Implementing Closed Loop Control For Boost Converter

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***Abstract*— This project identifies the use of a Proportional Integral controller for the closed loop control of Boost converter. Many devices all around the world make use of a direct current voltage to operate. However, at times, a voltage level higher than the one provided as input is required. For such cases, the Boost DC-DC converter is brought into use. The proposed Proportional Integral (PI) controller controls the Boost DC-DC converter to regulate the output voltage. The required equations along with a detailed description of the working of the Proportional Integral controller have been given. The simulation for Boost converter and PI controlled Boost converter using MATLAB SIMULINK have also been attached.**

***Keywords*— Boost converter, PI controller**

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I. Introduction

Electronic components are designed with specific performance characteristics suiting the target applications. In various industrial applications, there arises a requirement to obtain an output DC voltage level different from the input DC voltage level. This is where DC-DC converters are brought into use. These high voltage gain converters are employed in multiple sophisticated applications, including data centers, DC distribution systems, and radar systems. Quite analogous to the AC transformer with a turns ratio that can be varied as per requirement, the DC-DC converter steps up or steps down the DC voltage level of the input provided. In this project, a Proportional Integral (PI) controller is used for the Boost converter which steps up the supply voltage and provides a constant DC output which can then be used in various industrial applications.

II. Step–Up DC-DC Converters

Step-up DC-DC Converters can produce voltage higher than the provided input voltage. Boost converters are used wherever we cannot provide a high enough input voltage with batteries or there is not enough space for accommodating more batteries.

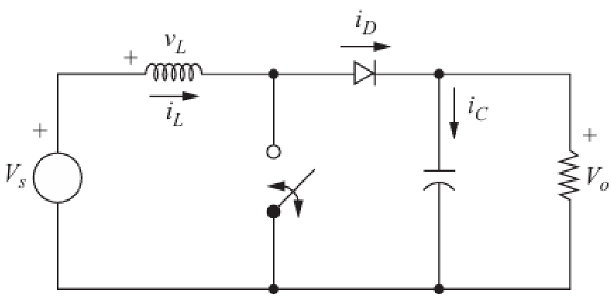

Fig. 2.1 Circuit Diagram for Boost Converter

A. *Steady State Analysis of Boost Converter*

The analysis of the converter assumes the following:

1. The components are ideal.
2. The capacitor is very large
3. The inductor current is continuous and always positive.
4. The switch is closed for time D*T and open for (1-D) * T, where the switching period is T.
5. Steady-state conditions exist.
6. The output voltage is held constant at voltage Vo.

Here, D is the duty cycle of the gating pulse provided to the switch which may be a MOSFET or an IGBT.

We examine the inductor voltage and current for the closed switch and again for the open switch. We can classify the working of the Boost converter into two different modes:

Mode I: In this mode, the switch is turned ON. The input current, which begins to rise, flows through the inductor and the switch.

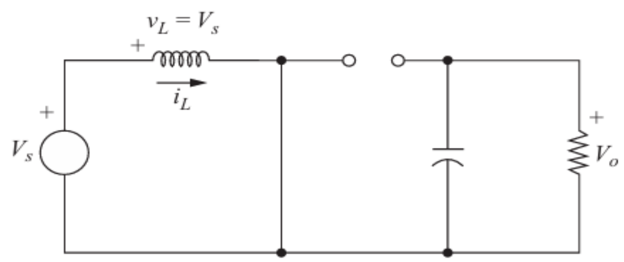

Fig. 2.2. Circuit Diagram for Boost Converter with switch closed

As shown in the above figure, when the switch is closed, a negative voltage appears across the diode, and it enters the reverse biased mode. If we apply Kirchhoff's voltage law appropriately, we obtain the following equations:

$$v_L = V_s = L\frac{di_L}{dt} \quad \text{or} \quad \frac{di_L}{dt} = \frac{V_s}{L}$$

By making certain approximations in the change of the inductor current equation, we can derive the following equations:

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{\mathrm{DT}} = \frac{Vs}{L}$$

Solving for i_L for the switch closed,

$$(\Delta iL)closed = \frac{VsDT}{L}$$

Mode II: The switch is open during this mode. Current starts flowing through the inductor, the diode, the capacitor and the capacitor connected across the load. The polarity across the inductor reverses and it starts discharging through the load.

