Boost Converter Control in PFC Mode

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CONTENT

1 INTRODUCTION

In industrial applications, power factor is a very important indicator to power plant. When the power factor is not equal to 1, the current waveform does not follow the voltage waveform. This results not only in power losses, but may also cause harmonics that travel down the neutral line and disrupt other devices connected to the line. The closer the power factor is to 1, the closer the current harmonics will be to zero since all the power is contained in the fundamental frequency. One problem with switch mode power supplies (SMPS) is that they do not use any form of power factor correction (PFC).

In this workshop, a boost converter for the system below with unit power factor would be implemented. The key point to achieve this goal is to control the switch of the transistor u. The process will be explained step by step.

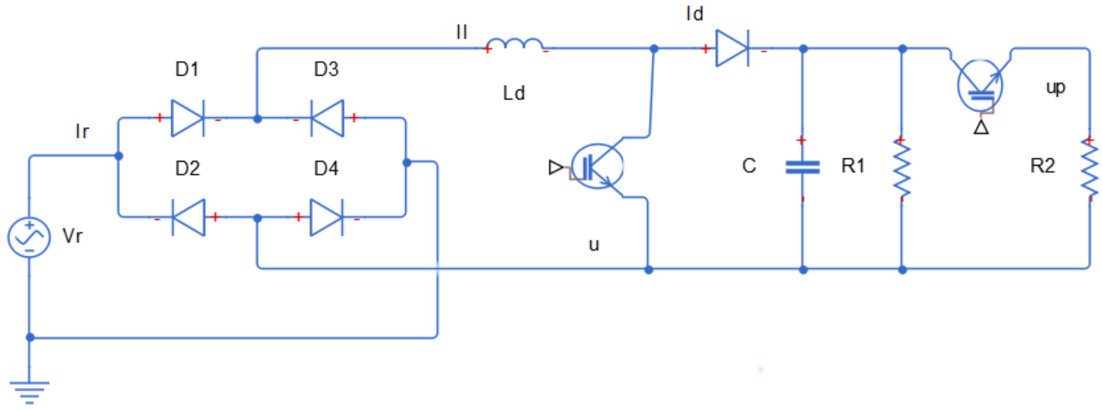

Fig 1 System Structure

The specifications are as below:

- Vre = 115v (effective value) ;
- Fr = 400Hz;
- L = 1mH;
- C = 500μF;
- R1 = 1KΩ ;
- R2 = 100Ω;

2 MODEL OF STRUCTURE

The system could be defined by the differential equations below:

$$V_r = L\frac{dI_l}{dt} + (1-u)V_c$$

$$I_l(1-u) = C\frac{dV_c}{dt} + \frac{V_c}{R}$$

Where：

- V_r: voltage of the AC source
- L: inductance of the inductor;
- V_c: voltage of the load;
- I_l: current in the inductor;
- R: the resistance due to R1 and R2;
- C: capacitance of the capacitor;

u: the state of the transistor, u=1 means transistor is on, u=0 means transistor is off.

Based on the above differential equations, we have the Simulink model below to represent the circuit.

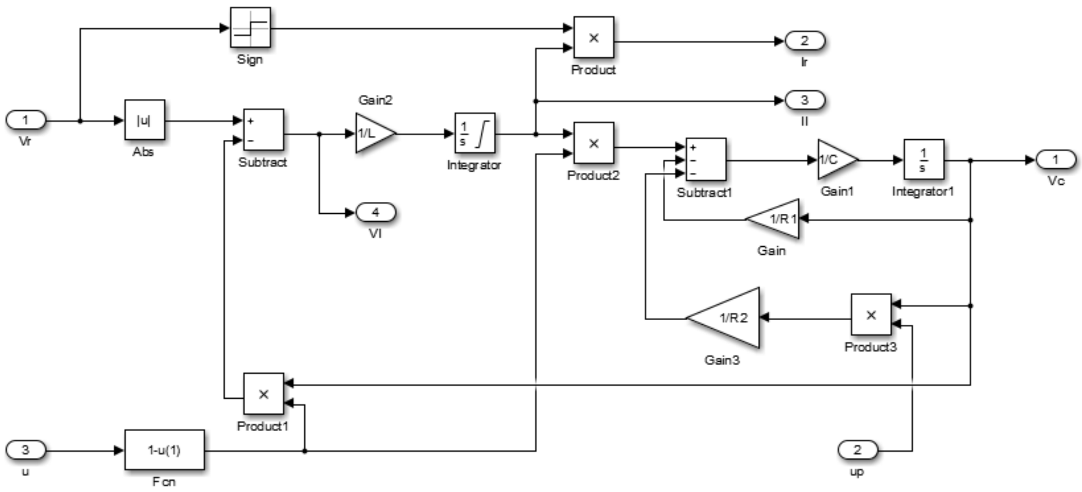

Fig 2 Model of Converter

3 Current Loop Study

In this section, a current with the same frequency of the AC source is used as reference to control the switch transistor. At first hysteresis control method is used, then a PWM modulator is used to have a constant switching frequency.

