ISSN:2321-1156

International Journal of Innovative Research in Technology & Science(IJIRTS)

"DESIGN OF COMPENSATOR FOR DC-DC BUCK CONVERTER"

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ABSTRACT - DC-DC converters are power electronics circuits that convert a dc voltage to a different dc voltage level, often providing a regulated output. In ideal switching DC-DC converters, the output voltage is a function of the input voltage and duty ratio. In real circuits with non ideal components; the output is also the function of the load current because of resistances in the components. A power supply output is regulated by modulating the duty ratio to compensate for variations in the input or load. A feedback control system for power supply control compares output voltage to a reference and converts the error to a duty ratio. This work focuses on design of open and closed loop DC-DC Buck Converter, and design of Type 2 and Type 3 error amplifier with compensation, and also comparison of performance of Type 2 and Type 3 error amplifier compensator.

KEYWORDS - Buck converter, Transfer function, Compensator, Pulse Width Modulation (PWM), Duty Cycle, Matlab, Simulink.

I. INTRODUCTION

A *DC*-to-*DC* converter is an electronic circuit which converts a source of direct current (*DC*) from one voltage level to another. It is a class of power converter. *DC* to *DC* converters are important in portable electronic devices such as cellular phones and laptop computers, which are supplied with power from batteries primarily. Such electronic devices often contain several sub-circuits, each with its own voltage level requirement different from that supplied by the battery or an external supply (sometimes higher or lower than the supply voltage). Additionally, the battery voltage declines as its stored power is drained. Switched *DC* to *DC* converters offer a method to increase voltage from a partially lowered battery voltage thereby saving space instead of using multiple batteries to accomplish the same thing. Most *DC* to *DC* converters also regulate the output. Some exceptions include high-efficiency *LED* power sources, which are a kind of *DC* to *DC* converter that regulates the current through the *LED*s, and simple charge pumps which double or triple the input voltage.

In real circuits with non ideal components, the output is also the function of the load current because of resistances in the components. The output of buck converter alone usually is unstable. So the concerned criteria are rise time, overshoot, settling time and steady state error, to get the desired output and to reduce the undesired output. To get the desired output and to reduce the error in the output voltage and current, buck converter must be provided with feedback compensator with error amplifier.

This work focuses on design of open and closed loop DC-DC Buck Converter, and design of type 2 and type 3 error amplifiers with compensation, and also comparison of performance of type 2 and type 3 compensator. ss

II. BLOCK DIAGRAM OF BUCK CONVERTER

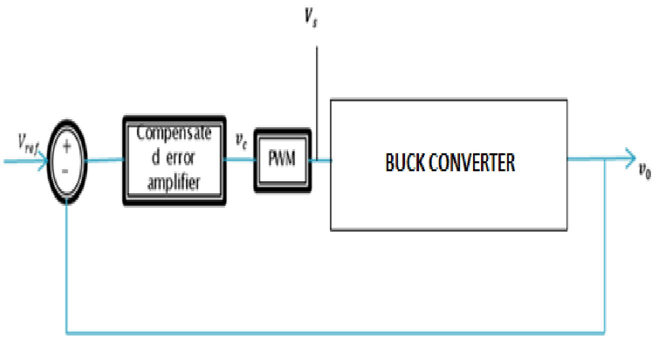


Figure (1) Control representation of Buck Converter

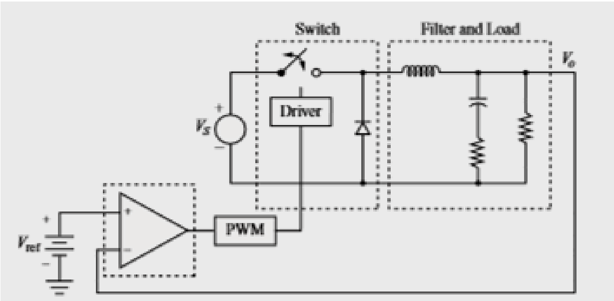


Figure (2) Buck converter with feedback

The above figure shows the overall block diagram of the project work and it consists of following parts

- The switch including the diode and drive circuit.
- The output filter.
- The compensated error amplifier
- The pulse width modulating circuit that converts the output of the compensated error amplifier to a duty ratio to drive the switch.

