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Closed Loop Voltage Control of Boost Converter Using PI Controller

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***Abstract* — Switching-mode converters are widely used today to provide power processing for various applications. These are electronic devices that are used whenever we want to change DC electrical power efficiently from one voltage level to another. DC-DC converters are nonlinear dynamical systems. The non linearity's arise primarily due to switching, power devices, and passive components, such as inductors, and parasitic. The static conversion properties of the elementary switching converters (buck, boost and buck-boost) have been thoroughly understood very long back, which has become one of the main reasons of their ever-increasing applications in electrical energy conversion. Boost converter is one of the DC-DC converter which step up the source voltage. This project describes about modeling and controlling the boost converter. To control the duty cycle closed loop implementation of boost converter is carried out using digital control unit (using microcontroller).**

***Index Terms*—PI controller, boost converter;**

I. INTRODUCTION

Switching-mode converters are widely used today to provide power processing for various applications. These are electronic devices that are used whenever we want to change DC electrical power efficiently from one voltage level to another. DC-DC converters are nonlinear dynamical systems. The non- linearity arise primarily due to switching, power devices, and passive components, such as inductors, and parasitic. The static conversion properties of the elementary switching converters (buck, boost and buck-boost) have been thoroughly understood very long back, which has become one of the main reasons of their ever-increasing applications in electrical energy conversion. Modelling and analysis of switching DC-DC converters can be either numerical or analytical. In numerical techniques, various algorithms or circuit simulators are used to produce quantitative result. These methods are easy to use, but they are time consuming and failed to provide the design insight needed to understand the behaviour of the switching regulators. Analytical techniques, on the other hand, provide analytic expressions representing the operation and performance of the converters. Perhaps the small signal analysis uses circuit averaging, state-space averaging, or PWM switch modelling. DC-DC converter is modelled using large signal analysis, whose output is monitored using PID controller.

A boost converter (step-up converter) is a DC-to-DC power converter with an output voltage greater than its input voltage. It is a class of switched-mode power supply (SMPS) containing at least two semiconductors (a diode and a transistor) and at least one energy storage element, a capacitor, inductor, or the two in combination. Filters made of capacitors (sometimes in combination with inductors) are normally added to the output of the converter to reduce output voltage ripple. Power for the boost converter can come from any suitable DC sources, such as batteries, solar panels, rectifiers and DC generators. A process that changes one DC voltage to a different DC voltage is called DC to DC conversion. A boost converter is a DC to DC converter with an output voltage greater than the source voltage. A boost converter is sometimes called a step-up converter since it "steps up" the source voltage. Since power $P = VI$ must be conserved the output current is lower than the source current.

Boost converters are used in regulated power supplies. Regenerative braking stores energy back into the battery, while increasing the life of fiction pads on brake shoe. For current to flow into battery, the bus voltage should be higher than the battery terminal voltage. Piezoelectric materials convert mechanical energy into electrical energy and vice versa. In dense populated areas like railway station, bus stand etc, where more amount of vibration energy will be present, the produced electric energy from the piezoelectric materials is very low of the order of 2-3 volts. In order to charge high voltage batteries like 12V battery through crystal boost converter circuit is used. Boost regulator LED drives generate the high voltage required to drive the multiple LED's in series, ensuring current matching between the LED's. These LED's offer highest efficiency, lowest noise. Problem with batteries small or large is that their output voltage varies as the variable charge is used up, and at some point of time battery voltage becomes too low to power the circuit being supplied. However if this low output level can be boosted up to a useful level again using a boost converter the battery life can be extended. In photo voltaic applications the voltage produced will be very small enough to feed the grid. In order to integrate this PV system boost converter can be used.