3.1 Hysteresis Control

The main idea of the hysteresis control is to force the current I_l which we want to control to follow the reference value with a limited deviation *H*. By finding a good value of *H*, we can limit the switching frequency in order to limit the switching losses.

The goal is to limit the switching frequency to 50KHz, and the voltage in the load should be Vc = 300v.

The control diagram is as below (see the Simulink file boostConverterCurrentA.slx). The hysteresis value *H* is inside the Relay component.

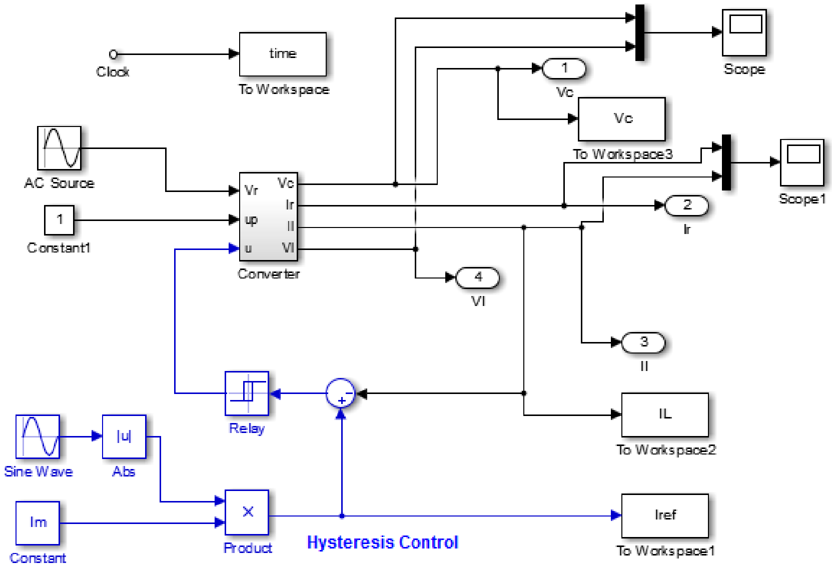

Fig 3 Hysteresis Control Block

We should compute the peak value of the reference current based on Vc value. Because the average input power should be equal to output power, we have:

$$\frac{\sqrt{2}V_{re}\cdot I_m}{2} = \frac{V_c^2}{\left(\frac{R_1R_2}{R_1+R_1}\right)}$$

Where I_m is the peak value of the reference current. From this equation we got $I_m = 12.17A$

3.1.1 Test of Hysteresis Value

At first we'd like to have a test of the hysteresis value. It is set to be:

$$H = \frac{I_m}{30} = 0.4058A$$

After setting the H and Im value in the model above we can simulate the model and get the result.