The inductor current starts decreasing. After the inductor has completely discharged, the switch may be turned ON again for the converter to enter Mode I again. Also, the energy stored in the capacitor is conveyed to the load.

The following figure represents the converter in Mode II.

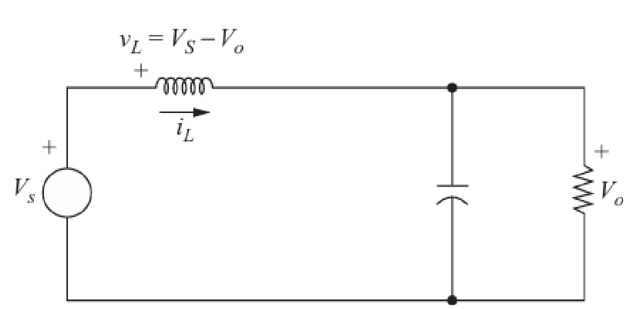

Fig. 2.3. Circuit Diagram for Boost Converter with switch open

We also obtain the given equations:

$$v_L = V_s - V_o = L\frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{V_s - V_o}{L}$$

The current changes linearly as the rate of change of this current does not change while the switch is on. When the switch is open,

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{\text{(1-D)T}} = \frac{V_S - V_O}{L}$$

The net change in iL must be zero. So,

$$(\Delta i_L)_{\text{closed}} + (\Delta i_L)_{\text{open}} = 0$$

$$\frac{V_s DT}{L} + \frac{(V_s - V_o)(1-D)T}{L} = 0$$

For Vo,

$$V_S(D - D + 1) - V_O(-D + 1) = 0$$

$$V_O = \frac{V_S}{1-D}$$

Since 0<D<1, the output is greater than or equal to the provided input voltage.

B. SMALL SIGNAL ANALYSIS OF BOOST CONVERTER

For the small signal analysis of Boost converter, we take the following assumptions into consideration:

•The switch is closed for time D*T and open for (1-D)*T, where T is the switching time.

• For the current to be considered constant throughout the operation of the converter, the inductor taken is of large enough value.

• The capacitor is very large, and the output voltage is held constant.

$$\begin{bmatrix} L\dfrac{di_l(t)}{dt} \\ C\dfrac{dV(t)}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\dfrac{1}{R} \end{bmatrix} \begin{bmatrix} i_l(t) \\ V(t) \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \begin{bmatrix} V_g(t) \\ 0 \end{bmatrix} \qquad (1)$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} i_l(t) \\ V(t) \end{bmatrix} y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} i_l(t) \\ V(t) \end{bmatrix} \qquad (2)$$

$$\begin{bmatrix} L\dfrac{di_l(t)}{dt} \\ C\dfrac{dV(t)}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ 1 & -\dfrac{1}{R} \end{bmatrix} \begin{bmatrix} i_l(t) \\ V(t) \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \begin{bmatrix} V_g(t) \\ 0 \end{bmatrix} \qquad (3)$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} i_l(t) \\ V(t) \end{bmatrix} y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} i_l(t) \\ V(t) \end{bmatrix} \qquad (4)$$

The state-space averaging technique can be employed to obtain the average of both the ON-state and OFF-state equations.

State-space representation of state variables is shown below

$$\dot{X} = Ax + Bu \; \dot{X} = Ax + Bu \qquad (5)$$

$$y = Cx + Du \; y = Cx + Du \qquad (6)$$

Let us assume D=0. We perform state space averaging,

A = A1×D + A2×D/

B = B1×D + B2×D/

C = C1×D + C2×D/

Finally, we get the matrices and the dynamic equations in state space representation:

$$A = \begin{bmatrix} 0 & -D' \\ D' & -\dfrac{1}{R} \end{bmatrix}; B = \begin{bmatrix} 1 \\ 0 \end{bmatrix};\; c = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

$$\begin{bmatrix} L\dfrac{di_l(t)}{dt} \\ C\dfrac{dV(t)}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -D' \\ D' & -\dfrac{1}{R} \end{bmatrix} \begin{bmatrix} i_l(t) \\ V(t) \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} V_g(t) \qquad (7)$$

$$\mathbf{y} = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} i_l(t) \\ V(t) \end{bmatrix} \qquad (8)$$

