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ANALYSIS OF BOOST CONVERTER WITH REFERENCE TO PHOTOVOLTAIC SYSTEMS

Mr. Rajesh Kumar [1], Mr. Mirza Omar Beg [2], Dr. Vipin Kumar [3]

[1, 3] Department of Electrical Engineering, UIET Rohtak, M.D. University Rohtak
[2] Integration Advisor, Shell, The Hague, South Holland, Netherlands
Email: - rjesh10391@gmail.com [1] , omarbeg@gmail.com [2], drvipin.uiet@mdurohtak.ac.in [3]

Abstract— Recent studies have shown that there is considerable modernization. This modernization has led to increase in the energy usage. And the majority of energy usage till today is via coal/thermal power plants, this is causing major concerns in the environment. Also these resources are limited. This becomes the prime factor for the economies to invest in renewable energy sources. Out of which solar is predominant in Indian subcontinent. However due to it varying nature, it can cause non linearity. Hence the authors have analyzed these non linearity in photovoltaic system from the converters end. With the aid of MATLAB simulation boost converters transfer function is framed and tested for Bode as well as root locus plots. After that various controller are explored namely PID controller and Type 3 compensator. Finally hardware for boost converter is designed and its effect on input voltage variation is seen.

Keywords— Renewable Energy, Solar Energy, Photovoltaics, MATLAB, PID, Type 3 Compensator, Boost Converter

Introduction

It is evident in today's world that there is tremendous technological growth, which has led to significant increase in production, as can be clearly seen from the Fig.1 and Fig. 2 [1].
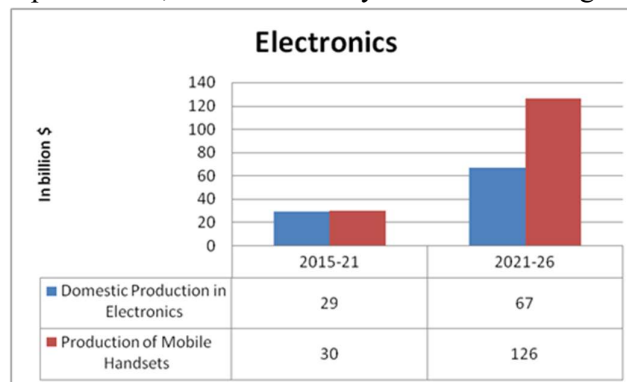

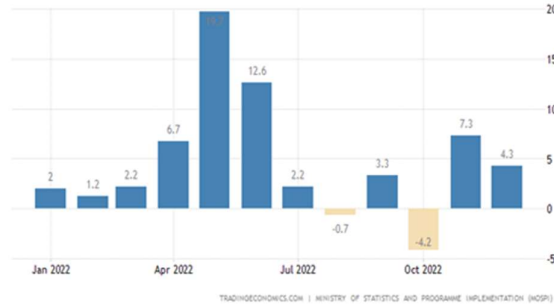Fig. 1: Production of Electronics over the Years

Fig. 2: Industrial Growth in India

With this escalation in technology, it can be inferred that the demand for energy has also increased, which is clearly evident from the Fig. 3 [2]. However when the energy composition is observed from the Fig. 4, it can be seen that to date, the majority of the energy production is via coal fired power plants.
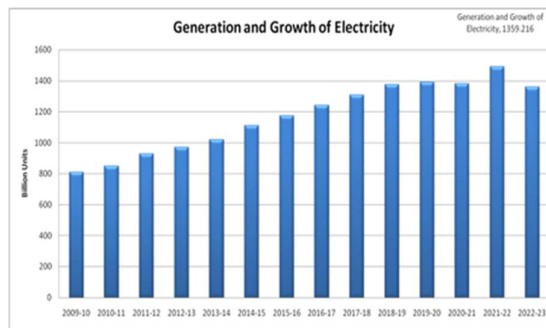

