VOLTAGE CONTROL OF DC-DC BUCK CONVERTER AND ITS REAL TIME IMPLEMENTATION USING MICROCONTROLLER

Submitted by

DIPAK KUMAR DASH
Roll No-211EE2380
M. Tech. in Power Control & Drives
Dept. of Electrical Engineering

Under the Guidance of

Prof. Bidyadhar Subudhi

DEPARTMENT OF ELECTRICAL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA-769008

Dipak kumar Dash

VOLTAGE CONTROL OF DC-DC BUCK CONVERTER AND ITS REAL TIME IMPLEMENTATION USING MICROCONTROLLER

Thesis submitted in partial fulfilment of the requirements for the award of the Master of Technology in Electrical Engineering with Specialization in "Power Control and Drives"

By

Dipak kumar Dash

Roll No: 211EE2380

May-2013

Under the guidance of

Dr. Bidyadhar Subudhi

Dept. of Electrical Engineering

National Institute of Technology

Rourkela-769008

Dedicated to my family & teachers

Department of Electrical Engineering
National Institute of Technology, Rourkela
Odisha, INDIA - 769008

CERTIFICATE

This is to certify that the Thesis Report entitled "Voltage Control of DC-DC Buck Converter and its Real Time Implementation Using a Microcontroller, submitted by Mr Dipak Kumar Dash bearing roll no. 211EE2380 in partial fulfilment of the requirements for the award of Master of Technology in Electrical Engineering with specialization in "Power Control and Drives" during session 2011-2013 at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance. I believe that the thesis fulfils part of the requirements for the award of degree of Master of Technology in Power Control and Drives. The results embodied in the thesis have not been submitted for award of any other degree.

Dr.Bidyadhar Subudhi
Dept. of Electrical Engineering
National Institute of Technology
Rourkela-769008

DECLARATION

I hereby declare that the investigation carried out in the thesis has been carried out by me. The work is original and has not been submitted earlier as a whole or in part for a degree/diploma at this or any other institution / University.

Dipak Kumar Dash

ACKNOWLEDGEMENTS

I wish to express my sincere thanks and deep sense of gratitude to Dr.Bidyadhar Subudhi, for his inspiration, tremendous support, vision, and dedication to the successful completion of this work. His futuristic vision and realistic ideas have created an ever increasing zeal to work and explore many new things. He has been a great source of inspiration to work with and I shall always cherish my association with him with immense pleasure.

I thank Prof. Anup Kumar Panda, Head of the Department of Electrical Engineering, National Institute of Technology, Rourkela, for providing me facilities to carry out my thesis work in the Department of Electrical Engineering.

My sincere gratitude to all the faculty members of Department of Electrical Engineering, NIT Rourkela for their affection and support.

I will be failing in my duty if I do not express my thanks to the staff of Electrical Engineering Department for their timely help as and when require.

Words fail to express my deep sense of gratitude especially towards my family members for their patient love, moral encouragement and support which enabled me to complete this course. I thank all my friends who have extended their cooperation and suggestions by way of discussion at various steps in completion of this thesis. Finally, I would like to thank the almighty to enlighten the ignorance with in me and supporting me in my ups and downs to always fight back.

Dipak Kumar Dash

ABSTRACT

The switched mode dc-dc converters are some of the simplest power electronic circuits which convert one level of electrical voltage into another level by switching action. These converters have received an increasing deal of interest in many areas. This is due to their wide applications like power supplies for personal computers, office equipment, appliance control, telecommunication equipment, DC motor drives, automotive, aircraft, etc. The analysis, control and stabilization of switching converters are the main factors that need to be considered. Many control methods are used for control of switch mode dc-dc converters and the simple and low cost controller structure is always in demand for most industrial and high performance applications. Every control method has some advantages and drawbacks due to which that particular control method consider as a suitable control method under specific conditions, compared to other control methods. The voltage control of buck converter using PI, PID controller ,PIDSMC and microcontroller based PID control are modeled and are evaluated by computer simulations.. In addition to this, the closed loop feedback system using PID controller method will be implemented against transient response in the system. This project is only limited to design the closed-loop feedback system using proportional technique for buck converter. The controller will be implemented on a PIC microcontroller (PIC16F4011) and programmed through a computer using software of Mp Lab C compiler. The programmed PIC16F4011 will be able to automatically control the duty cycle of the system in order to apply an appropriate duty cycle to the system. It has been found that the transient performance and steady state performance is improved using microcontroller based PID controller. The simulated open loop and closed loop performance is verified experimentally. The experimental system is found to be more advantageous and cost effective with microcontroller.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.1. Overview