We can obtain the steady state solution by putting,

$\dot{X}$ =0 and using,

X= $A^{-1} \times B \times U$

Then from equation labelled (7), the relation

$$V = \frac{V_g}{1-D} \qquad (9)$$

Is obtained. Linearization of the constructed small signal model is performed about the steady state operating point to obtain the transfer function of the system. The following equations are used for linearization:

$$\hat{X} = A\hat{x} + B\hat{u} + \{(A_1 - A_2)X + (B_1 - B_2)U\}\hat{d}$$

$$A1 - A2 = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix};\; B_1 - B_2 = 0$$

$$\begin{bmatrix} L\dfrac{d\hat{i_l}(t)}{dt} \\ C\dfrac{d\hat{V}(t)}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -D' \\ D' & -\dfrac{1}{R} \end{bmatrix} \begin{bmatrix} \hat{i_l}(t) \\ \hat{V}(t) \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \begin{bmatrix} \hat{V_g}(t) \\ 0 \end{bmatrix} \begin{bmatrix} V \\ -I \end{bmatrix} \hat{d}$$

Upon solving the last equation given above using Laplace transform and further making v^g(s) equal to zero, we obtain the transfer function between the control input and output voltage as given in the following equation:

$$\frac{\hat{v}(s)}{\hat{d}(s)} = \frac{-\dfrac{I}{C\left[s - \dfrac{D' * V}{I * L}\right]}}{\left[s^2 + \dfrac{s}{c * R} + \dfrac{D'^2}{L * C}\right]}$$

III. PROPORTIONAL INTEGRAL CONTROLLER

The use of Proportional Integral controller is made in those industrial applications and control systems where proportional control is necessary to speed up the settling of the output at its steady state value and, further, integral control is required to reduce the steady state error.

The controller is essentially a closed-loop feedback control mechanism that is used to adjust the variable used in the controlling process by manipulating the value of the variable based on the error between the output value and the expected value.

Two terms are used to define the working of a PI controller.

i) Proportional term

ii) Integral term

The Proportional controller gives an output which is directly proportional to the error signal fed back to the controller. There may be a chance of generation of offset, which we may describe as a drift from the set point, while working with a Proportional controller. As increase in the gain of the controller keeps on occurring, the system might become unstable. To prevent this from happening, the Integral part of the controller is introduced. It removes the steady state error.

The method of changing the parameters of the controller to obtain the desired output from the system is called Controller tuning. We employ this method to ensure minimum deviation of the output from the set point.

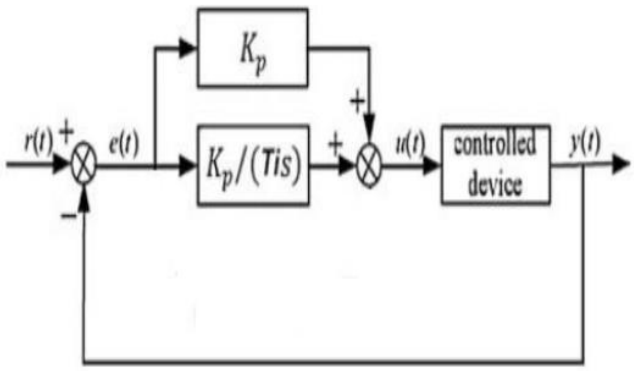

Fig. 3.1. Block Diagram for Proportional Integral Controller

A. PI CONTROLLED BOOST CONVERTER

In the given circuit diagram, we observe that our main components are the PI controller, the Boost converter and the PWM generator.

Any change in the input may lead to changes in the output. To obtain a constant DC voltage as the output, the output generated by the Boost converter is fed to a comparator which compares it with a reference signal. The output given by the comparator is the error signal. The error signal is then given to the PI controller.

The controller generates an output which is compared again with a triangular waveform generated by a pulse width modulation (PWM) generator. The pulses produced thus are used to commute the MOSFET used as the switch i n the Boost converter. The PI controller regulates the output voltage. The output voltage is thus controlled to produce the required output voltage.