The dc input voltage of the converter is assumed to have zero internal impedance. It could be a battery source however in most cases the input is a diode rectified ac line voltage with a large filter capacitance to provide low internal impedance and a low ripple dc voltage source.

- **Compensated Error Amplifier:** An error amplifier is most commonly encountered in feedback unidirectional voltage control circuits where the sampled output voltage of the circuit under control is fed back and compared to a stable reference voltage. Any difference between the two generates a compensating error voltage which tends to move the output voltage towards the design specification.
- **PWM:** The most common control method pulse-width modulation (PWM). This method takes a sample of the output voltage and subtracts this from a reference voltage to establish a small error signal (V_{ERROR}). This error signal is compared to an oscillator ramp signal. The comparator outputs a digital output (PWM) that operates the power switch. When the circuit output voltage changes, V_{ERROR} also changes and thus causes the comparator threshold to change. Consequently, the output pulse width (PWM) also changes. This duty cycle change then moves the output voltage to reduce the error signal to zero, thus completing the control loop.
- **Buck converter:** An efficient alternative to the linear regulator is switch. In a switch circuit, the transistor operates as an electronic switch by being completely on or completely off. Assuming switch is ideal, the output is same as input when the switch is closed, and output is zero when switch is open. In this work MOSFET is used as a switch. The input of buck converter is switch output which is v_x=$v_s d$ on an averaged circuit basis in the continuous current mode. The buck converter consists of an RLC filter. In the output stage of the converter, a small filter is treated as an integral part of the dc-dc converter. Compensation associated with the amplifier determines control loop performance and provides for a stable control system.

III DIFFERENT MODES OF OPERATION:

❖ **Continuous mode**

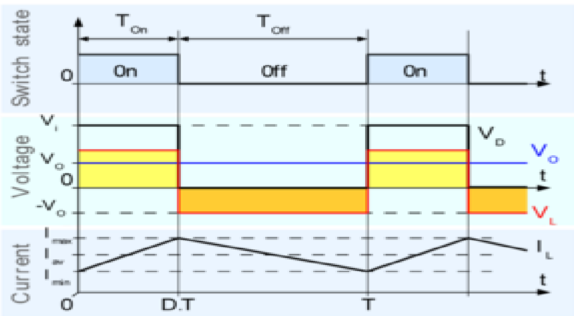


Figure (3) A buck converter continuous mode operation

$$\frac{V_i - V_o}{L}t_{on} - \frac{V_o}{L}t_{off} = 0$$

$$(V_i - V_o)DT - V_o(1-D)T = 0$$

$$\Rightarrow V_o - DV_i = 0$$

$$\Rightarrow D = \frac{V_o}{V_i}$$

❖ **Discontinuous mode**

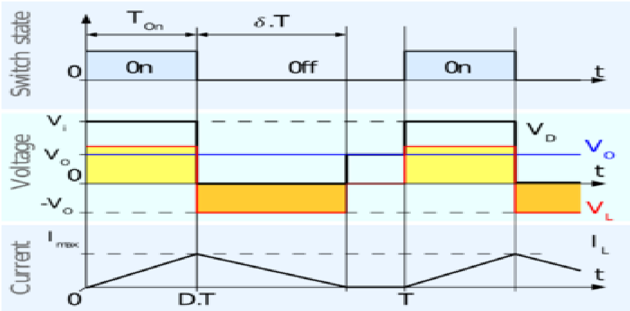


Figure (4) evolution of the voltages and currents with time in an ideal buck converter operating in discontinuous mode.

$$I_{L_{Max}} = \frac{V_i - V_o}{L}DT$$

$$V_o = V_i\frac{1}{\frac{2LI_o}{D^2V_iT} + 1}$$

This analysis assumes that the diode remains forward biased for the entire time when the switch is open, implying that the inductor current remains positive. An inductor current that remains positive throughout the switching period is known as continuous current. Conversely, discontinuous current is characterized by the inductor currents returning to zero during each period.