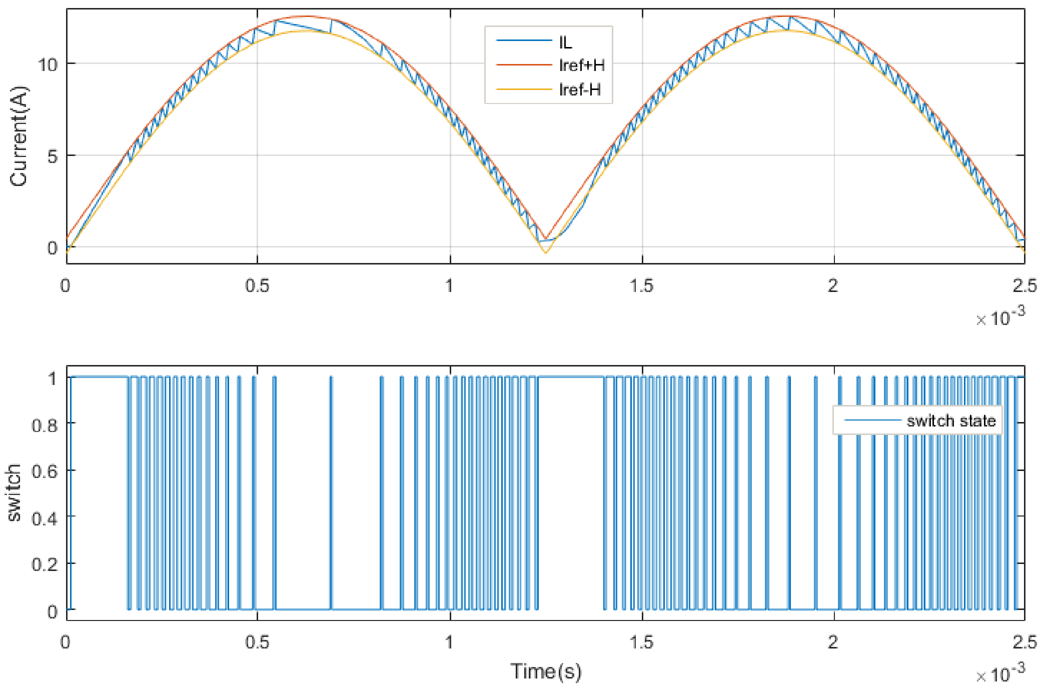

Fig 4 Switch State and current

As can be seen from this figure, when switch is on, the load is short circuit, so the current in the inductor will increase until bigger enough than reference value Iref+H. Then the switch turns off, the load is connected to the circuit. The current will charge the capacitor and supply the load, so it will decrease. Until the current goes less than the reference value Iref-H, the switch turn on again.

By measuring the transition point of the switch state, the approximate maximum switching frequency could be got. In this case it's about 81KHz.

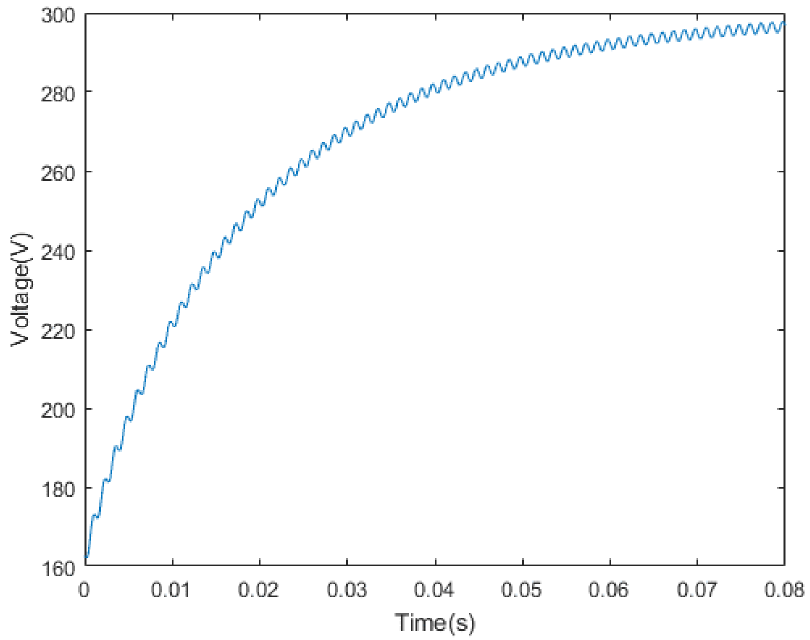

Fig 5 Voltage of the Load

We can see that the voltage goes up from 160v, which is the initial value we set in the integrator in the model, to about 300v as we expected. Though there is some fluctuation due to switching.

3.1.2 Compute the Hysteresis Value to Limit Switching Frequency

The relationship between H and phase θ is as below:

$$H = \frac{(\sqrt{2}V_{re}sin\theta - m \cdot L)(V_c - \sqrt{2}V_{re}sin\theta + m \cdot L)}{2F_d \cdot L \cdot V_c}$$

Where: F_d is the switching frequency, and $m = I_m \cdot \omega \cdot sin\theta$

The relationship between the duty cycle α and θ is as below.

$$\alpha = 1 - \frac{\left|\sqrt{2}V_{re}sin\theta\right|}{V_c}$$

From these equations, we could draw the figure below.