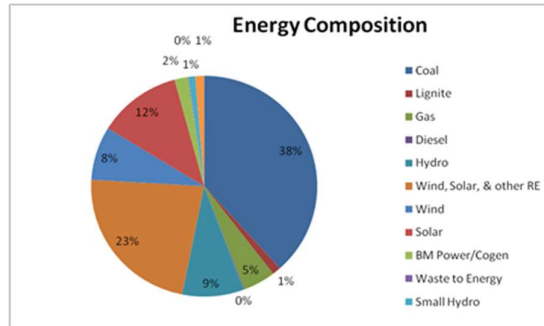Fig. 3: Generation and Growth of Electricity

Fig. 4: Energy Composition

As fossil fuels are conventional resources and the discovery of reserves takes time, it becomes important to switch to renewable energy sources, especially due to pollution concerns. Moreover, it can be seen from the Fig. 5 that the growth of renewable energy has increased over the years.
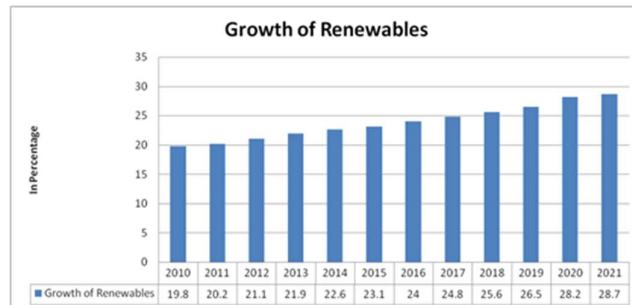
Fig. 5: Growth of Renewable in India

Among renewable energy sources, solar seems to have experienced significant growth in the Indian subcontinent, for the stated reasons:

As is known, India is located in the tropical region and receives abundant sunlight throughout the year. Even on cloudy days, solar panels can generate a significant amount of electricity. The decrease in cost over the years has made the solar power more affordable than other renewable energy sources such as wind or hydro. Since solar energy can be generated at the point of consumption, it helps in reducing the need for expensive transmission infrastructure, which aids in improving access to electricity in remote and rural areas of the country.

As we know, solar insolation changes throughout the day, which causes non-linearities. These non-linearities are analyzed through control system parameters, such as time domain analysis and frequency domain analysis. The analysis is conducted on boost converter's end. Various types of controllers and compensators are designed accordingly, and hardware is finally modelled for the boost converter.

[Organization]

Boost Converter

As implied by the name, a boost converter plays an important role in increasing voltage levels, i.e. higher than the input voltage. This function is achieved by periodically opening and closing an electronic switch. The components of boost converter include a DC voltage source, inductor L, switch S, diode D, capacitor C, and resistive load. The circuit diagram for the boost converter is shown below in the Fig. 6.

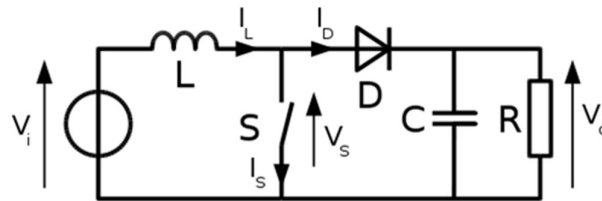

Fig. 6: Boost Converter

The boost converter can be mathematically modelled using turn on and turn off conditions. When the switch is on

$$L\frac{di_L}{dt} = V_i \qquad (1)$$
$$C\frac{dV_C}{dt} = \frac{-V_0}{R} \qquad (2)$$

Which may be written as

$$\frac{di_L}{dt} = \frac{V_i}{L}$$

$$\frac{dV_0}{dt} = \frac{-V_0}{RC}$$

Similarly when the switch is off:

$$\frac{di_L}{dt} = \frac{V_i - V_0}{L}$$

$$\frac{dV_0}{dt} = \frac{i_L}{C} - \frac{V_0}{RC}$$

Since the rate of change is constant we have:

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t}$$

Over the switching cycle average inductor must be zero, therefore we have;

$$(\Delta i_L)_{on} - (\Delta i_L)_{off} = 0$$

$$\Rightarrow \frac{V_i DT}{L} - \frac{(V_i - V_0)(1 - D)T}{L} = 0$$

This equation may be used to represent duty cycle as

$$D = 1 - \frac{V_i}{V_0}$$

Now these equations may be combined as :

$$\frac{di_L}{dt} = \frac{V_i - SV_0}{L}$$

$$\frac{dV_0}{dt} = \frac{Si_L}{C} - \frac{V_0}{RC}$$

Where S represents the switch action as

$$S = \begin{cases} 0, & Switch\ is\ on \\ 1, & Switch\ is\ off \end{cases}$$

Using these equations the boost converter can be mathematically modelled as shown in Fig. 7.
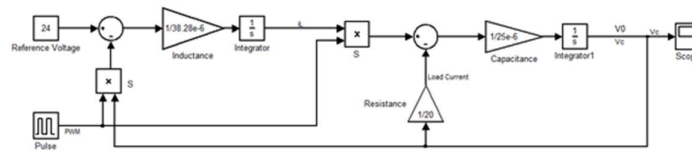

Fig. 7: Mathematical Modeling for Boost Converter

To design the boost converter, we need to compute the minimum required inductor and capacitor for a given set of parameters such as switching frequency, duty cycle and load resistance. This can be done by following these steps: first, calculate the output voltage and input voltage of the converter. Next determine the desired ripple current and voltage for the output. Then, use these values to calculate the minimum required inductor and capacitor. Finally, verify that the selected components meets the desired specifications and make any necessary adjustments.

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

$$C_{min} = \frac{D}{R(\Delta V_0/V_0)f}$$

Due to variation in solar radiation, the input voltage to the system fluctuates, resulting in a non-constant duty cycle. For the following experiment, the open circuit voltage is set to 21V DC, and it has been observed that the minimum duty cycle required is 12.5% to maintain the desired voltage.

The voltage and power values in this experiment justify selection of MOSFET for the boost converter. Hence the parameter for boost converter design is as shown in Table I:

Parameter	Value
Switching Frequency	250kHz
Inductor	38.28μH
Capacitor	25μF
Load Resistance	20 Ω
Reference Voltage	24Vdc

Table 1: Boost Converter Parameters

The circuit model of boost converter which is implemented in MATLAB is as shown below:
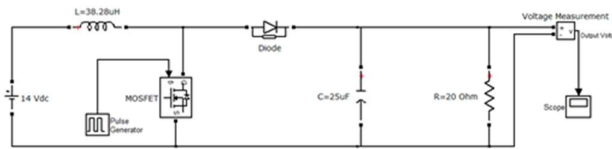

Fig. 8: Open Loop Circuit Model for Boost Converter

The gate pulse is generated by means of pulse generator block or by Sine- Triangle Pulse Width modulation and fed into the gate terminal of the state of MOSFET.

State Space Averaging

The essence of state space averaging is the averaging of the state space equations of a converter over one or more switching cycles.

The state space model for on and off of the boost converter is as follows:

For switch on:

$$\begin{bmatrix} \dot{i_L} \\ \dot{V_0} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -1/RC \end{bmatrix} \begin{bmatrix} i_L \\ V_0 \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \end{bmatrix} V_i$$

$$\downarrow \qquad\quad \downarrow \qquad\quad \downarrow \quad \downarrow$$
$$\dot{X} \qquad\quad A_1 \qquad\quad X \quad B$$
$$\uparrow \qquad\qquad\qquad\quad \uparrow \quad \uparrow$$

$$\begin{bmatrix} \dot{i_L} \\ \dot{V_0} \end{bmatrix} = \begin{bmatrix} 0 & -1/L \\ 1/C & -1/RC \end{bmatrix} \begin{bmatrix} i_L \\ V_0 \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \end{bmatrix} V_i$$