II. BLOCK DIAGRAM

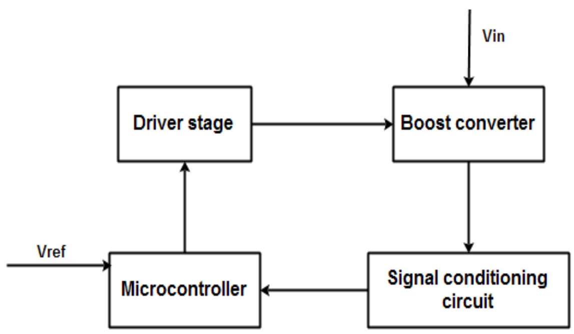

Figure 1. Block diagram

Boost converter:

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Boost converter is one of the DC-DC converters which step up the source voltage. The boost converter is a popular non-isolated power stage topology, sometimes called a step-up power stage. This operates by periodically opening and closing an electronic switch. It is called a boost converter because the output voltage is larger than input.

Voltage current relationships:

The analysis assumes the following.

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

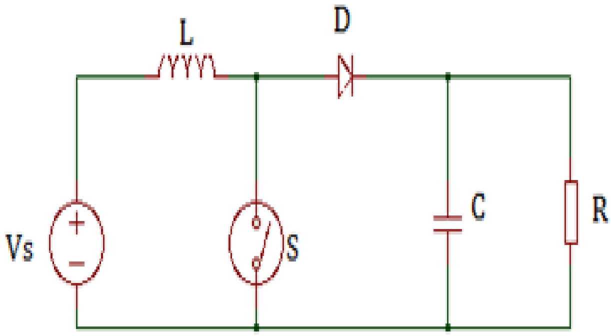

Figure 2. Boost converter

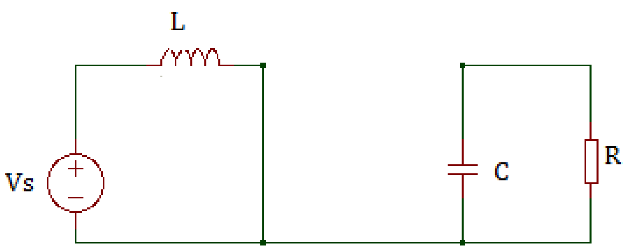

Figure 3. Boost converter for switch closed.

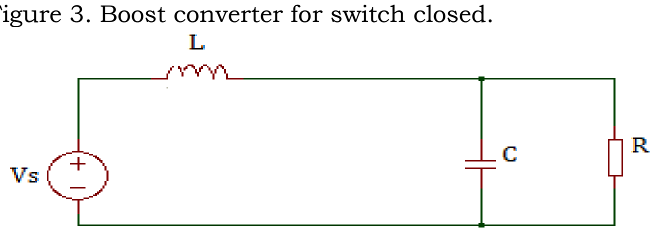

Figure 4. Boost converter for switch open.

Analysis for switch closed condition as shown in figure3: When the switch is closed, the diode is reverse biased, Kirchhoff's law around the path containing the source, inductor, and closed switch is

$$V_L = V_S = L\frac{di_L}{dt} \quad (1)$$

The rate of change of current is a constant, so the current increases linearly while the switch is closed. The change in inductor current is computed from

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_s}{L} \quad (2)$$

Solving for Δi_L , for the switch closed,

$$(\Delta i_L)_{closed} = \frac{V_s DT}{L}$$

Analysis for switch open condition as shown in figure 4:

When the switch is opened the diode current cannot change instantaneously, so the diode becomes forward biased to provide a path for inductor current. Assuming that the output voltage V_O is a constant, the voltage across the inductor is

$$V_L = V_S - V_O = L\frac{di_L}{dt}$$

The rate of change of inductor current is a constant, so the current must change linearly while the switch is open. The change in inductor current while a switch is open is

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

Solving for Δi_L,

$$(\Delta i_L)_{open} = \frac{(V_S - V_O)(1-D)T}{L} \quad (3)$$

For steady-state operation, the net change in inductor current must be zero. Using equations and solving for V_O,

$$V_O = \frac{V_S}{1-D} \quad (4)$$

Also, the average inductor current must be zero for periodic operation. The average inductor current is given by,

$$I_L = \frac{V_S}{(1-D)^2 R} = \frac{V_O^{\ 2}}{V_S R} = \frac{V_O I_O}{V_S} \quad (5)$$