Switch mode DC-DC converters efficiently convert an unregulated DC input voltage into a regulated DC output voltage. Compared to linear power supplies, switching power supplies provide much more efficiency and power density. Switching power supplies employ solid-state devices such as transistors and diodes to operate as a switch: either completely on or completely off. Energy storage elements, including capacitors and inductors, are used for energy transfer and work as a low-pass filter. The buck converter and the boost converter are the two fundamental topologies of switch mode DC-DC converters. Most of the other topologies are either buck-derived or boost-derived converters, because their topologies are equivalent to the buck or the boost converters. Traditionally, the control methodology for DC-DC converters has been analog control. In the recent years, technology advances in very-large-scale integration (VLSI) have made digital control of DC-DC converters with microcontrollers and digital signal processors (DSP) possible. The major advantages of digital control over analog control are higher immunity to environmental changes such as temperature and aging of components, increased flexibility by changing the software, more advanced control techniques and shorter design cycles. Generally, DSPs have more computational power than microcontrollers. Therefore, more advanced control algorithms can be implemented on a microcontroller.

Switch-mode DC-DC converters are used to convert the unregulated DC input to a controlled DC output at a desired voltage level. Switch-mode DC-DC converters include buck converters, boost converters, buck-boost converters, Cuk converters and full-bridge converters, etc. Among these converters, the buck converter and the boost converter are the basic topologies. Both the buck-boost and Cuk converters are combinations of the two basic topologies. The full-bridge converter is derived from the buck converter.

There are usually two modes of operation for DC-DC converters: continuous and discontinuous. The current flowing through the inductor never falls to zero in the continuous mode. In the discontinuous mode, the inductor current falls to zero during the time the switch is turned off. Only operation in the continuous mode is considered in this dissertation.

1.2. Motivation

The switched mode dc-dc converters are some of the simplest power electronic circuits which convert one level of electrical voltage into another level by switching action. These converters have received an increasing deal of interest in many areas. This is due to their wide applications like power supplies for personal computers, office equipment, appliance control, telecommunication equipment, DC motor drives, automotive, aircraft, etc. The analysis, control and stabilization of switching converters are the main factors that need to be considered. Many control methods are used for control of switch mode dc-dc converters and the simple and low cost controller structure is always in demand for most industrial and high performance applications. Every control method has some advantages and drawbacks due to which that particular control method consider as a suitable control method under specific conditions, compared to other control methods. The control method that gives the best performances under any conditions is always in demand.

1.3 Thesis objectives

- To design a DC-DC buck converter of 24V/3V.
- To design a PID controller to obtain constant output voltage.
- Implementation of PID controller logic in microcontroller.
- To design SMC and implementation in microcontroller.

1.4 Literature Review

Voltage-mode control and Current-mode control are two commonly used control schemes to regulate the output voltage of dc-dc converters. Both control schemes have been widely used in low-voltage low-power switch-mode dc-dc converters integrated circuit design in industry. Feedback loop method automatically maintains a precise output voltage regardless of variation in input voltage and load conditions. Currently, there exist many different approaches that have been proposed for the PWM switching control design, e.g., state space averaging methods PID control, optimal control, sliding mode control and fuzzy control etc.