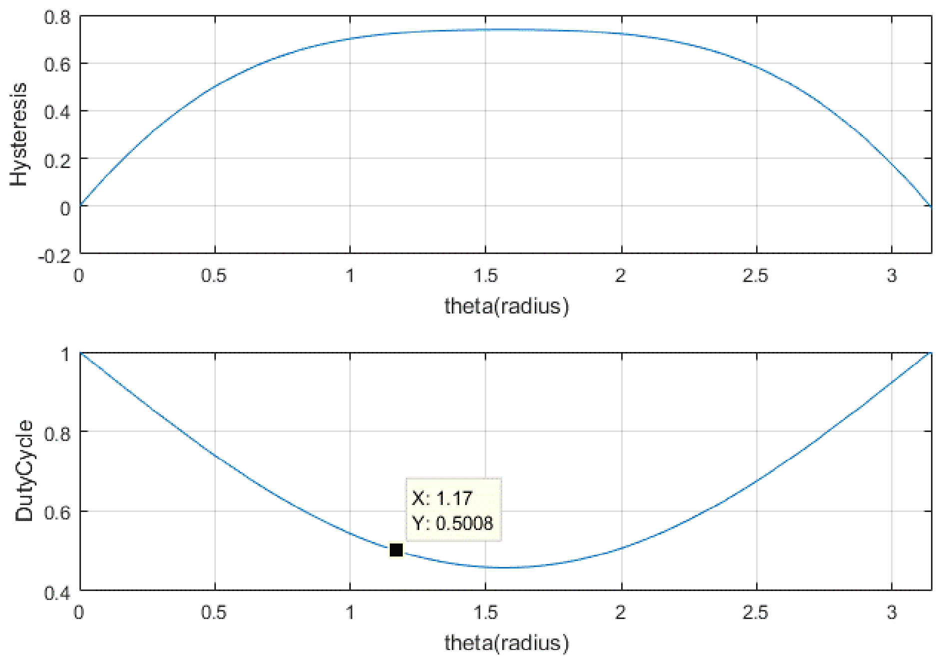

Fig 6 Relations between H and θ; α and θ

When $\alpha = 0.5$; we can get maximal switching, from the figure above, we get H = 0.7231 when $\alpha = 0.5$.

So the hysteresis value we need is 0.7231.

3.2 PWM Modulator Control

In this part a PWM modulator is used to operate the switch with a constant frequency Fd = 50KHz. The control part is as below (see the Simulink file [boostConverterCurrentB.slx]):

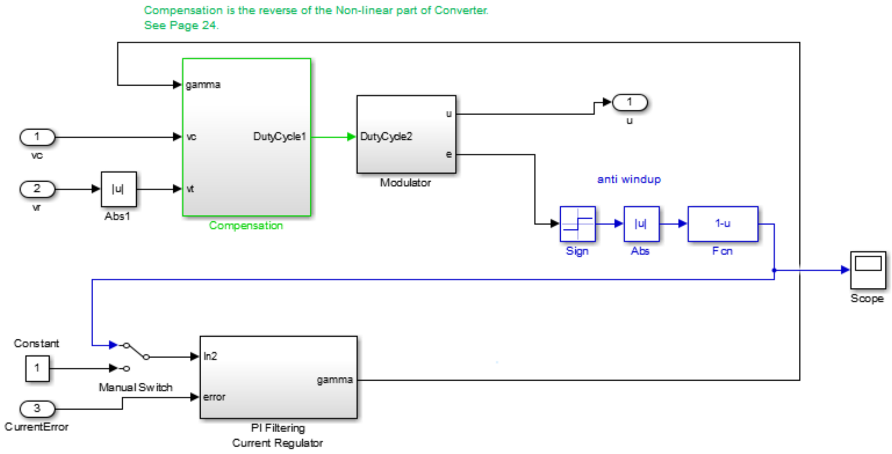

Fig 7 Control part of the boost converter

The three sub blocks in the model are shown as below:

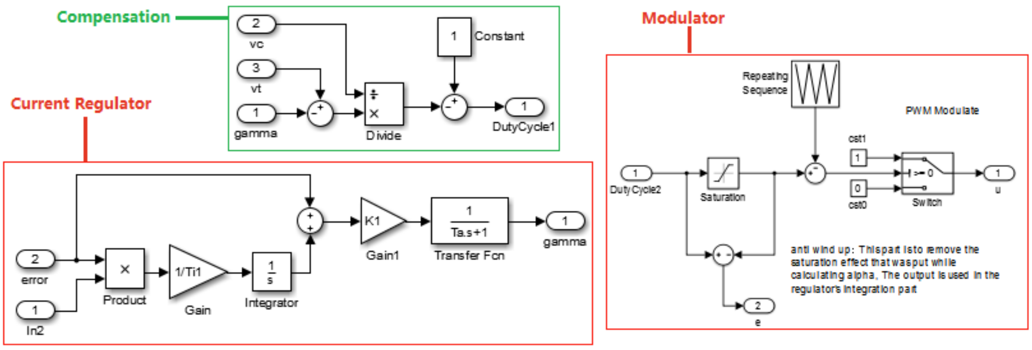

Fig 8 Detail of the Control Part

When the modulator error is saturated, the integration wind-up could be prevented in the current regulator. This function is implemented in the blue part of Fig7.