Maximum and minimum inductor currents are determined by using the average value and change in current from equations

$$I_{\max} = I_L + \frac{\Delta i_L}{2} = \frac{V_S}{(1-D)^2 R} + \frac{V_S DT}{2L} \quad (6)$$

$$I_{\min} = I_L - \frac{\Delta i_L}{2} = \frac{V_S}{(1-D)^2 R} - \frac{V_S DT}{2L} \quad (7)$$

The minimum inductance is given by

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$$L_{\min} = \frac{D(1-D)^2 R}{2f} \tag{8}$$

And the inductance is given by

$$L = \frac{V_s D}{\Delta i_L f} \tag{9}$$

An expression for ripple voltage is given by

$$\frac{\Delta V_O}{V_O} = \frac{D}{RCf} \tag{10}$$

Expressing capacitance in terms of output voltage ripple yields

$$C = \frac{D}{R\left(\frac{\Delta V_O}{V_O}\right) f} \tag{11}$$

Design of inductor and capacitor

Specifications:

$V_s = 5V \qquad V_{out} = 10V \qquad \frac{\Delta V_O}{V_O} = 0.01$ Switching frequency=45 KH_Z

$$D = 1 - \frac{V_s}{V_{out}} = 1 - \frac{10}{5} = 0.8$$

$$L_{\min} = \frac{D(1-D)^2 R}{2f} = \frac{0.8(1-0.8)^2 X 10^3}{2X45X10^3} = 355\mu H$$

$L > L_{\min}$

Therefore $L = 390\mu H$

$$I_L = \frac{V_s}{(1-D)^2 R} = \frac{5}{(1-0.8)^2 X 10^3} = 0.125A$$

$$\Delta I_L = \frac{V_s XDT}{2L} = \frac{5(0.8)}{2X390X10^{-6} X 45X10^3} = 0.113A$$

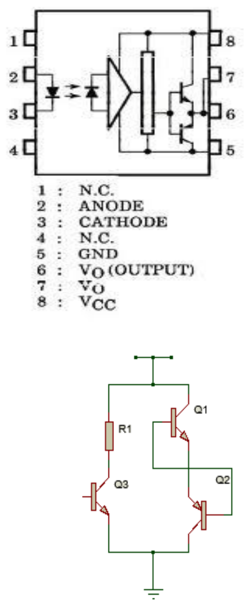
$$I_{L\max} = I_L + \Delta I_L = 0.125 + 0.113 = 0.236A$$

$$I_{L\min} = I_L + \Delta I_L = 0.125 - 0.113 = 0.012A$$

$$C = \frac{D}{RX\frac{\Delta V_O}{V_O}Xf} = \frac{0.8}{10^3 X (0.01) X 45X10^3} = 1.77\mu F$$

Driver stage:

Minimizing power losses in electronic switches is an important objective when designing power electronic circuits. On-state power losses occur because the voltage across the conducting switch is not zero. Switching losses occur because a device does not make transition from one state to another state instantaneously, and switching losses in many converters are larger than on-state losses. These switching losses in DC-DC converters can be minimized by drive circuits designed to provide fast switching transitions.



TLP 250 Double emitter-follower driver-circuit

Figure 5.Driver stage

Signal conditioning circuit:

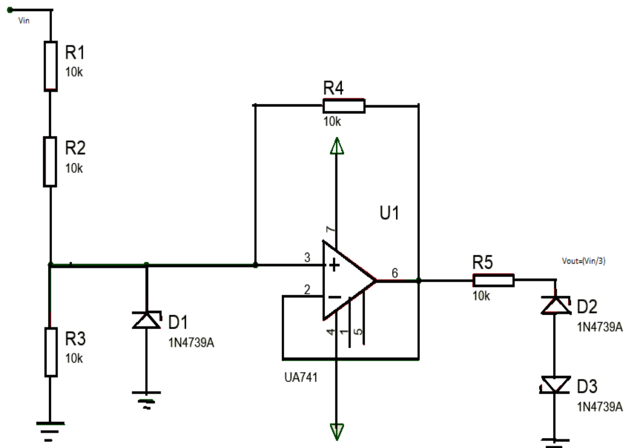


Figure 6. Signal conditioning circuit

In electronics, signal conditioning means manipulating an analog signal in such a way that it meets the requirements of the next stage for further processing. In control engineering applications, it is common to have a sensing stage (which consists of a sensor), a signal conditioning stage (where usually amplification of the signal is done) and a processing stage (normally carried out by an ADC and a micro-controller). Operational amplifiers (op-amps) are commonly employed to carry out the amplification of the signal in the signal conditioning stage.

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Signal conditioning can include amplification, filtering, converting, range matching, isolation and any other processes required to make sensor output suitable for processing after conditioning. Filtering is the most common signal conditioning function, as usually not all the signal frequency spectrum contains valid data. The common example is 60 Hz AC power lines, present in most environments, which will produce noise if amplified. Signal amplification performs two important functions one is increases the resolution of the input signal, and increases its signal-to-noise ratio. Commonly used amplifiers on signal conditioning include sample and hold amplifiers, peak detectors, log amplifiers, antilog amplifiers, instrumentation amplifiers and programmable gain amplifiers. Signal isolation must be used in order to pass the signal from the source to the measurement device without a physical connection. It is often used to isolate possible sources of signal perturbations. It is important to isolate the potentially expensive equipment used to process the signal after conditioning from the sensor.

Microcontroller:
The power of microcontrollers lies in their small size and adaptability. As opposed to fixed digital circuitry, microcontrollers can be programmed to perform many applications and can be later changed when improvement are required. This saves both time and money when a field upgrade is required. However, there are limitations with respect to processing power and memory With the advances in processing capability, many more applications can be realized today with microcontrollers than ever before, especially due to their low power profile. Indeed, the flexibility of these devices will ensure their incorporation in designs many years into the future. With the advent of Flash memory, the microcontroller can be programmed hundreds of thousands of times without any problems. Also, they incorporate a wide array of modules such Analog to Digital Converters, USB, PWM, and Wireless transceivers, enabling integration into any kind of application.

PI tuning of boost converter
Closed loop of boost converter:

Procedure for getting the step response of closed loop Boost Converter

- Obtain the transfer function of Boost converter-Gp(s)
- Obtaining transfer function of PID controller-Gc(s)
- Plotting root locus for Gp(s)*Gc(s) as shown in figure 7.
- Selecting a value of gain 'K'
- Building a closed loop transfer function using selected value of gain 'K'
- Plotting the step response for the closed loop system to check the stability of the system.

Transfer function obtained from program

$$Gp(s) = \frac{-31250(s - 6.667e004)}{s(s^2 + 416.7s + 2.778e007)}$$

Controller transfer function is given as below by

$$Gc(s) = \frac{1}{s}$$

Transfer function of the system

$$Gp(s) * Gc(s) = \frac{-25199.552(s - 6.667e004)}{(s + 60.58)(s^2 + 356s + 2.773e007)}$$