The dc-dc switching converters are the widely used circuits in electronics systems. They are usually used to obtain a stabilized output voltage from a given input DC voltage which is lower (buck) from that input voltage, or higher (boost) or generic (buck–boost). Each of these circuits is basically composed of transistor and diode making up the switching circuit and inductor and capacitor building the filter circuit. In addition to these, the circuit may have feedback circuit for the purpose of controlling the output parameters [1]. The design of buck converters and boost converters with a review over their state space equations led us to the derivative that the operation of such dc-dc converters is performed through two modes let the first mode be the on-state and the later is the off-state depending on the switching circuit [2-4]. After the study of the state space model of the converters the basic controlling circuits were implemented through voltage control, current control, PI and PID control techniques which were best for steady state analysis. However their performance was questioned for transient analysis [3-5]. This motivated the development of several non-linear control techniques for dc-dc converters like sliding mode control, hysteresis control etc. [6-7]. But the difficulty in implementing their mathematical model to the physical circuit led to the development of various feedback controllers [10].Switched mode dc-dc converters represent a particular class of the VSS, since there structure is periodically changed by the action of controlled switches and diodes. So it is appropriate to use sliding mode controllers in dc-dc converters [11].The use of SM (nonlinear) controllers can maintain a good regulation for a wide operating range. So, a lot of interest is developed in the use of SM controllers for dc-dc converters [12]. Siew-Chong Tan presented a detail discussion on the use of SM control for dc-dc power converters [13].Then SM controller is applied in higher order converters in 1989 [14]. Huang et al. applied SM control for cuk switching regulator. After this, series of related works on the cuk converter was carried out [15]-[18]. Fossas and Pas [19] applied a second-order SM control algorithms to buck converter for reduction of chattering. Then, two types of SM-control for boost and buck-boost converters: one using the method of stable system centre [20] and the other using sliding dynamic manifold [21] is proposed by Yuri B.Mattavelli et al. [22] proposed a general-purpose sliding-mode controller, which is applicable to most dc-dc converter topologies. The circuit complexity is same as current-mode controllers and it provides extreme robustness and speed of response against line, load and parameter variations. The same group derived small signal models for dc-dc converters with SM control, which allows the selection of control coefficients, the analysis of parameter variation effects, the evaluation of the closed loop performances like audio susceptibility, output and input impedances, and reference to output transfer function [23].Zhang li and QIU Shui-sheng implemented Proportional-Integral sliding mode controller in dc-dc converters. They showed that the implementation of PI SM control is simpler than other SM control schemes and steady state error is eliminated [24].Mahadeviet al. [25] Proposed state space averaging method to PWM based SM controlled dc-dc converters with a constant switching frequency. They also applied neural networks into their PWM-based SM controlled converters [26].Dc-dc converters can be operated either in continuous conduction mode (CCM) or in discontinuous conduction mode (DCM). Dc-dc converters that operated in DCM provide faster transient response (due to its low inductance) at the expense of higher device stresses. He also presented a fixed frequency PWM based sliding mode controllers for dc-dc converters operating in DCM [27]-[28].

1.5 Thesis Organisation

This thesis consists of this introductory chapter and five other chapters arranged as follows:

Chapter.1 covers the basic ideas, introduction, literature survey and the objective of the thesis.

Chapter.2. describes different converter topologies and their different mode of operation in MATLAB/SIMULINK environment.

Chapter .3 concerns about the different types of controllers that can be applied to dc-dc buck converter in MATLAB/ SIMULINK and analysis of results obtained in various cases using different controller topology for output voltage of dc-dc buck converter.

Chapter.4 covers the design procedure of dc-dc buck converter using microcontroller with PID algorithm as the base.

Chapter. 5 cover general conclusions and future scope with references and appendices.

DISCUSSION AND ANALYSIS OF VARIOUS CONVERTER TOPOLOGIES

2.1 Background

The switching converters convert one level of electrical voltage into another level by switching action. They are popular because of their smaller size and efficiency compared to the linear regulators. DC-DC converters have a very large application area. These are used extensively in personal computers, computer peripherals, and adapters of consumer electronic devices to provide dc voltages.

There are some different methods of classifying dc-dc converters. One of them depends on the isolation property of the primary and secondary portion. The isolation is usually made by a transformer, which has a primary portion at input side and a secondary at output side. Feedback of the control loop is made by another smaller transformer. Therefore, output is electrically isolated from the input. This type includes Fly-back dc-dc converters. However, in portable devices, since the area to implement this bulky transformer and other off-chip components is very big and costly, so non-isolation dc-dc converters are more preferred. The non-isolated dc/dc converters can be classified as follows:

- Buck converter (step down dc-dc converter),
- Boost converter (step up dc-dc converter),
- Buck-Boost converter (step up-down dc-dc converter, opposite polarity), and
- Cuk converter (step up-down dc-dc converter).

The dc-dc buck converters and the dc-dc boost converter are the simplest power converter circuits used for many power management and voltage regulator applications.

Hence, the analysis and design of the control structure is done for these basic converter circuits.