The gain of the control loop should be approximately 1. So the compensation part is the reverse form of the nonlinear part of the converter. And the gain of the current regulator and the transfer function $\frac{1}{Ls}$ should be reciprocal. The transfer function of current regulator is like below:

$$R_1(s) = K_1\left(\frac{1 + T_{i1} \cdot s}{T_{i1} \cdot s}\right)\frac{1}{1 + T_a \cdot s}$$

To obtain a band pass frequency: $F_{bpc} = 8KHz$

$$T_{i1} = \frac{\sqrt{10}}{2\pi \cdot F_{bpc}}$$

$$T_a = \frac{1}{2\pi \cdot F_{bpc} \cdot \sqrt{10}}$$

$$K_1 = L \cdot 2\pi \cdot F_{bpc}$$

We can simulate the model with or without the anti-windup by switch the manual switch. As can be shown below, the current in the inductor is almost the same. This is because the duty cycle seldom goes beyond the saturation limit.

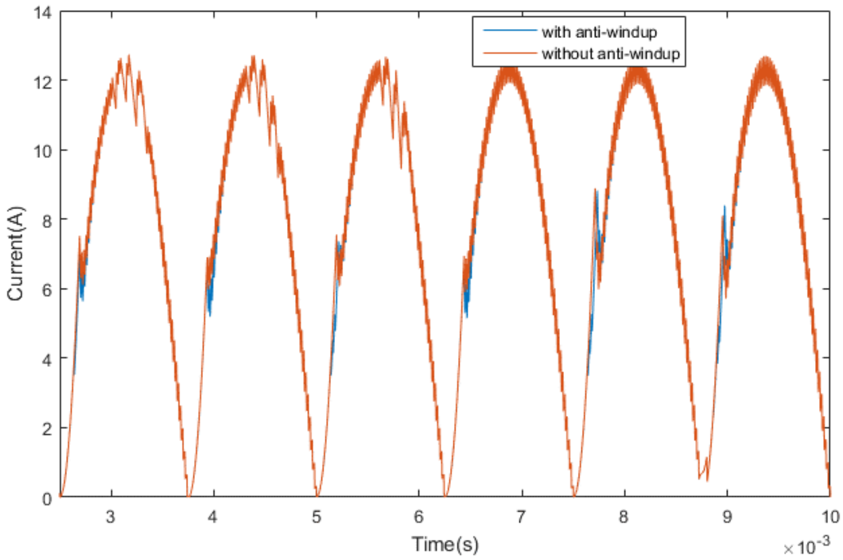

Fig 9 Inductor Current

4 VOLTAGE LOOP STUDY

In this section, A new voltage loop is created. The output is the reference current of the inductor, which will feed the input of the PWM modulator in section 3.2.

We want to get the transfer function between Iref and Vc. By neglecting the voltage of the inductor, we have：

$$\frac{dV_c}{dt} + \frac{1}{R \cdot C} V_c = \frac{1}{C} \cdot \frac{V_r}{V_c} \cdot I_{ref}$$

With this equation, the transfer function between V_c and I_{ref} could not be obtained. Nevertheless, with $x = V_c^2$, the equation above could be transformed to :

$$\frac{R \cdot C}{2} \cdot \frac{dx}{dt} + x = R \cdot V_r \cdot I_{ref}$$

So we get the transfer function between x and I_{ref}:

$$T_v'(s) = \frac{x(s)}{I_{ref}(s)} = \frac{R \cdot V_r}{\frac{R \cdot C}{2} \cdot s + 1}$$

Where $x = V_c^2$

A voltage regulator is added to the model like below (see Simulink model file boostConverterVoltage.slx):