IV. COMPENSATOR

❖ **BASICS OF COMPENSATOR**

An open loop DC-DC converter cannot regulate its output voltage due to variation in input voltage and changes in load. Compensator is used to overcome this problem, so that the converter will produces stable output voltage.

- Compensators are specialized filters.
- The additional component which compensates for deficient performance of the original system is known as "Compensator".
- Compensation is the alteration or adjustment of system to obtain desired performance.

❖ **TYPES OF COMPENSATOR**

(A) TYPE 1 COMPENSATOR.
(B) TYPE 2 COMPENSATOR.
(C) TYPE 3 COMPENSATOR.

(A) TYPE 1 COMPENSATOR:

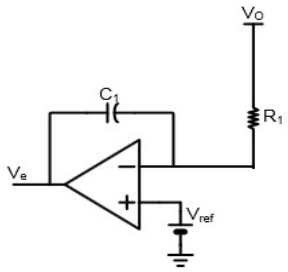


Figure (5) Type 1 compensator using the op-amp

Figure shows the schematic of the traditional Op-Amp with Type I configuration. The operational amplifier (the traditional Op-Amp) represents the basis of the closed-loop system. Its function, in a feedback system, is to amplify the error detected between a fixed and stable reference level and the monitored state variable. In this Type I configuration, we derive H(s) by dividing the capacitor impedance (C1) by the upper resistor. The transfer function is $\frac{v_e}{v_{out}} = -\frac{1}{R1C1S}$

(B)TYPE 2 COMPENSATOR

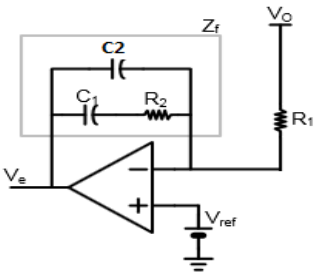


Figure: (6) Type 2 compensator using the op-amp

A Type II compensation amplifier adds an RC branch to flatten the gain, and improve the phase response in the mid-frequency range. The increased phase is achieved by increasing the separation of the pole and zero of the compensation. Offering an origin pole, one zero, and one high-frequency pole, the Type II compensator provides a phase boost up to 90 degrees. Figure shows the electrical configuration, and the transfer function is obtained by calculating the impedance offered by the network placed in the Op-Amp feedback path (Zf) and dividing it by the upper resistor (R1).

$$\mathrm{Zf} = (\mathrm{R2} + \frac{1}{sC1}) \| \frac{1}{sC2} = \frac{\left(R2 + \frac{1}{sC1}\right)(\frac{1}{sC2})}{R2 + \frac{1}{sC1} + \frac{1}{sC2}}$$

$$Zi = R1$$

The gain function G(s) is expressed as the ratio of the compensated error amplifier small signal output v_c to the input,which is the converter output v_o