2.2 DC-DC BUCK CONVERTER

The buck converter circuit converts a higher dc input voltage to lower dc output voltage. The basic buck dc-dc converter topology is shown

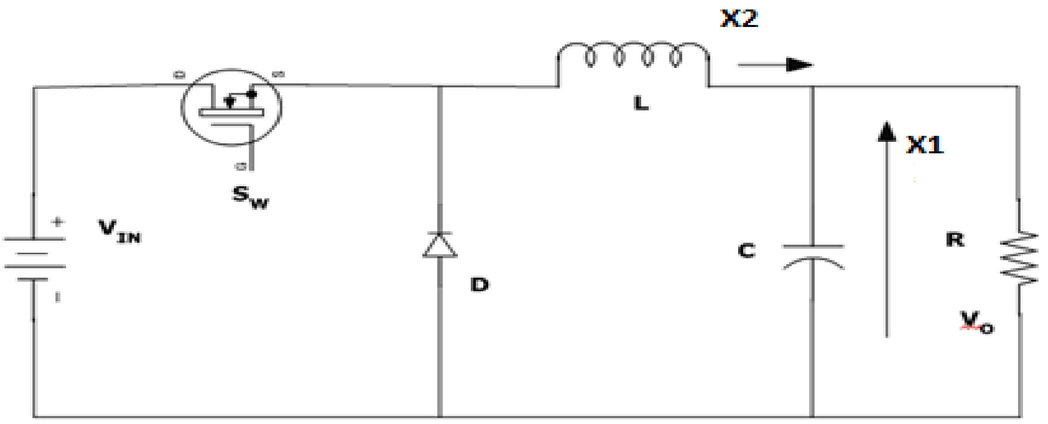


Fig.2.1 DC-DC buck converter

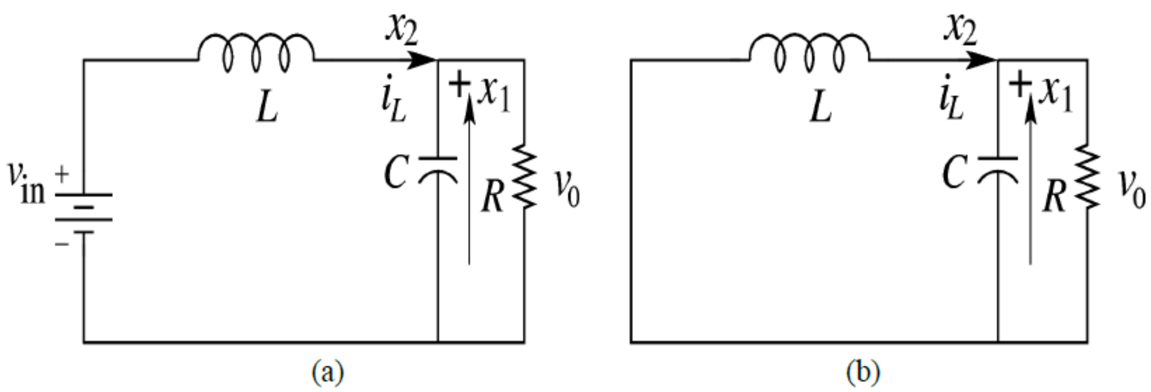


Fig. 2.2 Operating Modes of Buck Converter

a: On State b: Off State

It consists of a controlled switch (S_W), an uncontrolled switch (D), an inductor (L), a capacitor(C), and a load resistance(R).

The first sub-circuit state is when the switch is turned on, diode is reverse biased and inductor current flows through the switch. When the switch (S_W) is on and D is reverse biased, the dynamics of inductor current (I_L) and the capacitor voltage (V_C) are

$$\frac{d\, I_L(t)}{dt} = -\frac{1}{L} \times (Vo - Vin) \qquad (2.1)$$

$$\frac{dVc}{dt} = \frac{1}{C} i_c(t) \qquad (2.2)$$

The second sub-circuit state is when the switch is turned off and current freewheels through the diode. When the switch $S_w$iss off and *D* is forward biased, the dynamics of the circuit are

$$\frac{d\, I_L(t)}{dt} = -\frac{1}{L} \times Vo \qquad (2.3)$$

$$\frac{dVc}{dt} = \frac{1}{C} ic(t) \qquad (2.4)$$

The operation of dc-dc converters can be classified by the continuity of inductor current flow. So dc-dc converter has two different modes of operation that are

(a) Continuous conduction mode (CCM)

(b) Discontinuous conduction mode (DCM)

A converter can be designed in any mode of operation according to the desired value. When the inductor current flow is continuous of charge and discharge during a switching period, it is called Continuous Conduction Mode (CCM).When the inductor current has an interval of time staying at zero with no charge and discharge then it is said to be working in Discontinuous Conduction Mode (DCM) operation and the waveform of inductor current.

2.3 BUCK CONVERTER IN OPEN LOOP MODE

To demonstrate the performance of the proposed dc-dc buck converter, in MATLAB/Simulink with the parameters as given in Table 2.1. A constant voltage source of 24 V is input to the converter with R load having the value R =5Ω, . The complete model consists of a voltage source, a linear load, a voltage source PWM converter.