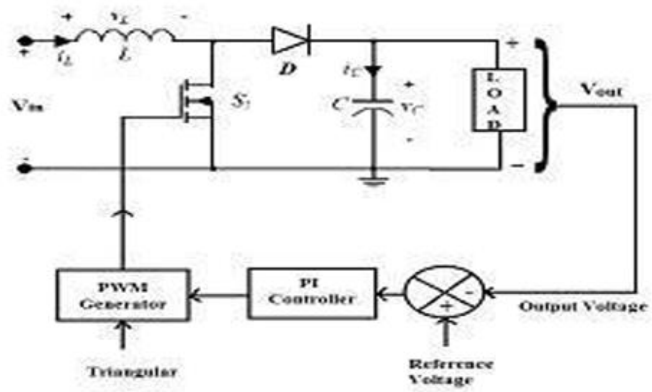

Fig. 3.2. Block Diagram for PI controlled Boost Converter

IV. BOOST CONVERTER DESIGN

The average power supplied by the source must be the same as that absorbed by the load. We make use of this fact to determine the current in the inductor. So, output power is determined as

$$P_o = \frac{V_o^2}{R} = V_o I_o$$

and input power is $V_sI_s = V_sI_l$. Upon equating both the powers, we get

$$V_s I_L = \frac{V_o^2}{R} = \frac{[V_s/(1-D)]^2}{R} = \frac{V_s^2}{(1-D)^2} R$$

For I_1, we get,

$$\boxed{I_L = \frac{V_s}{(1-D)^2 R} = \frac{V_o^2}{V_s R} = \frac{V_o I_o}{V_s}}$$

Also,

$$I_{\max} = I_L + \frac{\Delta i_L}{2} = \frac{V_s}{(1-D)^2 R} + \frac{V_s DT}{2L}$$

$$I_{\min} = I_L - \frac{\Delta i_L}{2} = \frac{V_s}{(1-D)^2 R} - \frac{V_s DT}{2L}$$

I_{min} must be positive. This condition should be essentially fulfilled for continuous inductor current. The following equation is used to determine the breaking point between continuous and discontinuous current though the inductor

$$I_{\min} = 0 = \frac{V_s}{(1-D)^2 R} - \frac{V_s DT}{2L}$$

$$\frac{V_s}{(1-D)^2 R} = \frac{V_s DT}{2L} = \frac{V_s D}{2Lf}$$

Thus,

$$(Lf)_{\min} = \frac{D(1-D)^2 R}{2}$$

$$\boxed{L_{\min} = \frac{D(1-D)^2 R}{2f}}$$

Inductor value must always be greater than $L_{min.}$
Also

$$L = \frac{V_s DT}{\Delta i_L} = \frac{V_s D}{\Delta i_L f}$$

The capacitor current waveform can be used to calculate the peak-to-peak output voltage ripple. The change in capacitor charge can be calculated from

$$|\Delta Q| = \left(\frac{V_o}{R}\right) DT = C\Delta V_o$$

Ripple voltage is

$$\Delta V_o = \frac{V_o DT}{RC} = \frac{V_o D}{RCf}$$

$$\boxed{\frac{\Delta V_o}{V_o} = \frac{D}{RCf}}$$

where f is the switching frequency. We can also write,

$$C = \frac{D}{R(\Delta V_o / V_o) f}$$

DESIGNING PARAMETERS OF OPEN LOOP BOOST CONVERTER

Vs = 12V
Vo = 24V
Output power Po = 100W
Switching Frequency Fs = 25KHz
Duty cycle D = 50%
L = 144×10^-06 H
C = 69.44 ×10^{-6} F
R = 5.76 Ω