For switch off

Averaging over switching with $T_{on} = DT$ and $T_{off} = (1-D)T$ we have:

$$\dot{X} = \{A_1 D + A_2(1-D)\}X + BV_i$$

$$\Rightarrow \dot{X} = AX + BV_i$$

Where, $A = A_1 D + A_2(1-D)$

From these equations, resultant equations is

$$\begin{bmatrix} \dot{i}_L \\ \dot{V}_0 \end{bmatrix} = \begin{bmatrix} 0 & -(1-D)/L \\ 1-D/C & -1/RC \end{bmatrix} \begin{bmatrix} i_L \\ V_0 \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \end{bmatrix} V_i$$

For practical cases we know that inductor, capacitor, MOSFET and diode resistance may be introduced to make the model more versatile.

$$L\frac{di_L}{dt} = D[V_i - (R_L + R_{on})i_L] + (1-D)\left[V_i - \left(R_L + R_{on} + \frac{RR_C}{R+R_C}\right)i_L - \frac{V_0 R}{R+R_C}\right]$$

$$C\frac{dV_C}{dt} = D\left[-\frac{V_0}{R+R_C}\right] + (1-D)\left[\frac{R}{R+R_C}i_L - \frac{V_0}{R+R_C}\right]$$

Firstly, for convenience, the boost converter is modeled in an open loop configuration. Once the transfer function is obtained, a controller is designed for the closed loop system. Using the Embedded MATLAB function block, state equations are modeled with inputs including the input voltage (V_{in}) and duty cycle (D), while the outputs are voltage across the load (V_{out}). Additionaly inductor current (I_L) and capacitor voltage (V_c) are used as feedback. A subsystem named "Boost" is then constructed with inputs of V_{in} (input voltage) and control voltage ($V_{control}$).
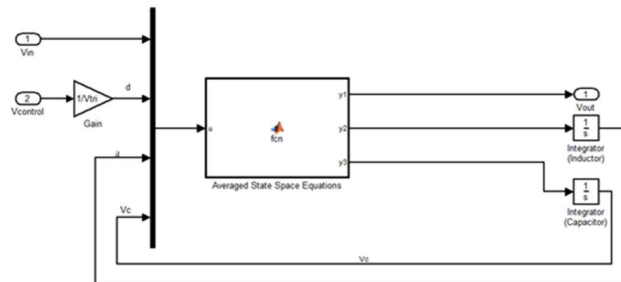

Fig. 9: Embedded MATLAB Function

Fig. 10: Subsystem Boost

To design a closed loop configuration, a feedback controller needs to be designed. This can be achieved by estimating the open loop transfer function of the boost converter. Two different methods can be used for estimating the transfer function. The first method involves introducing perturbation in the state spaced averaged model and subsequently developing the small signal model of the boost converter mathematically. The second method involves using MATLAB's linear analysis tool to generate the frequency response and transfer function of the open loop model of the boost converter.

For small signal model we introduce perturbation in the state variable and input of the state averaged boost converter model.

$x = X + \tilde{x}$

$d = D + \tilde{d}$

$v = V + \tilde{v}$

The new state equation hence becomes:

$\dot{\tilde{x}} = [A_1 D + A_2(1 - D)]\tilde{x} + [(A_1 - A_2)X]\tilde{d}$

And the output equation hence becomes:
$V_0 = CX$, where $C = [R \quad 0]$

Transfer function can hence be computed from:

$TF(s) = C[sI - A]^{-1}B$

Therefore the obtained transfer function is

$$\frac{\tilde{v}_0(s)}{\tilde{d}(s)} = \frac{(1 - D)V_0 - (Li_L)s}{LCs^2 + \frac{L}{R}s + (1 - D)^2}$$

The transfer function obtained can be linearized using an analysis tool which is given as:

$$\frac{\tilde{v}_0(s)}{\tilde{d}(s)} = \frac{-7.47 \times 10^4 s + 1.468 \times 10^{10}}{s^2 + 2000s + 3.762 \times 10^8}$$