2.3.1 PARAMETERS [7]

Switching frequency	fs=20KHz
Input voltage	Vg=24 V
Duty cycle	D=0.125
Inductance	L= 0.087 mH
Capacitance	C=135 μF;
Load resistance	R_o =5 Ω;

Table 2.1

2.4 **SIMULATION**

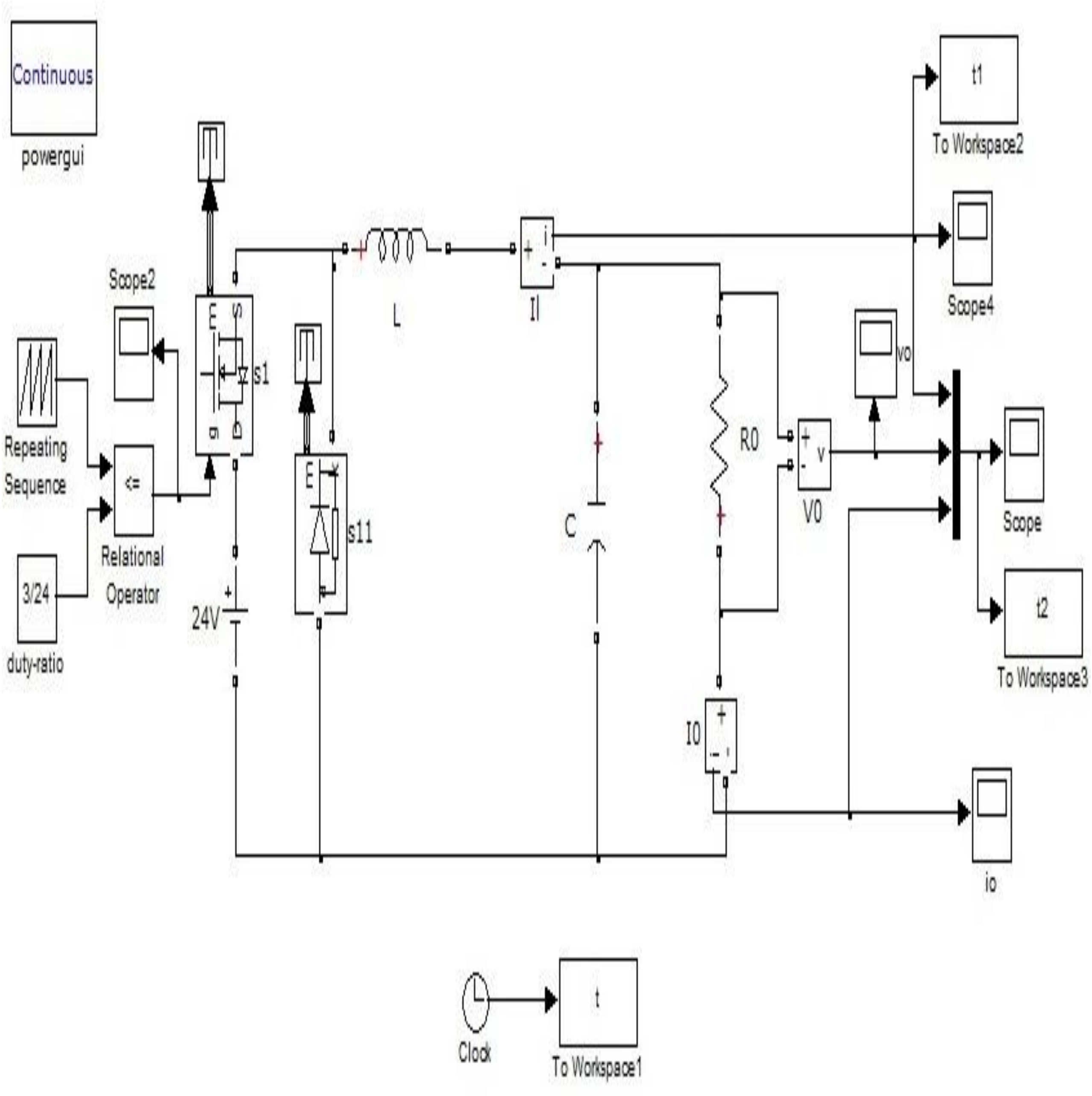


Fig.2.3 Simulink model for Buck Converter

2.4.1 RESULTS AND DISCUSSION

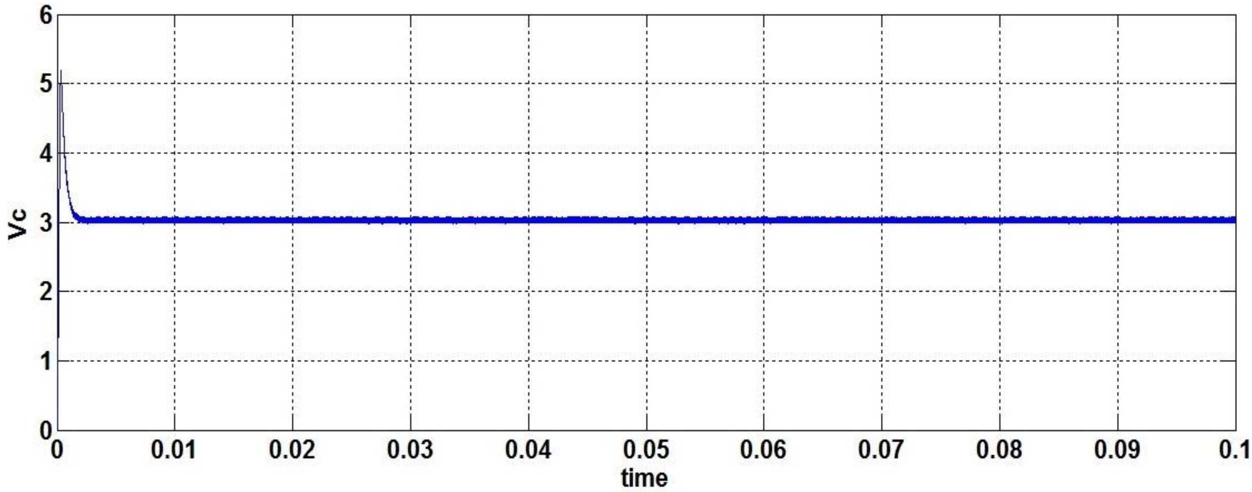


Fig 2.4 Capacitor voltage

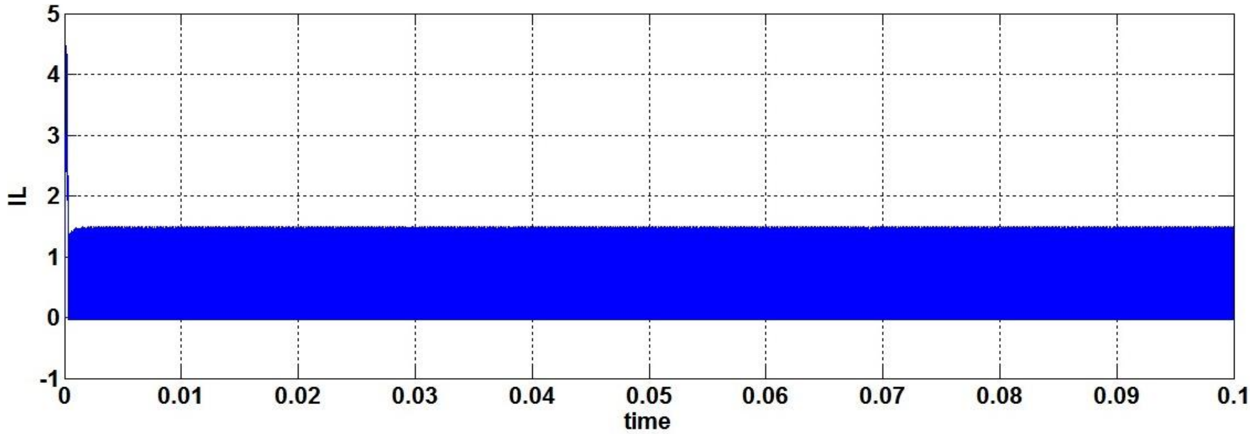


Fig 2.5 Inductor current

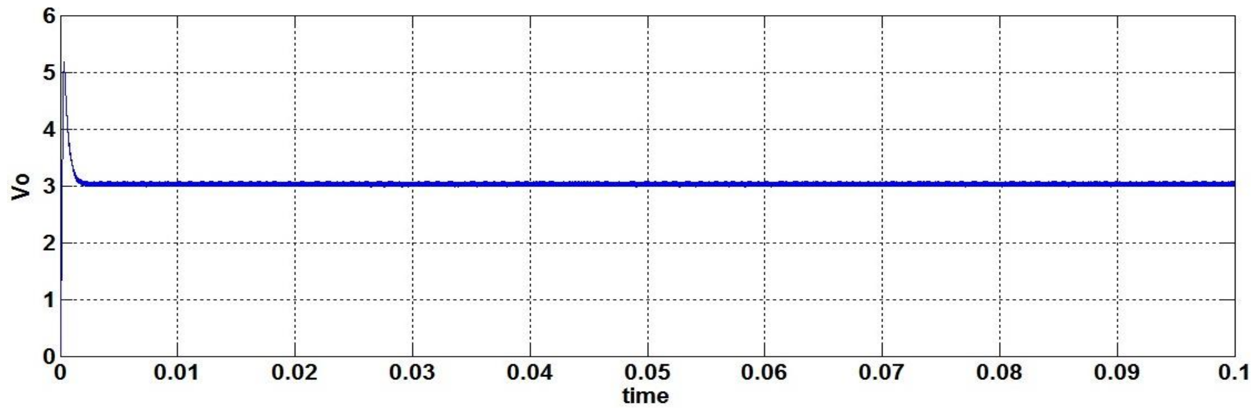


Fig 2.6 Output voltage

Summary

From the response obtained in MATLAB/Simulink the overshoot of output voltage is 73.3% and rise