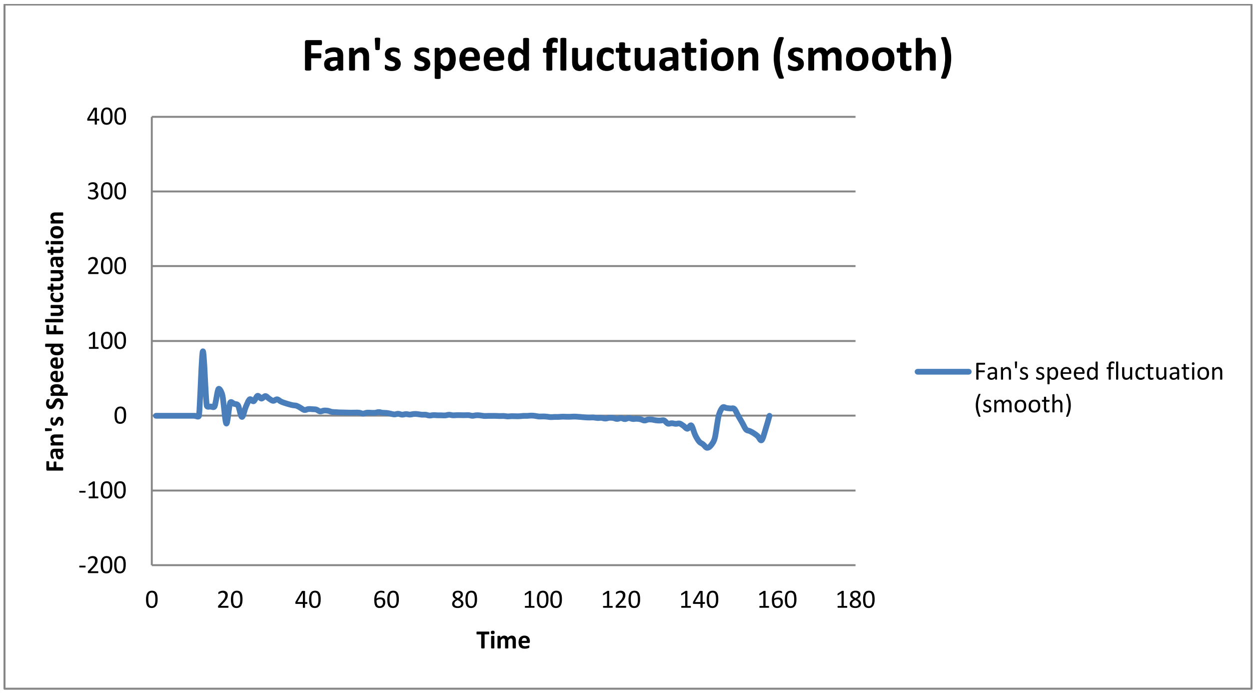

Figure 15. Smooth fan's speed fluctuation

Combined Model:

A schematic of our combined control diagram in Fig NN:

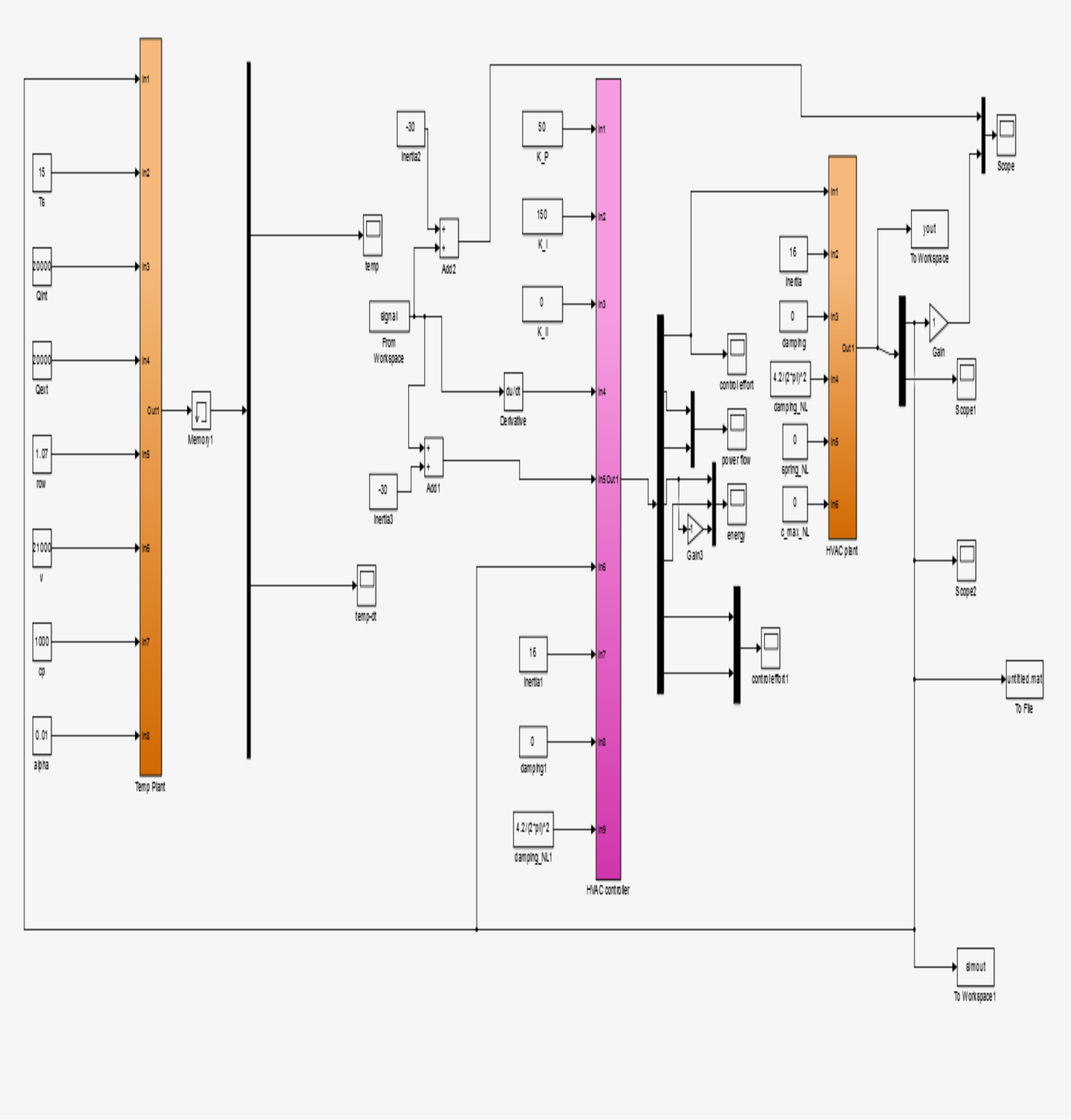

Figure 16. Combined model

RESULT:

Tracking system:

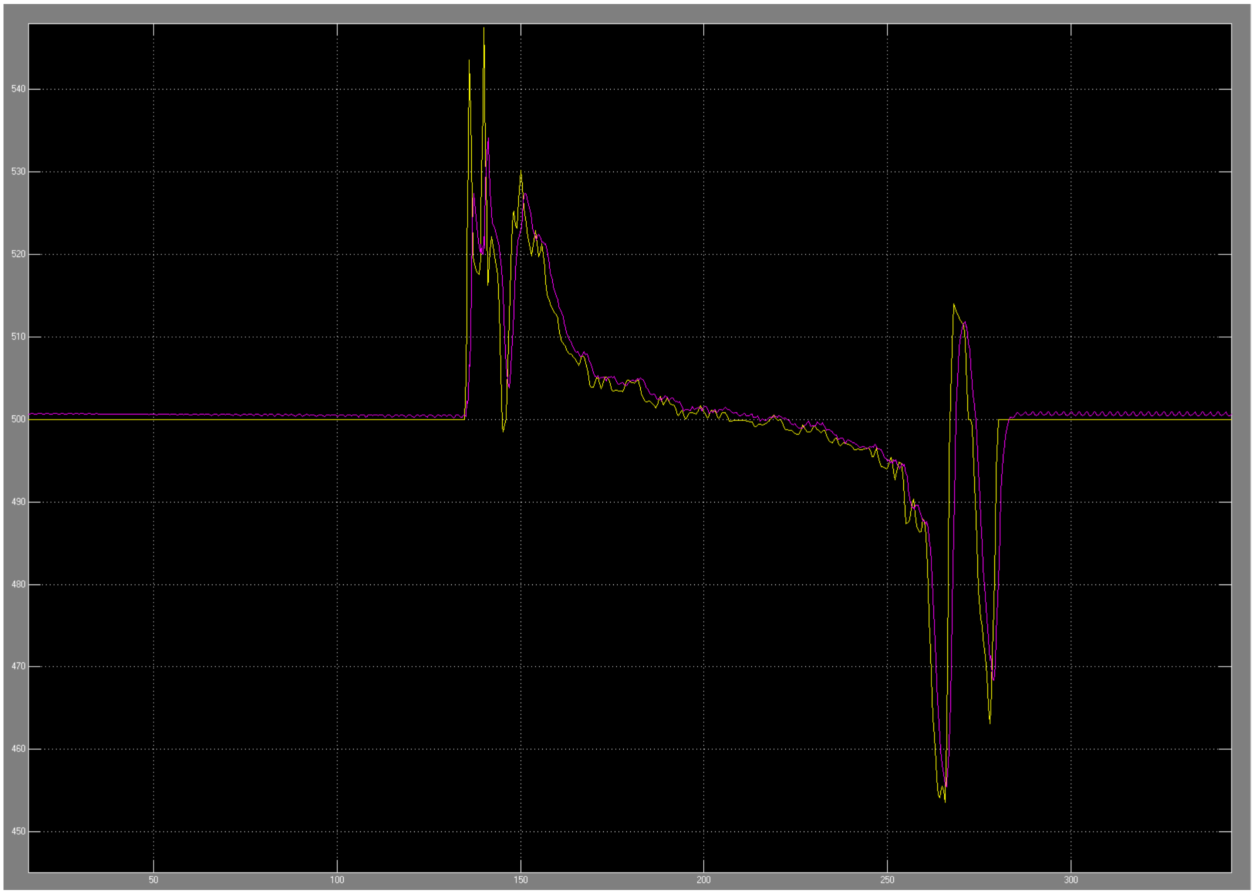

Figure 17. Tracking system

This graph tells us how our system is tracking command signal. Both lines are speed motor in RPM; the yellow one is command signal and the purple one is our fan’s speed. We can see that there is no overshoot and the fan is almost following command signal intermittency. If we increase the degree of our moving-average, the fan can follow the command signal more precisely.

a graph of two different moving-average degrees is Shown in figure 17,18.