Controller Design
The boost converter transfer function can be rearranged in order that it looks identical to:

$$\frac{\tilde{v}_0(s)}{\tilde{d}(s)} = K_0 \frac{1 - \frac{s}{\omega_r}}{1 + \frac{s}{Q\omega_0} + \frac{s^2}{\omega_0^2}}$$

The corresponding parameters are found to be

Transfer Function Parameter	Value

ω_r	$1965.5\ k\ rad\ s^{-1}$
ω_0	$19.4\ k\ rad\ s^{-1}$
Q	9.6979
K_0	39.02

Table 2: Transfer Function Parameters

For computing damping ratio we have,

$$\zeta = \frac{1}{2Q} = 0.0515$$

This gives the indication that the converter is severly undamped.
Furthermore, using a root locus plot, it has been revealed that the transfer function of the boost converter includes one zero located in the right half plane, making the system unstable. This zero has been found to be at ω_r.This instability can be quantified with the aid of Bode plot in terms of gain and phase margins.
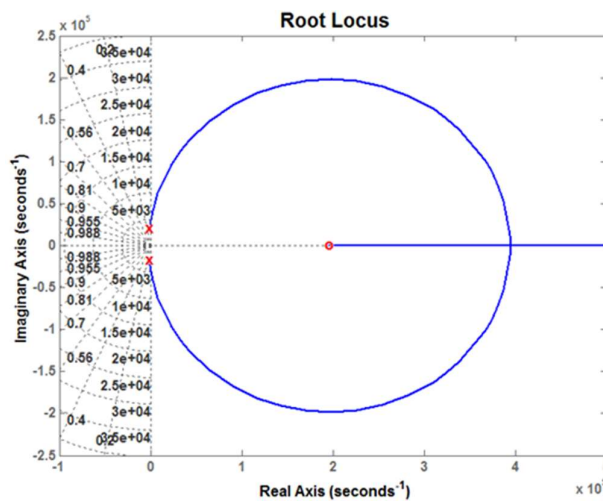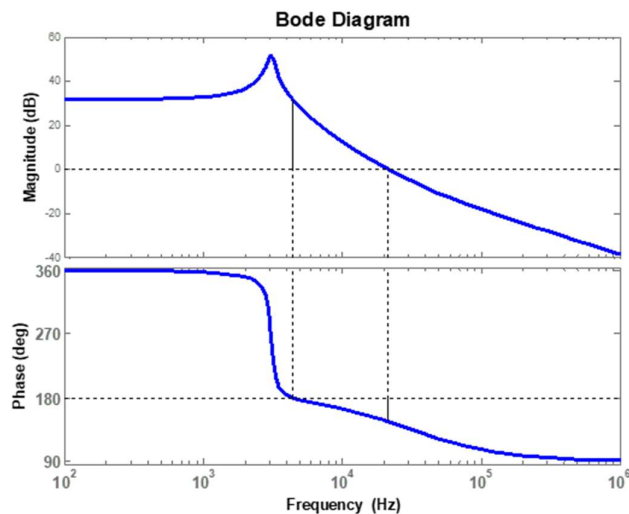

Fig. 11: Root Locus for Boost Transfer Function

Fig. 12: Bode Plot for Boost Transfer Function

The parameters obtained from Bode plot are as follows:

Stability Criterion	Value
Gain Margin	$-31.4\ dB$
Gain Crossover Frequency	$27.737\ k\ rad\ s^{-1}$
Phase Margin	-33.58^{0}
Phase Crossover Frequency	$134.83\ k\ rad\ s^{-1}$

Table 3: Bode Plot Margins

Since the open-loop boost converter transfer function contains zero in the right- hand plane, and negative phase and gain margins, we can conclude that the system is unstable.