time is 0.162 milliseconds .The settling time is 18 milliseconds. As overshoot, rise time and settling times are too high ,to minimise it different controllers are used.

CHAPTER-3

ANALYSIS OF BUCK CONVERTER OUTPUT WITH DIFFERENT CONTROLLER

3.1 Introduction

Voltage-mode control and Current-mode control are two commonly used control schemes to regulate the output voltage of dc-dc converters. Both control schemes have been widely used in low-voltage low-power switch-mode dc-dc converters integrated circuit design in industry. Currently, there exist many different approaches that have been proposed for the PWM switching control design, e.g., state space averaging methods, PI control, PID control, optimal control, sliding mode control, PIDSMC control and fuzzy control etc.

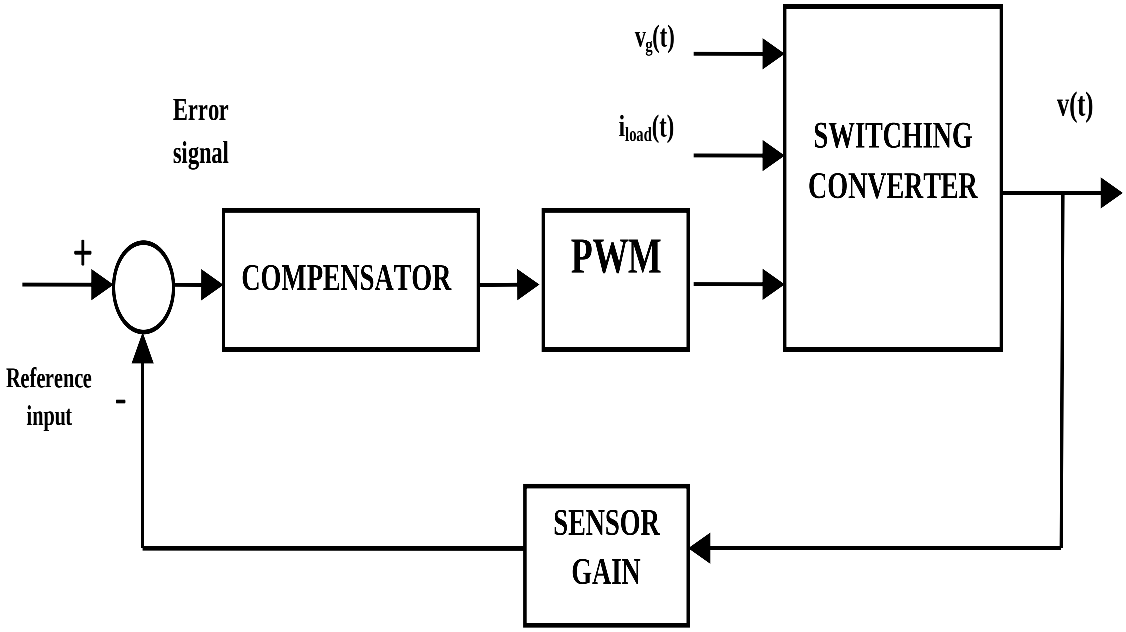


Fig . 3.1. Control circuit for DC-DC converter

3.2.PI Controller

A PI Controller fuses the properties of P and I controllers and the algorithm provides a balance of complexity and capability to be widely used in process control applications. It is reported that single input single-output PI controller controls 98% of control loop in paper and pulp industries. The equation which describes P controller is