$$G(s) = \frac{v_c(s)}{v_{o(s)}} = -\frac{Z_f}{Z_i}$$

$$= -\frac{(R2 + 1/sC1)(1/sC2)}{R1(R2 + 1/sC1 + 1/sC2)}$$

Rearranging terms and assuming C2 $_{<<}C_{1,}$

$$G(S) = \frac{v_c(s)}{v_{o(s)}}$$

$$= -\frac{s + 1/R2C2}{R1C2[s + (C1 + C2)/R2C1C2]}$$

$$\approx -\frac{s + 1/R2C1}{R1C2s(s6 + 1/R2C2)}$$

(C) TYPE 3 COMPENSATOR

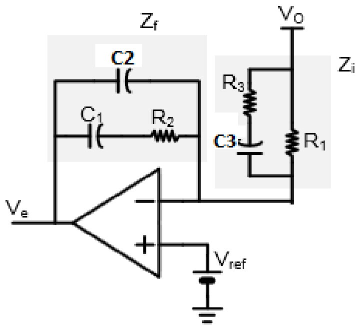


Figure (7) Type3 compensator using the op-amp

Figure shows the conventional Type III compensation using voltage Op-Amp. There are two poles and two zeros provided by this compensation. The Type III compensator is used when more than 90 degrees of phase boost are necessary. By adding another pole/zero pair to the Type II compensator, the Type III can theoretically boost the phase up to 180 degrees. The derivation of its transfer function does not really change, which means the principle remains the same with the Type II method. The small signal transfer function is expressed in terms of input and feedback impedances Z_i and Z_f,

$$G(s) = \frac{v_{c(s)}}{v_o(s)} = -\frac{Z_f}{Z_i} = -\frac{(R2 + 1/sC1)\|1/sC2}{R1\|(R3 + 1/sC3)}$$

Resulting in

$$G(s) = -\frac{R1 + R3}{R1R3C3} \frac{\left(s + \frac{1}{R2C1}\right)\left(s + \frac{1}{(R1+R3)C3}\right)}{s\left(s + \frac{C1+C2}{R2C1C2}\right)\left(s + \frac{1}{R3C3}\right)}$$

The reference voltage V_{ref} is purely dc and has no effect on the small-signal transfer function. Assuming $C_2 << C_1$ and $R_3 << R_1$,

$$G(s) \approx -\frac{1}{R3C2} \frac{(s + 1/R2C1)(s + 1/R1C3)}{s(s + 1/R2C2)(s + 1/R3C3)}$$

V. SOFTWARE IMPLEMENTATION

❖ STEADY STATE ANALYSIS (OPEN LOOP)

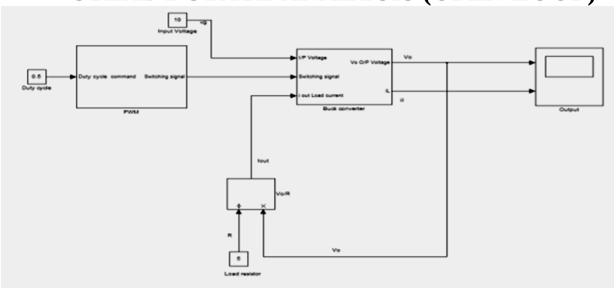


Figure (8) steady state analysis of open loop buck Converter

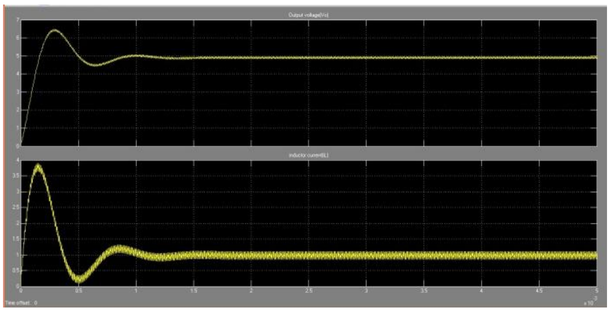


Figure (9) Output waveform

The figure above shows the simulation block diagram of open loop buck converter for steady state analysis. As shown, from the simulation results, the output voltage is 4.96v,percentage voltage ripple is 2.443%.