PID Controller

To control the error signal, a PID controller block is being used in MATLAB. It includes a build in tuner that can determine proportional, integral and derivative gains.
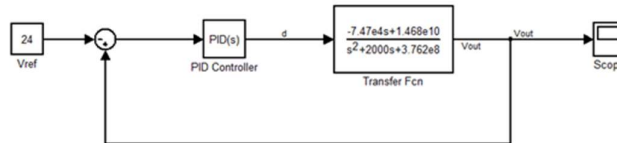

Fig. 13: PID Controller with Boost Transfer Function

The PID controller block uses the parallel type compensator formula:
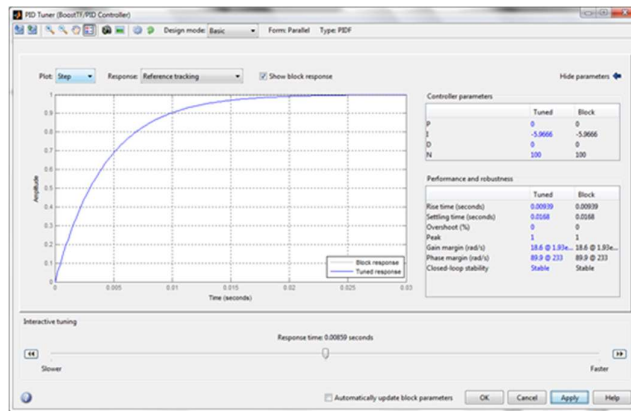
$$C(s) = P + I\frac{1}{s} + D\frac{N}{1 + N\frac{1}{s}}$$

Fig. 14: PID Tuner

The parameters of this PID controller are as follows:

PID Constants	Value
P	0
I	-5.96664
D	0
N	100

Fig. 15: PID Gain Parameters

Since these values are highly impractical other controllers are hence explored.

Type 3 Compensator
 The Type 3 compensator combines the advantage of Lag (PI) and Lead (PD) compensators. It is designed to offset the sharp phase drop that occurs after a resonant pole, which is achieved by adding a zero and pole to the transfer function. Therefore Type 3 compensator can be used to improve the phase margin of the system. In order to decide sufficient phase margin of the final compensated system we use,

$$\varphi_m = \tan^{-1} \sqrt{\frac{1 + \sqrt{1 + 4Q^4}}{2Q^4}}$$

From this equation it is evident that phase margin is the function of damping ratio. 52^0 is the minimum required phase margin found for critical damping of the system , $\zeta=1$. The transfer function of typical Type 3 compensator is given by:

$$C(s) = K_C \frac{\left(1 + \frac{s}{\omega_z}\right)^2}{s\left(1 + \frac{s}{\omega_p}\right)^2}$$

The desired crossover frequency is selected such that it lies between the resonant pole and RHP zero. Hence the required crossover frequency may be approximated as:

$$3f_0 < f_c < \frac{1}{3}f_r$$

From Fig.12, it is noted that the crossover frequency is 10.4KHz and phase margin is found to be $\emptyset=163^o$, this is sufficiently above the minimum requirement. The coincident zeros and poles can be calculated as:

$$f_p = f_c \tan\left(\frac{\pi + \varphi_m}{4}\right)$$

$$f_z = \frac{f_{c_C}}{\tan\left(\frac{\pi + \varphi_m}{4}\right)}$$

The gain of the controller is given by:

$$K_C = \frac{2\pi f_c f_p}{K_o f_z}$$

The parameter to determine controller transfer function are as follows:

Transfer Function Parameters	Value
ω_c	$10.4\ kHz$
φ_m	163°
ω_z	$4.8556\ k\ rad\ s^{-1}$
ω_p	$879.14\ k\ rad\ s^{-1}$
K_c	303.2066

Table 4: Parameter Defining Compensator Transfer Function

Thus we have the transfer function as :

$$C(s) = \frac{1.286 \times 10^{-5}s^2 + 0.1249s + 303.2}{1.294 \times 10^{-1}\ s^3 + 2.275 \times 10^{-6}s^2 + s}$$