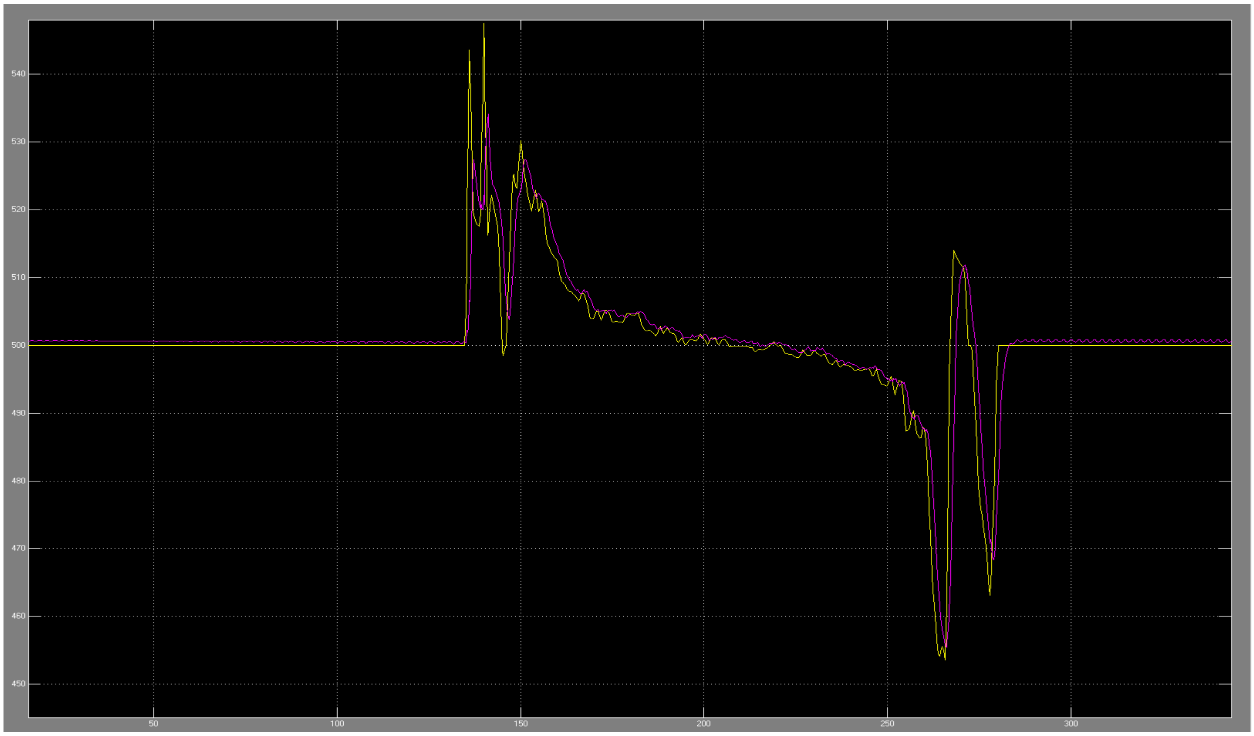

Figure 18. Tracking system with moving-average degree 5

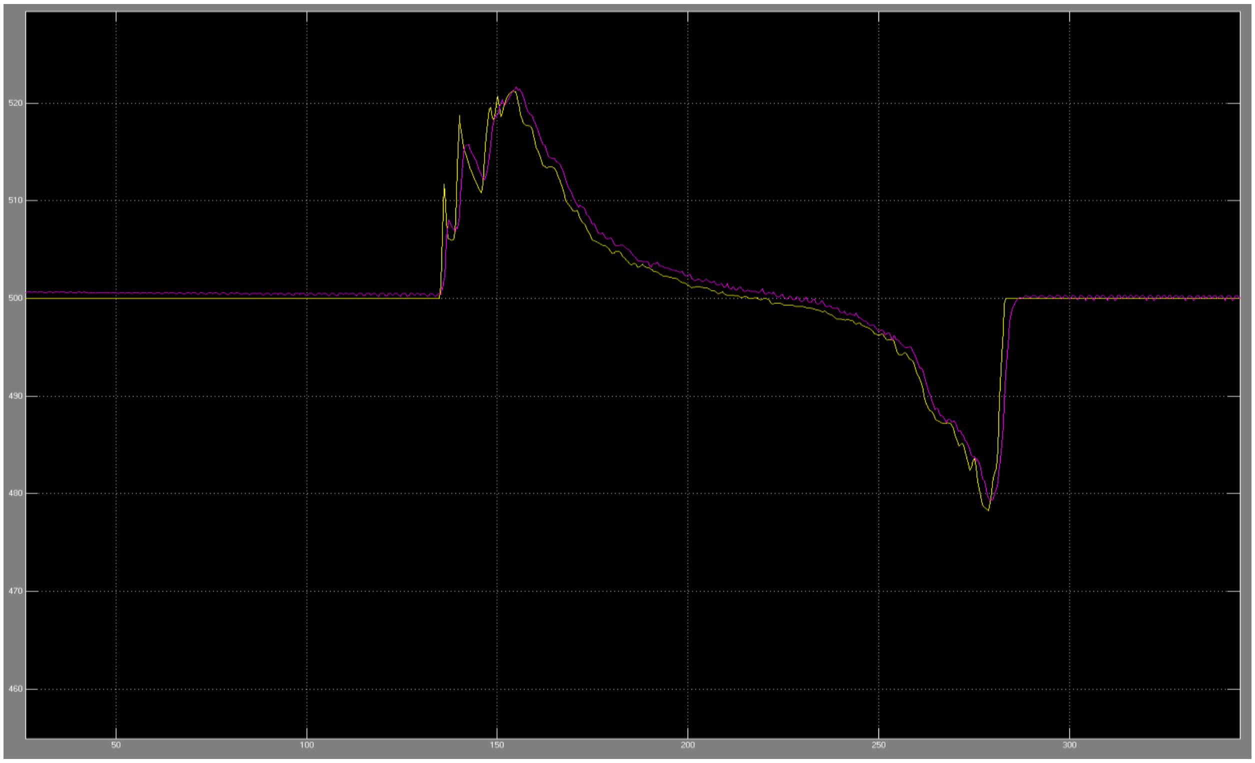

Figure 19. Tracking system with moving-average degree 20

Graph of Temperature fluctuation:

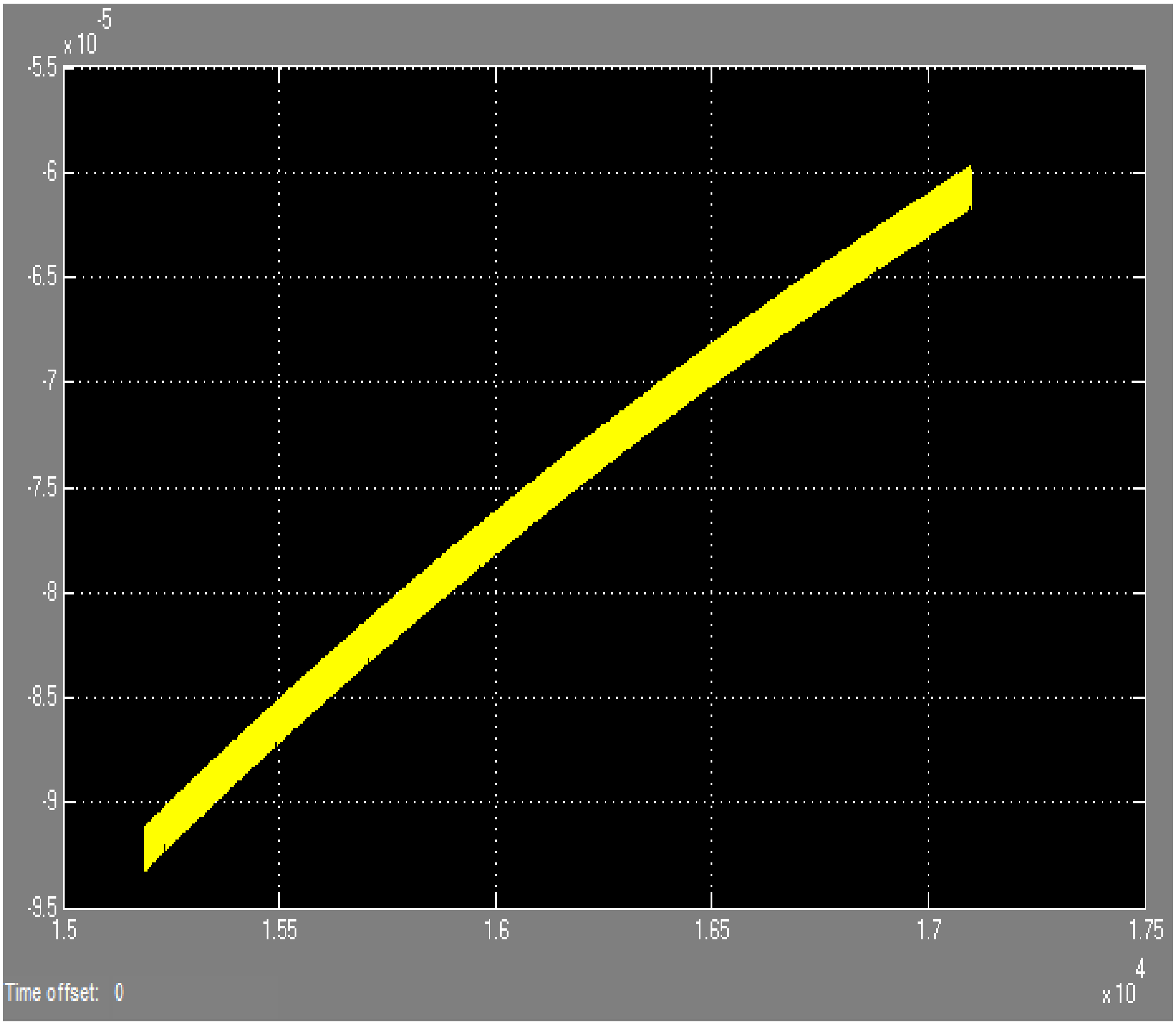

Figure 20. Temperature changing rate

As we can see in the graph, the temperature varies very little that humans cannot sense it. The amount of this change is determined only by the volume of the building that we are controlling. As the buildings get smaller, they will become more sensitive to the fan's changing speed.

Graph of temp:

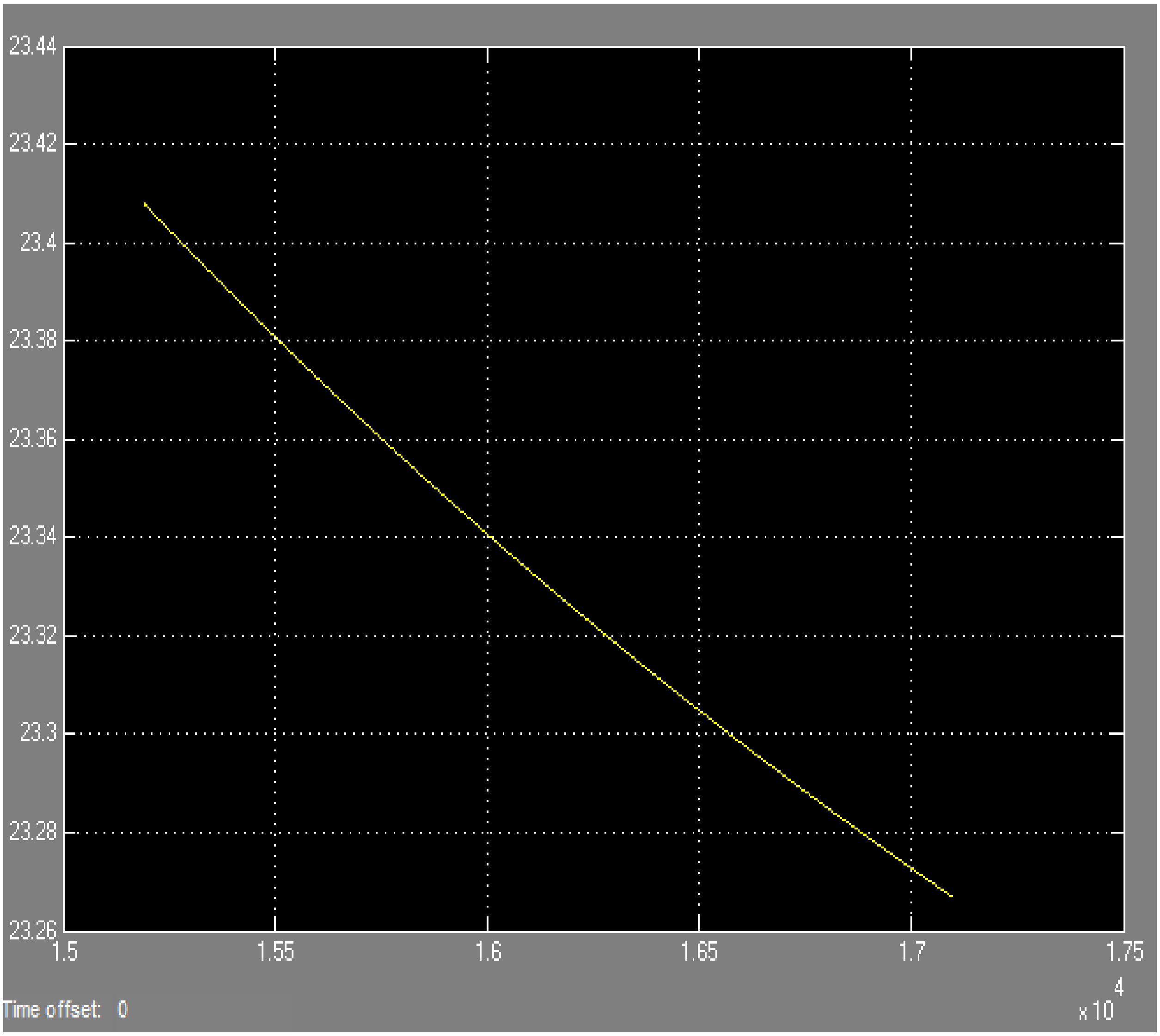

Figure 21. Temperature of building

This graph in figure 20. shows temperature in Centigrade. We set the starting temperature point at 35^c and it reaches 23^c, our desired temperature. Again, the amount of time that it takes to reach the desired temperature depends on the building volume.

Conclusion:

As I have argued in this project, it is possible to absorb a good amount of PV intermittency using electrical consumptions. I used cooling fans to absorb PV fluctuation. The amount of fluctuation that fans can absorb based on two factors. First is PV size; as the PV area gets larger, its cut-off frequency and its intermittency decreases and makes it easier for fans to follow. Second is the fan robustness; as a fan responds faster to speed changes it can absorb more fluctuation. The latter is based on fan characteristics such as fan size and fan moment of inertia.

In future, we can expand this method to include other consumers. The next consumer could be charging stations , which could be connected to PV system for electrical devices which has adopters such as laptops and home appliances, which are chargeable and work with batteries, and electric vehicles. With this method, we can reduce the effect of individual PV system on power system.

But there is a problem with this method. Since we are arguing for absorbing PV intermittency and not saving energy, there is no benefit for individual PV system owners to invest in this method. On the other hand, if we reduce PV intermittency, it would help the power system. Thus the utility companies need to determine the cost of this method for different buildings with different appliances. They also need to examine the effects of their PV intermittency on the power system.

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