❖ DYNAMIC ANALYSIS

- LINE REGULATION (OPEN LOOP)

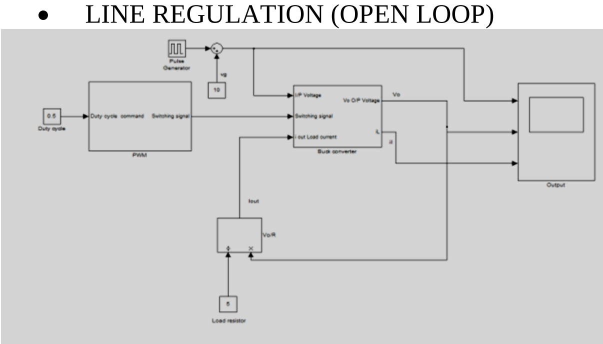


Figure (10) Line regulation of open loop buck converter

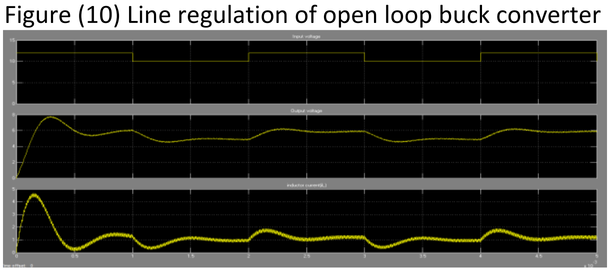
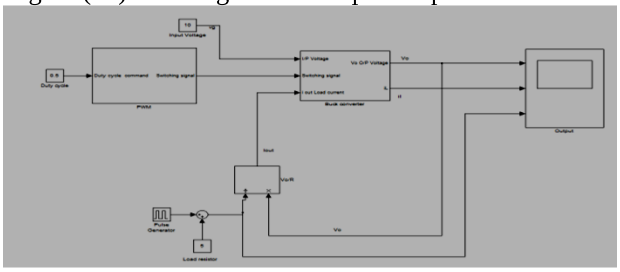


Figure (11) Output waveform

The figure above shows the simulation block diagram of open loop buck converter for dynamic analysis i.e., Line regulation. As shown, from the simulation results, the output voltage is 6.67v, settling time is 0.62ms, and the percentage overshoot is 0.5%.

- LOAD REGULATION (OPEN LOOP)

Figure (12) Load regulation of open loop buck converter



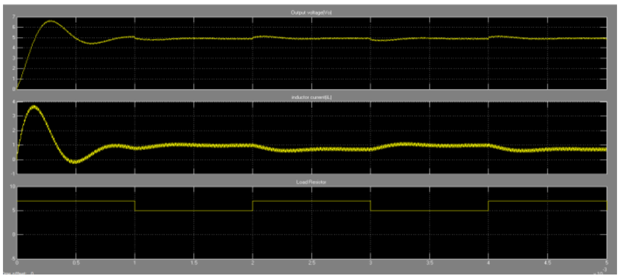


Figure (13) Output waveform

The figure above shows the simulation block diagram of open loop buck converter for dynamic analysis i.e. Load regulation. As shown, from the simulation results, the output voltage is 7.8v, settling time is 2ms, and the percentage overshoot is 0.8%.

VI. COMPARISION TABLE:

Comparison Table of Steady State analysis and dynamic analysis of open loop buck converter, Type 2 compensator and Type 3 compensator is shown below:

Table 1 : COMPARISION TABLE FOR STEADY STATE ANALYSIS

1. Steady state analysis

TYPE OF CIRCUIT	Vs(volts)	Vout(Volts)	Iout(amps)	Voltage ripple(%)	Current ripple(%)
Without compensator	10	4.96	5/5=1	2.443	24
Type 2 compensator	10	5.06	1	2.204	22
Type 3 compensator	10	5	1	0.46	22