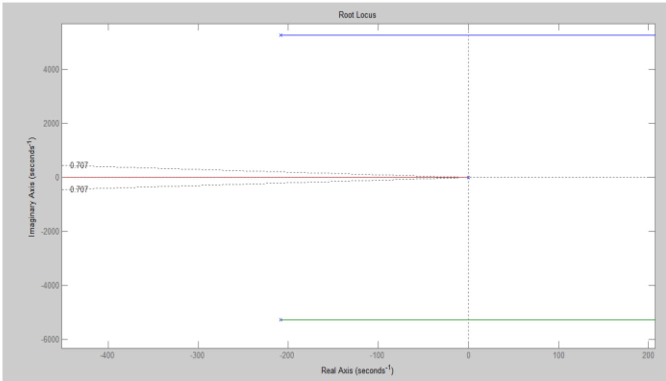

Figure 7:Root locus for transfer function of closed loop Boost converter

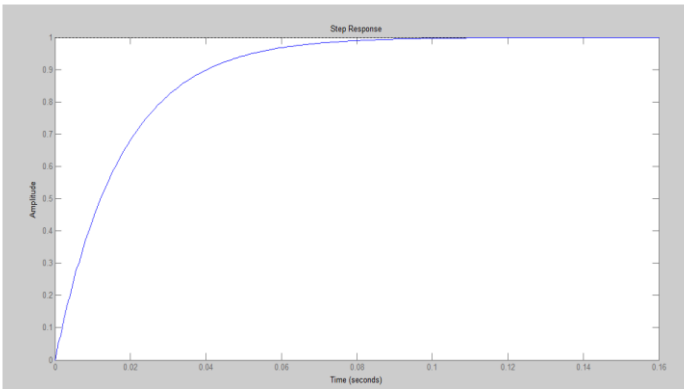

Figure 8.step response

MSP4302452:

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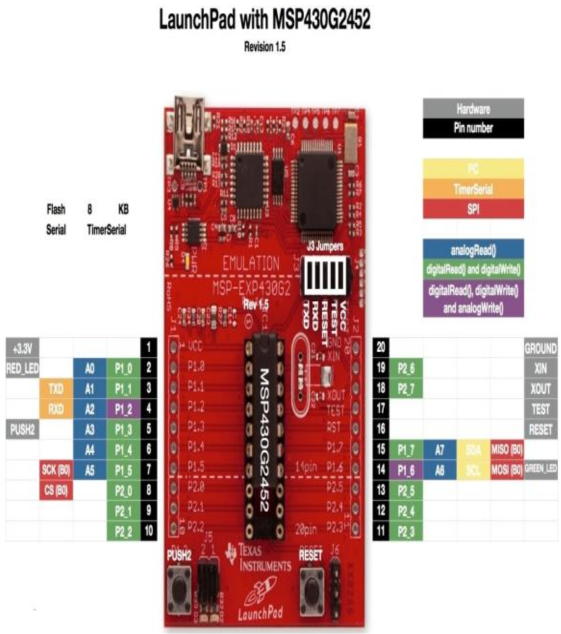


Figure 9.MSP430 launch pad

MSP430 family of ultra-low-power microcontrollers consist of several devices featuring different sets of peripherals targeted for various applications. The architecture, combined with five low-power modes, is optimized to achieve extended battery life in portable measurement applications. The device features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that contribute to maximum code efficiency. The digitally controlled oscillator (DCO) allows wake-up from low-power modes to active mode in less than 1 µs.

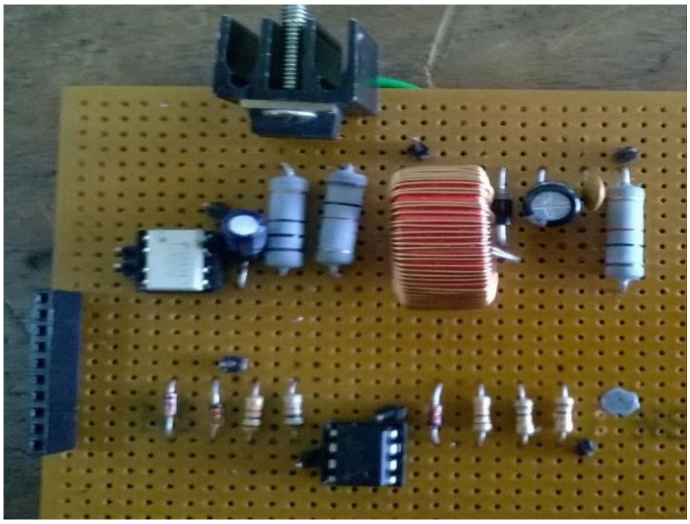
The MSP430G2x52 and MSP430G2x12 series of microcontrollers are ultra-low-power mixed signal microcontrollers with built-in 16-bit timers, and up to 16 I/O capacitive-touch enabled pins and built-in communication capability using the universal serial communication interface and have a versatile analog comparator. The MSP430G2x52 series have a 10-bit A/D converter. Typical applications include low-cost sensor systems that capture analog signals, convert them to digital values, and then process the data for display or for transmission to a host system.