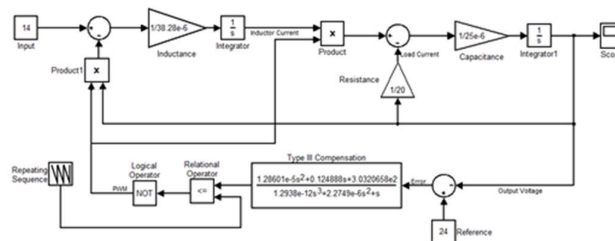This transfer function is again tested with the mathematical model of boost converter and results are recorded.
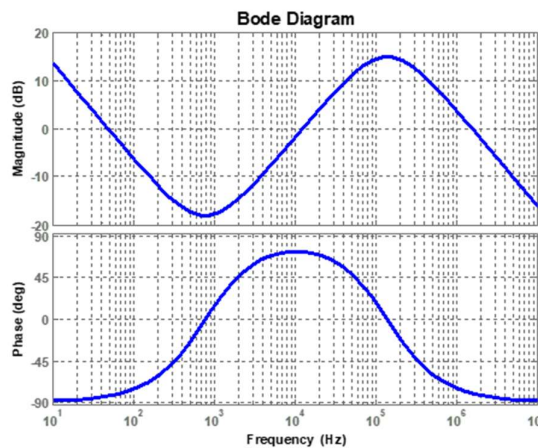

Fig. 16: Mathematical Model with Type 3 Compensator

Fig. 17: Bode Plot of Type 3 Compensator

Hardware

In current work voltage controlled boost converter is developed as shown in Fig. 18. In this closed loop strategy is used where the voltage feedback is fed into the op-amp IC 741 which

compares this to a reference voltage. The resultant error is amplified and fed into the IC 555 timer which in astable mode generates the required PWM gating signal for driving MOSFET. The input to the boost converter is varied to account for variation in solar panel output.
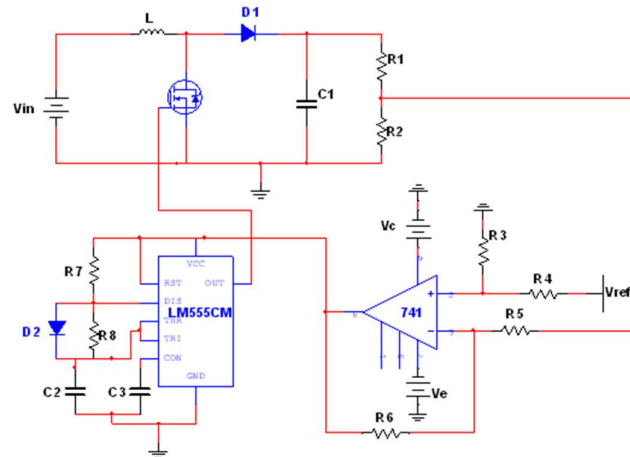

Fig. 18: Voltage Controlled Boost Converter Hardware Circuit

Circuit Parameters:

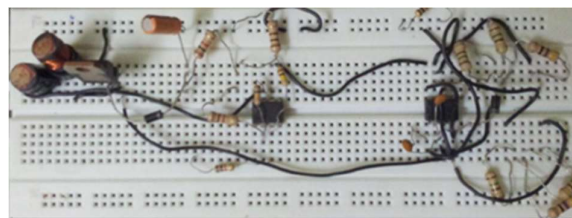| Circuit Parameter	Value
L	348µH
C	0.089µF
R_1	1kΩ
R_2	100kΩ
R_3	100Ω
R_4	1kΩ
R_5	1kΩ
R_6	100kΩ
R_7	347Ω
R_8	347Ω

Table 5: Hardware Circuit Parameters

Fig. 19: Hardware Circuit Implemented on Bread Board
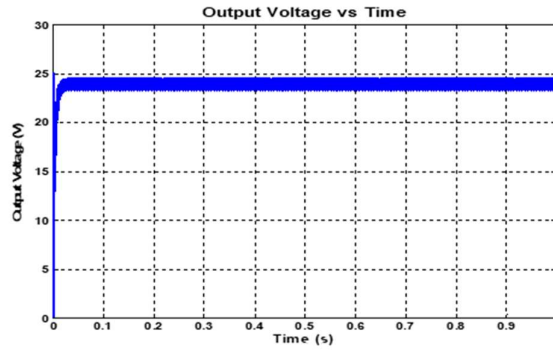
Results