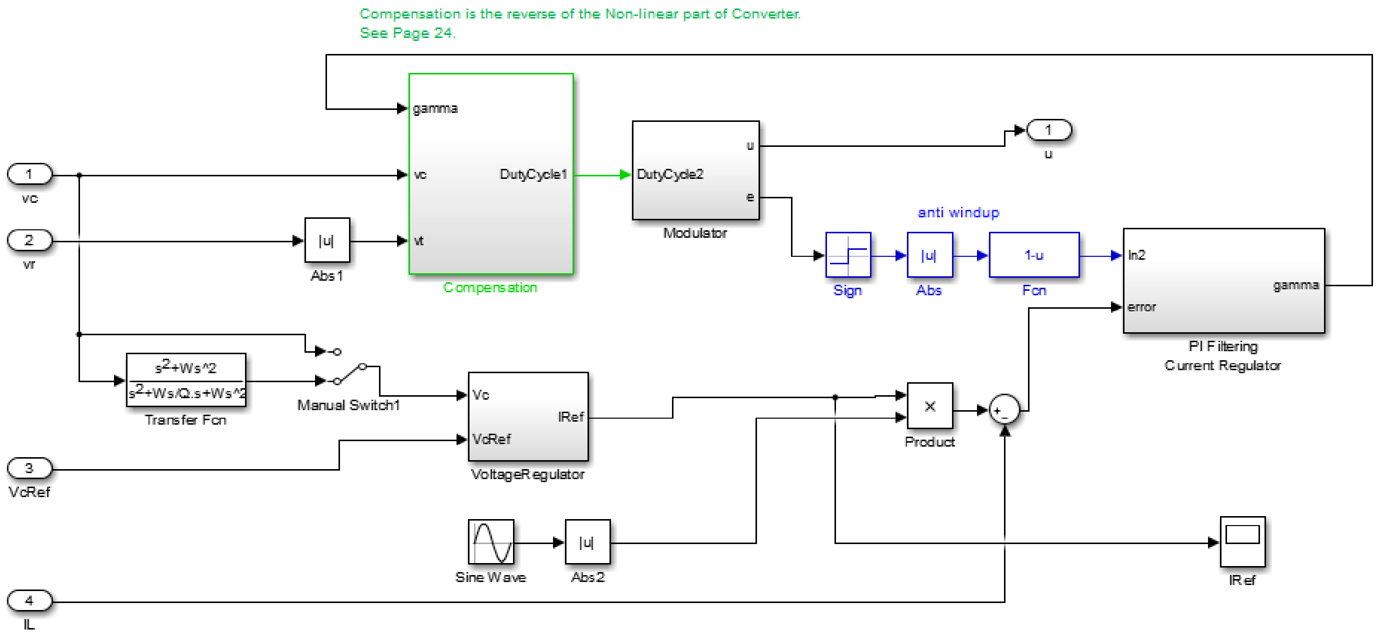

Fig 10 Voltage Loop Control Block

A notch filter is added after Vc to get a smooth Iref. The detail of the voltage regulator is as below.

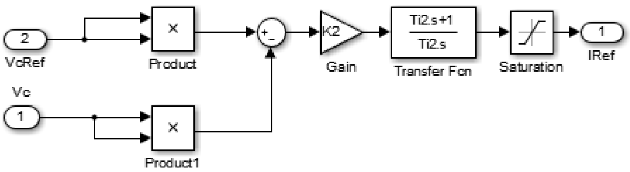

Fig 11 Voltage Regulator

4.1 Voltage regulator design

The input of the voltage regulator is the error between V_{cRef} and V_c, the output is I_{ref}. The transfer function of the regulator is:

$$R_2(\mathrm{s}) = K_2\left(\frac{1+T_{i2}\cdot s}{T_{i2}\cdot s}\right)$$

To obtain a band pass of $F_{bpv} = 80Hz$, with the same design method of current regulator, we have:

$$T_{i2} = \frac{\sqrt{10}}{2\pi \cdot F_{bpv}}$$

The gain of $R_2(\mathrm{s})$ at F_{bpv} should be reciprocal of $T_v'(s)$, so we have:

$$K_2 = \frac{2\pi \cdot F_{bpc} \cdot C}{2 \cdot \frac{2\sqrt{2}V_{re}}{\pi}}$$

4.2 Notch filter design

As can be analyzed from the simulation, the Vc has some variation. The frequency of this variation is twice of the AC source's frequency because of the rectifier. Due to this variation, the

Iref is not smooth enough. To improve the performance of the controller, a second order notch filter is added before the voltage regulator. The transfer function of this filter is as below:

$$F_r(\mathrm{s}) = \frac{s^2 + {\omega_s}^2}{s^2 + \frac{\omega_s}{Q} \cdot s + {\omega_s}^2}$$

Where ω_s is the stop band frequency, in our case: $\omega_s = 2\pi \cdot F_r$;

And Q (*quality factor*) is related to the bandwidth of the filter. It can be set: Q=2;