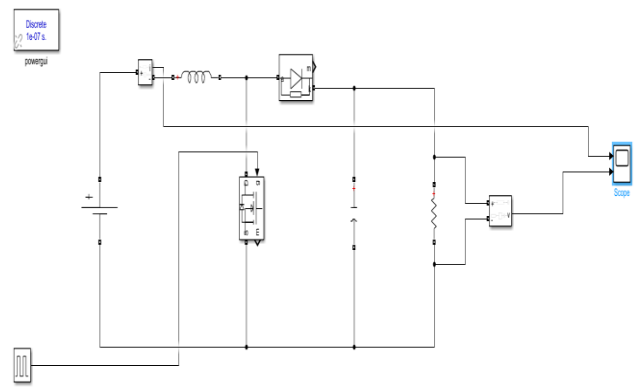

Fig. 4.1. Simulation of Open Loop Boost Converter

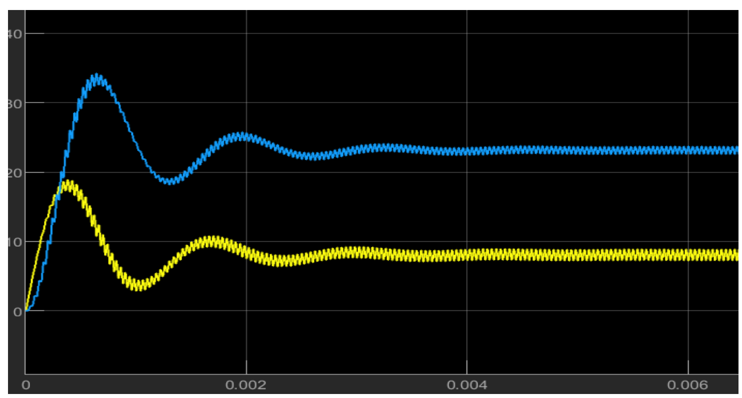

Fig. 4.2. Output Voltage (blue) and Input Current (yellow)

V. Designing Parameters of Boost Converter with PI Controller

Vs = 12V
Vo = 24V
Output power Po = 100W
Switching Frequency Fs = 25KHz
D = 50%
L = 144×10^{-6} H
C = 69.44 ×10^{-6} F
R = 5.76 Ω

Using above values to get the transfer function of boost converter. We get transfer function of boost converter with PI controller as

$$\frac{-0.0012\ s + 12}{1e{-}08\ s^2 + 2.5e{-}05\ s + 0.25}$$

MATLAB code of this transfer function to get bode plot, root locus and step response:

```
>> Vs=12;
>> Vo=24;
>> Po=100;
>> Fs=25000;
>> D=(Vo-Vs)/Vo;
>> R=Vo*Vo/Po;
>> Io=Vo/R;
>> I1=Io/(1-D);
>> dV=0.05*Vo;
>> C=(D*Io)/(Fs*dV);
>> dI=0.2*I1;
>> L=(D*Vs)/(Fs*dI);
>> num=[(-1)*I1*L Vo*(1-D)];
>> den=[L*C L/R (1-D)^2];
>> G=tf(num,den);
>> sisotool(G);
```

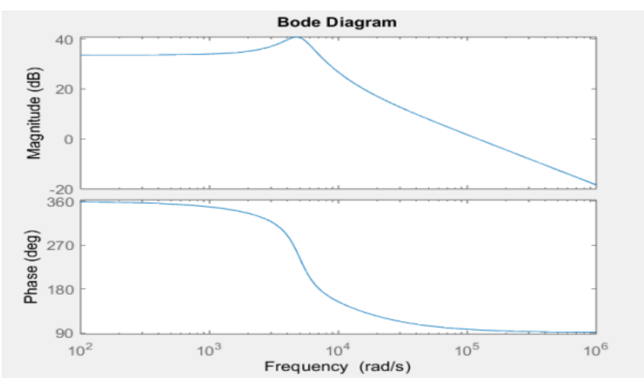

Fig. 5.1. Bode Plot of the obtained Transfer Function of the System

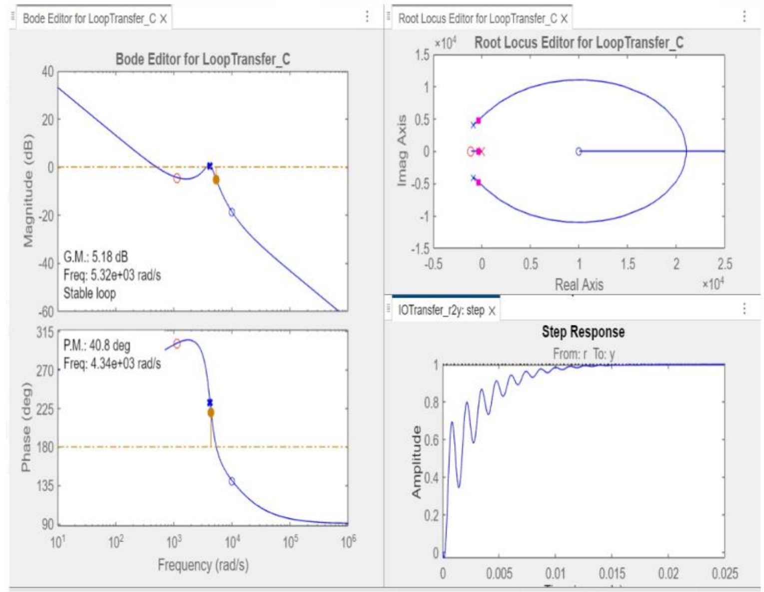

Fig. 5.2. Bode Diagram, Root Locus Plot and Step Response Plot obtained for the controller using SISO tools in MATLAB

Using MATLAB, we obtain the following transfer function for the PI controller,

$$9.3542 \times \frac{(1 + 0.00087s)}{s}$$

Comparing this with the transfer function ($K_p + K_i/s$), we obtain the values of $K_p = 0.008138$ and $K_i = 9.350562$. We finally, get the steady state value of the output voltage across the load resistance as 24.07 V.