Table 2 : COMPARISION TABLE FOR DYANAMIC ANALYSIS

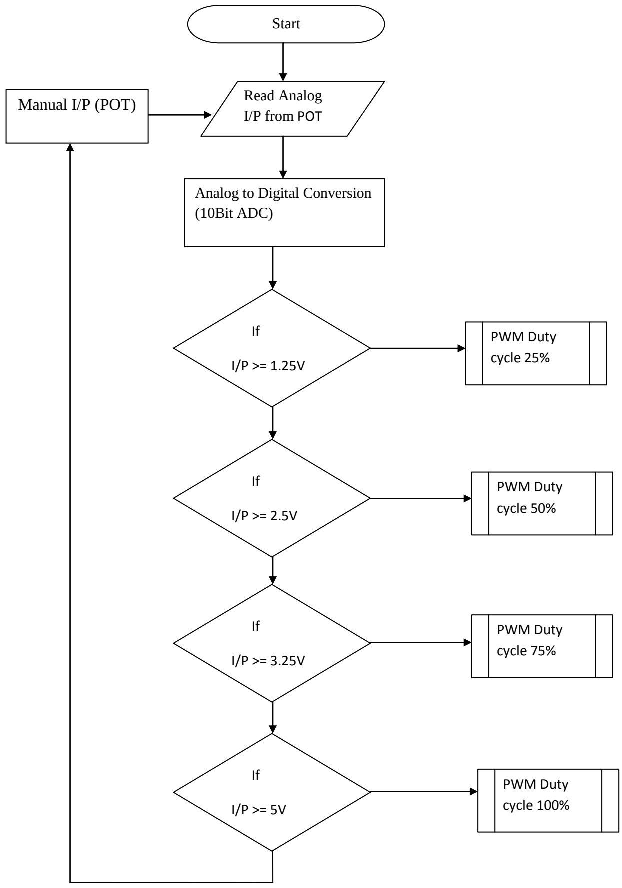
Dynamic Analysis

2. Load Regulation

Type	Vs (volts)	Iout (amps)	Vout (Volts)	Ts (msec)	Undershoot (%)	Overshoot (%)	Voltage ripple (%)	Current ripple (%)
Without compensator	10	0.7 To 1(vice versa)	6.67	0.62	2.59	0.5	2.42	33.33
Type 2 compensator			5.2	0.15	1	0.5	2.4	31.72
Type 3 compensator			5.04	0.09	0.27	0.28	0.5	30.66

3. Line Regulation

Type	Vs (volts)	Iout (amps)	Vout (Volts)	Ts (msec)	Undershoot (%)	Overshoot (%)	Voltage ripple (%)	Current ripple (%)
Without compensator	10 to 12(vice versa)	1	7.8	>2	2.6	0.8	2.41	29.52
Type 2 compensator			5.1	0.08	0.1	0.6	2.39	25.23
Type 3 compensator			5.04	0.05	0.08	0.09	0.5	24



Figure(14) Shows the flow chart for the generation of the PWM signal using **PIC16F877A**

VII. HARDWARE IMPLEMENTATION

- DESIGN OF HARDWARE COMPONENTS

Va=5V

v_s =12V

ΔI =25.77

f=100Khz

R=10Ω

$$L = \frac{v_a(v_s - v_a)}{f\Delta I v_s} = \frac{5(12-5)}{100*10^3*25.77*10} = 1.1uh$$

$$C = \frac{\Delta_I}{8*f*s\Delta v_c} = \frac{25.77}{8*100*10^3*2.2403} = 14.37uF$$