Boost Converter Simulations:

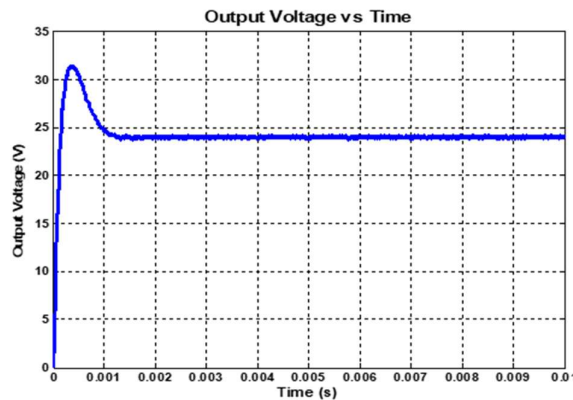Fig. 20: Boost Converter Circuit Model with PID Controller

Fig. 21: Boost Converter Circuit Model with Type 3 Compensator
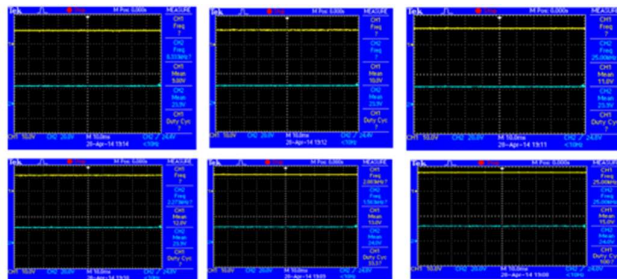
Boost Converter Hardware:

Figure 22: Constant Output Voltage of 24 V at Varied Inputs

Conclusion

The following work focuses on deeper analysis of boost converter with regards to photovoltaic technology. Firstly conventional boost converter charteristics are studied carefully followed by all the parameters calculations. Secondly it is observed how much stable the system is with frequency as well as time domain analysis. Then in order to improve stability various controllers are explored and these are summarized with the help of Fig. 23 and Table 6. Finally hardware is developed and tested for various inputs and resultant constant output of 24V is obtained which is shown in Fig.22.
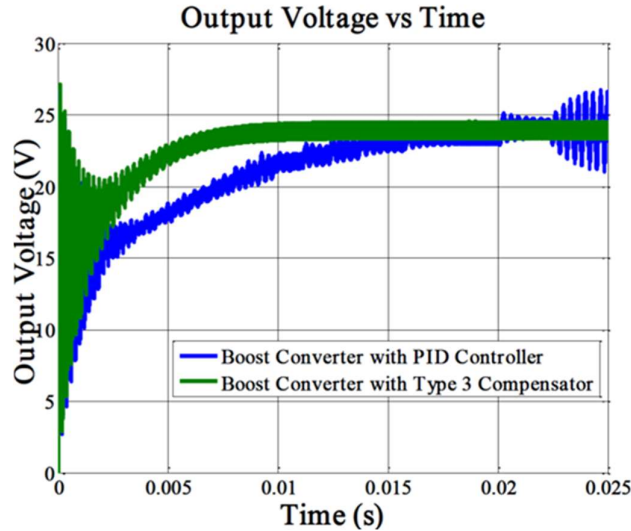
Fig. 23: Comparison of PID and Type 3 Controller

Stability Criterion	PID Controller	Type 3 Compensator
Gain Margin	Infinity	16.9 dB
Gain Crossover Frequency	Infinity	$22.26\,862$ $k\,rad\,s^{-1}$
Phase Margin	-138^0	92.148^0
Phase Crossover Frequency	233.862 $k\,rad\,s^{-1}$	$551.958\,k\,rad\,s^{-1}$

Table 6: Comparison of PID and Type 3 Controller

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