Difference of Vc before and after notch filter could be shown below;

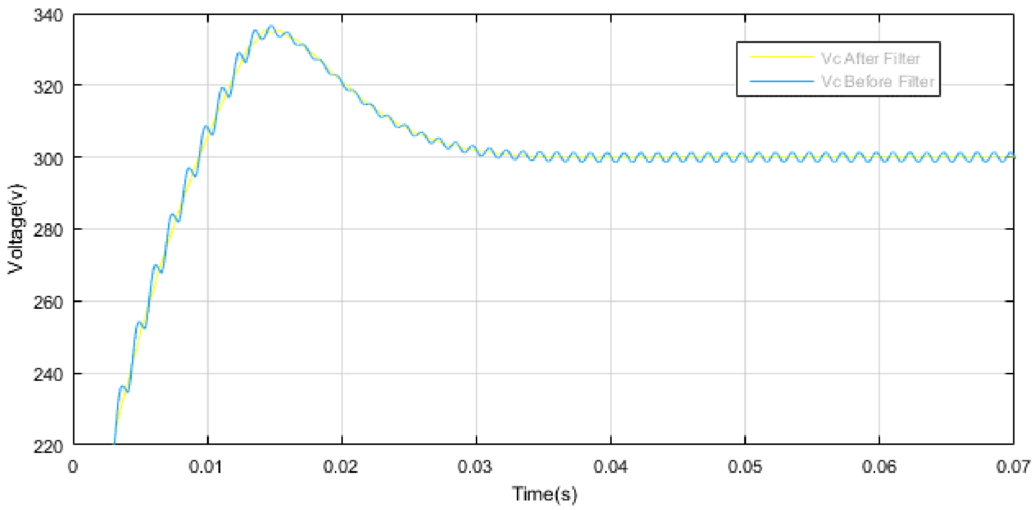

Fig 12 Vc Before and After Notch Filter

Defference of Vc; Iref with or with out nothch filter is shown below;

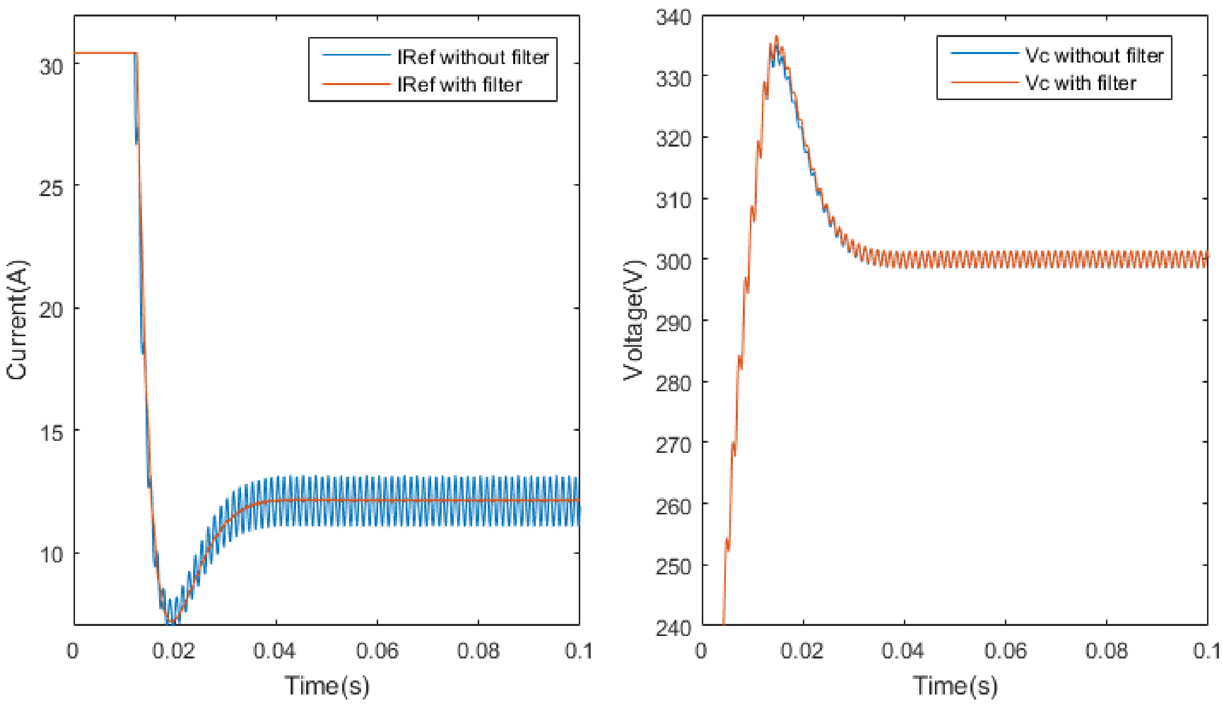

Fig 13 Defference of Vc; Iref with or without Notch Filter

It can be shown that with a notch filter, the load voltage becomes smoother.