VIII. HARDWARE CIRCUIT

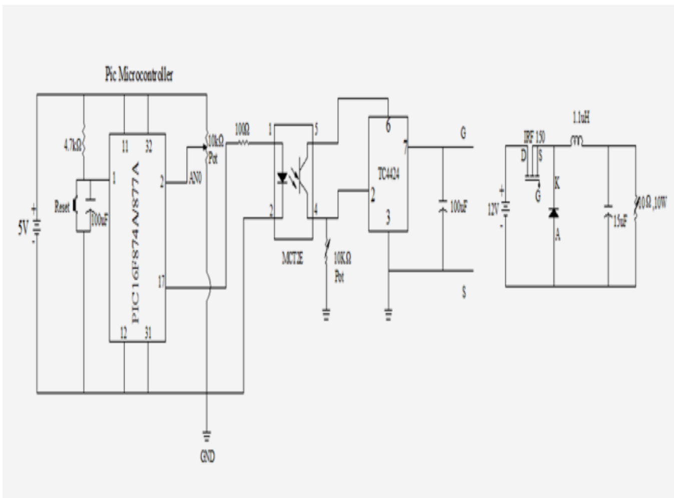


Figure (15) Hardware Circuit of open loop Buck Converter

IX. HARDWARE RESULTS

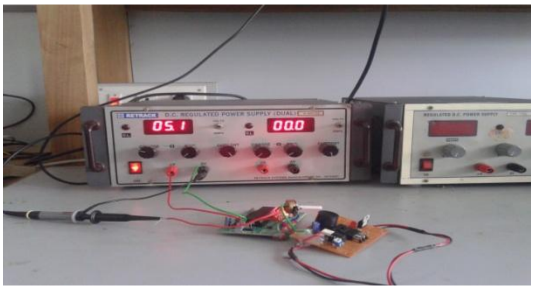


Figure (16) Hardware circuit of PWM

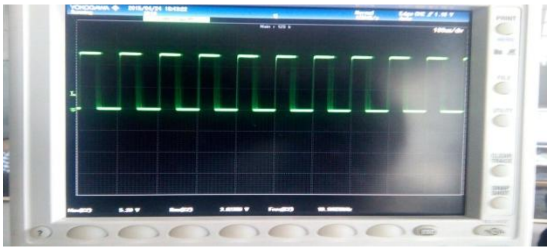


Figure (17) Output waveform of PWM

The output waveform of PWM is obtained as shown in the figure above. This is obtained with the help of PIC16F874A microcontroller IC and by varying 10KΩ pot.

Figure (18) Hardware circuit of open loop buck converter

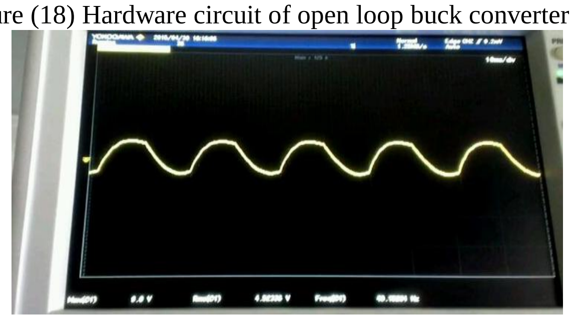


Figure (19) Output waveform of open loop buck converter

The output waveform of buck converter is as shown in the figure above. The MOSFET is used as a switch in the buck converter circuit. For the input voltage of 12v,the output voltage obtained is 4.96v.

X. CONCLUSION

DC-DC converters are power electronic circuits that convert a DC voltage level, often providing a regulated output. In this work design and modeling of buck converter is carried out and the same model is verified in the MATLAB SIMULINK environment. This steady state analysis is carried out for open loop buck converter. The Closed loop buck converter is designed, using error amplifier compensator in the feedback path. Type 2 and Type 3 error amplifier compensators are designed and the same is modeled and implemented in the MATLAB SIMULINK environment. Both LINE and LOAD regulations are determined for Type 2 and Type 3 compensator and comparative analysis is done between Type 2 and Type 3 compensator. It is found that Type 3 compensator gives dynamic performance than type 2.It is also found that type 3 compensator is having a settling time of 0.09ms and overshoot of 0.28% for a load change of 0.7 to 1 amp.

XI. FUTURE SCOPE

- The same method can be adopted for boost converter, buck boost converter and their ripple voltage, ripple current, percentage error, efficiencies can be determined.
- The hardware design can be made precise by adding a feedback circuit resulting in closed loop system.
- The feedback circuit can be obtained by using type 2 compensator or type 3 compensator. By adding the compensator it regulates its output voltage due to variation in input voltage and changes in load, by producing a stable output voltage.

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