Features:

- Low Supply Voltage Range: 1.8 V to 3.6 V
- Ultra-Low Power Consumption.
- Active Mode: 220 µA at 1 MHz, 2.2 V.
- Standby Mode: 0.5 µA.
- Off Mode (RAM Retention): 0.1 µA.
- Five Power-Saving Modes

III PROTOTYPING AND RESULTS

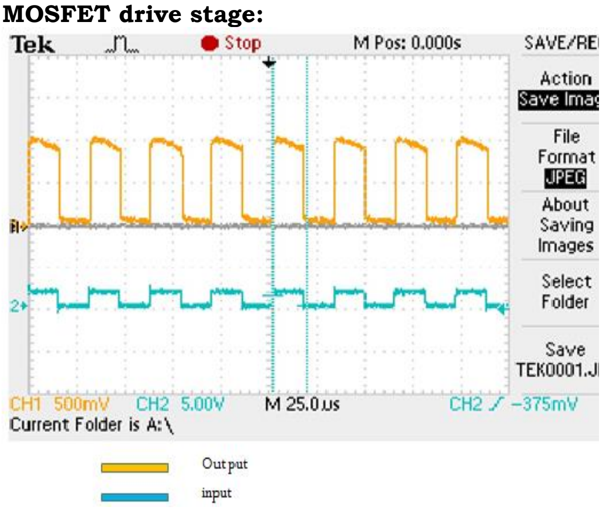
Hardware implementation of block diagram



Components used:

Components	Specification	Quantity
Resistors (Ohms)	10k 1k(2 watt) 1k 100(2watt)	4 2 1 1
Capacitors (Farad)	10u 33u 100n	1 1 1
TLP-250		1
MOSFET	IRF 840	1
Diode	1N5819 Zener (9.1V)	1 3
Op-amp	LM 324 UA 741	1 1
Inductance(Henry)	392uH	1

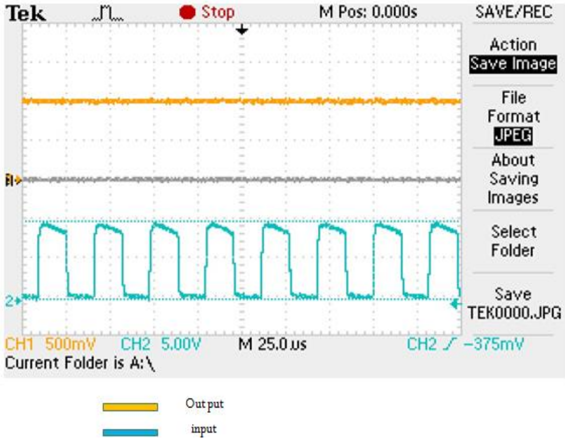
MOSFET drive stage:



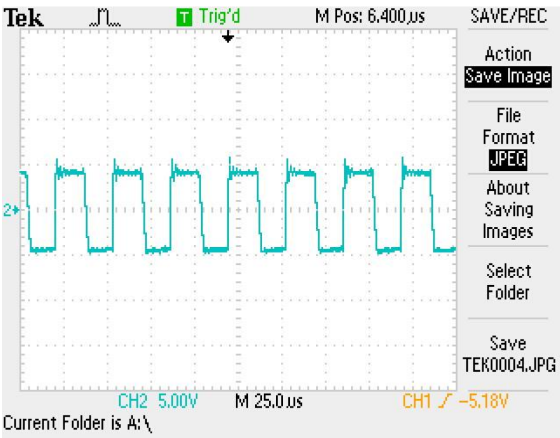
When pulse of 5V is given to the TLP250 output of 15V is obtained which is given to the gate terminal of MOSFET

Boost converter:

With 15V is given at the gate and 5V to the input of boost converter the output is 10V since duty cycle is 50% as show in below figure.