5 DISTURBANCE TEST

Two kinds of disturbances of load it modeled in the Simulink model (see file boostConverterVoltageDisturbance.slx) by using signal builder.

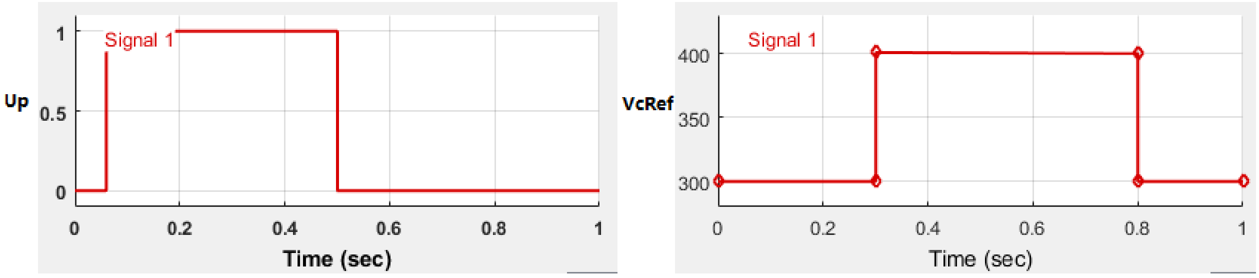

Fig 14 Input of Up and VcRef

The result can be seen as below:

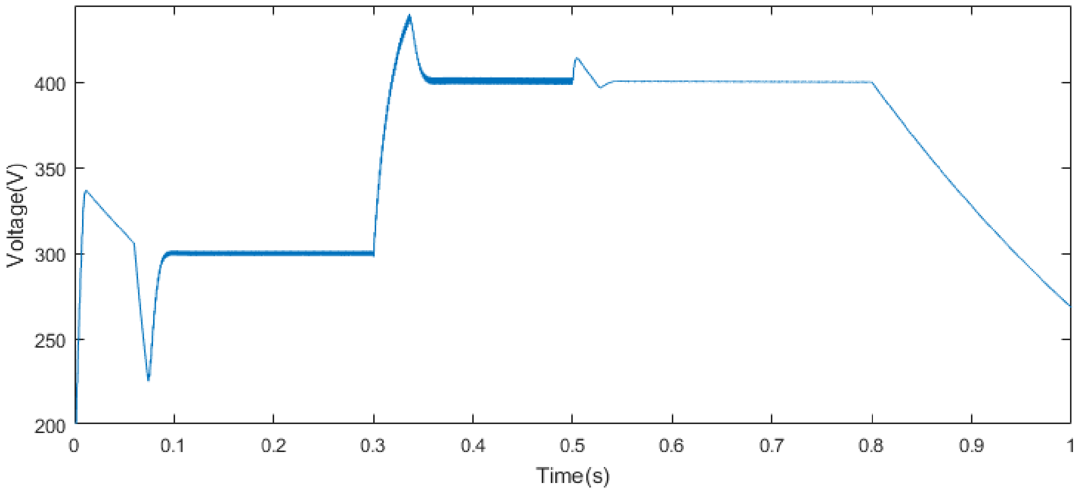

Fig 15 Output Vc with Disturbance Input

As can be seen from the simulation result, the Vc variation due to to the switch up in the load will recover quickly, while it will take longer time the recover from Vc reference value change.

6 CONCLUSION

This experiment demonstrates a power factor correction shemes where the first loop aims to regulate the boost dc output voltage and provide the amplitude for for the reference which controls sinusoidal current. A repetitive controller is inserted with PI controller. With this experiment we can observe that the Feed Forward current control method for boost signal phase PFC converters is a good way for power corrections. Using Simlink we have developed the current and voltage loop. Then in current loop we add modulation, convertor and a retifier to optimize and amplify the output.In the Voltage loop we add filters and rectifiers to smoothen the sinusoidal effect.

In this work shop, we have an integration study of several courses: control theory, power electronics, circuit analyze, etc. It's quite interesting that these models have very practical meaning to industrial applications and could be simulated and optimized in our class.