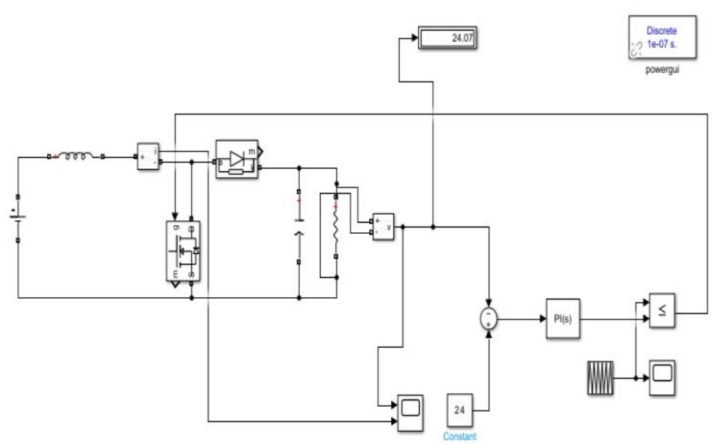

Fig. 5.3. Simulation of PI controlled Boost Controller

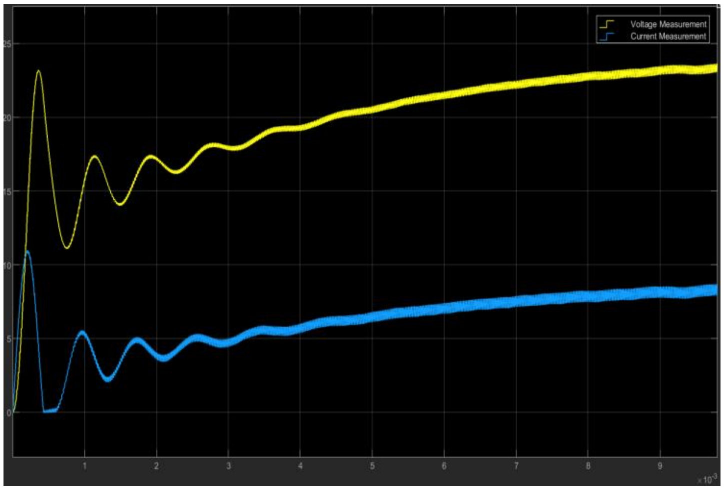

Fig. 5.4. Output Voltage (yellow) and Input Current (blue) for PI controlled Boost Converter

VI. Applications of Boost Converter

Boost converters find extensive use in industrial applications because of their efficient working. Some ways they are commonly found are:

1. Electric Vehicles: Suitable increased voltage levels are required for driving the electric motor and other systems of the vehicles. Boost converter plays a crucial role in doing so.

2. Systems which run on solar energy: In solar energy systems, proper optimization of power output is required. This is done by matching the voltage of the solar panel with the voltage of the ideal voltage required to charge the battery.

3. Power Supplies: Electronic devices like smartphones, laptops, etc. make use of Boost converters which are integrated in the power supply being used.

4. LED (Light Emitting Diode) Lighting: There is a requirement of a consistent and continuous current for LED lights for proper functioning. Boost converters are thus used here to ensure steady voltage output.

5. Portable Devices: Various portable devices like power banks and GPS units make use of Boost converters to convert lower input voltages into higher output voltages.

VII. CONCLUSIONS

Through this project, we can derive the conclusion that a PI controlled Boost converter is used to get constant voltage as output. We can tune the controller to obtain optimum values of K_p and K_i using MATLAB tools to obtain the output of the system as per our requirements. By comparing the output from the converter with a reference triangular wave, the PWM generator produces pulses which then control the switching ON and OFF of the switch brought into use by us in the circuit. Finally, we obtain the required output voltage.

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