Voltage across inductor:



Results of open loop converter:

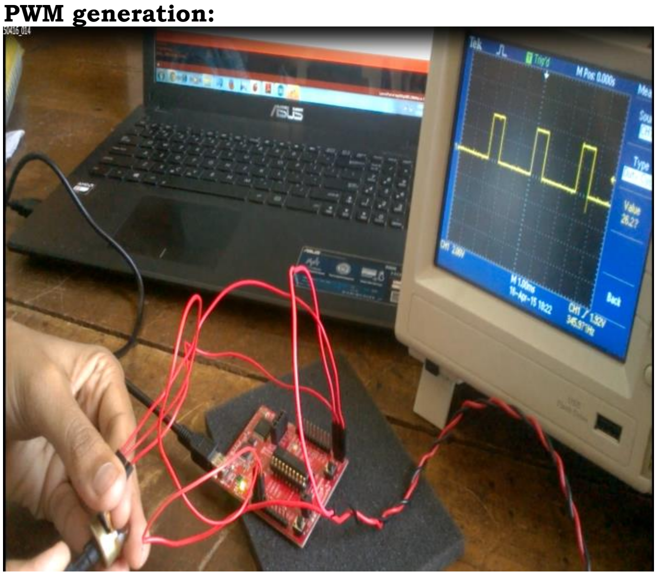
For fixed value of V_{in}

V_{in}	Duty cycle	V_{out}
5	0.1	5.6
5	0.2	6.3
5	0.3	7.2
5	0.4	8.3
5	0.5	10.1
5	0.6	12.7
5	0.7	17

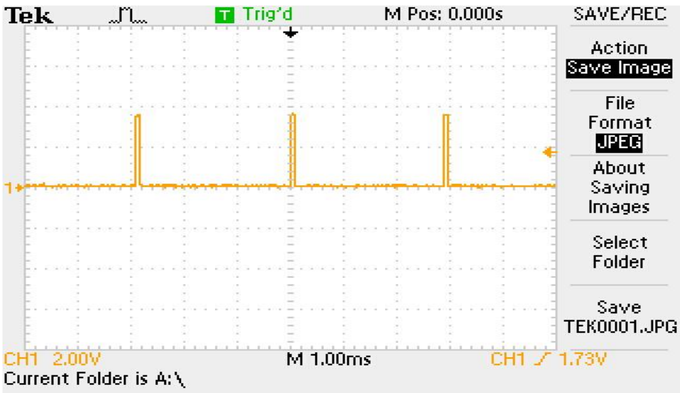
For fixed value of duty cycle

Duty cycle	V_{in}	V_{out}
0.6	0	0
0.6	1	2.6
0.6	2	4.9
0.6	3	7.8
0.6	4	10.1
0.6	5	12.6
0.6	6	15

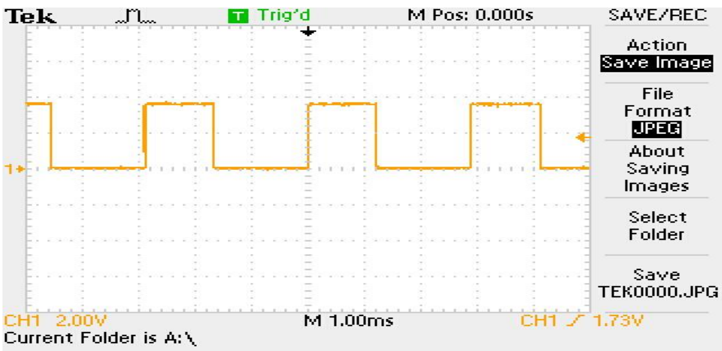
PWM generation:



Duty cycle=0.1

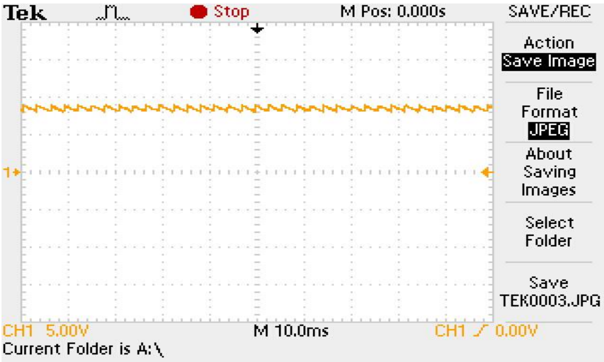


Duty cycle=0.48

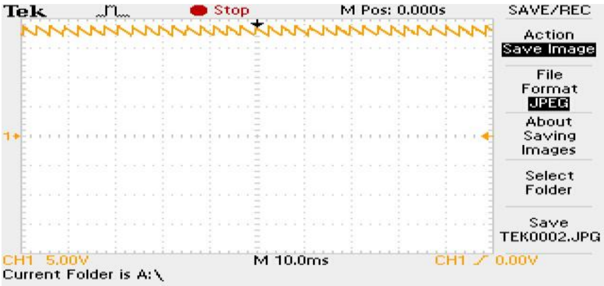


Open loop implementation:

V_{in}=4.5V , V_{out}=8V

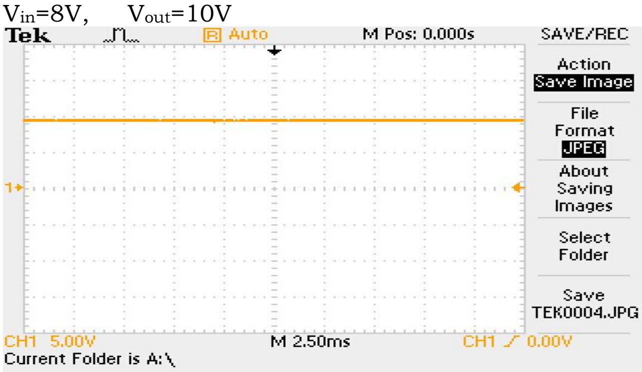


Vin=7V , Vout=18V

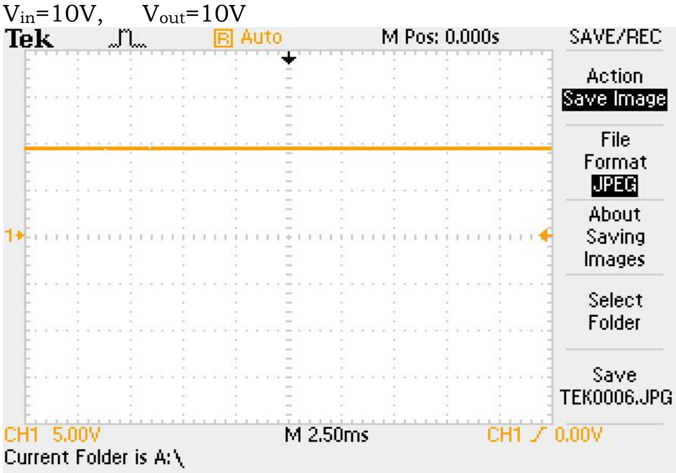


Results of closed loop converter:

V_{in}=8V, V_{out}=10V



V_{in}=10V, V_{out}=10V



Conclusion

- The primary advantage of a closed-loop feedback control system is its ability to reduce a system's sensitivity to external disturbances. Closed-loop systems are designed to automatically achieve and maintain the desired output condition by comparing it with the actual condition. Errors can be reduced by automatically adjusting the systems input, improves stability of an unstable system Produces a reliable and repeatable performance.

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