$$u(t) = K_P * e(t) \tag{3.1}$$

whereK$_p$is proportional gain, e (t) is the error and u(t) is the perturbation in output signal of PI controller from the base value corresponding to normal operating conditions. It with no integration property always exhibit static error in the presence of disturbances and changes in set-point and shows a relatively maximum overshoot and long settling time as shown in Figure 6. To remove steady-state offset in controlled variable of a process, an extra intelligence is added to the P controller and this intelligence is t integral action. The controller is a PI controller whose mathematical notation is depicted in equation.

$$u(t) = K_c \left[e(t) + \frac{1}{K_i} \int_0^t e(t)dt \right] \quad (3.2)$$

3.2.1.BUCK CONVERTER WITH PI CONTROLLER

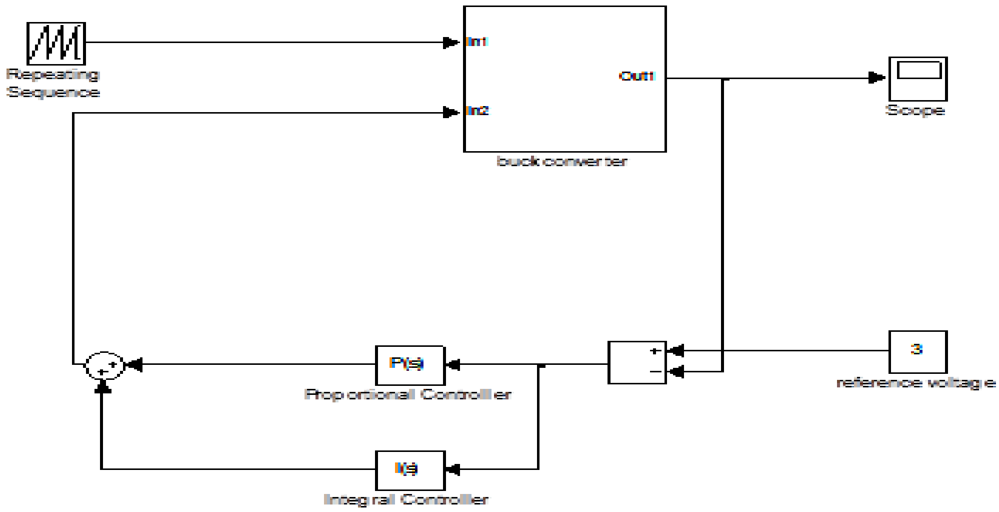


Fig.3.2. Simulink Diagram for Buck Converter with PI controller

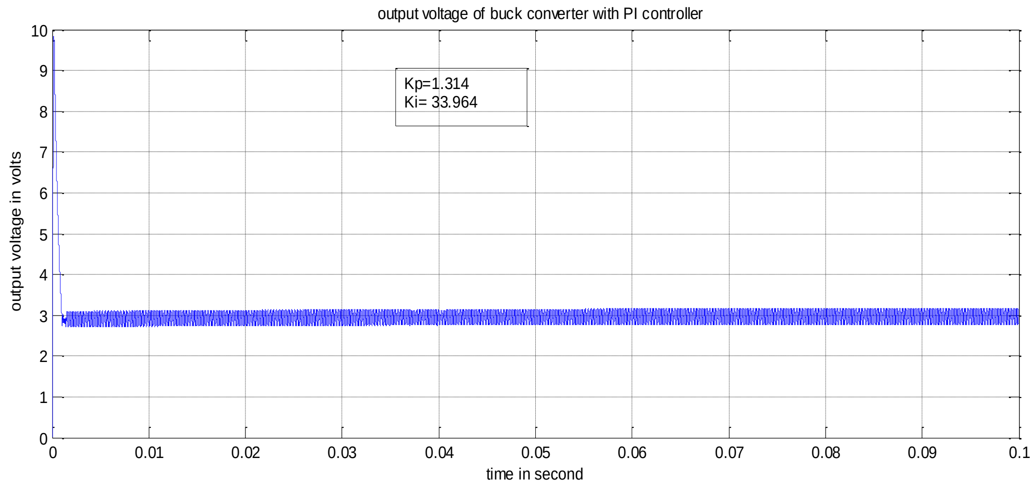


Fig3.2.2 Output voltage with PI controller

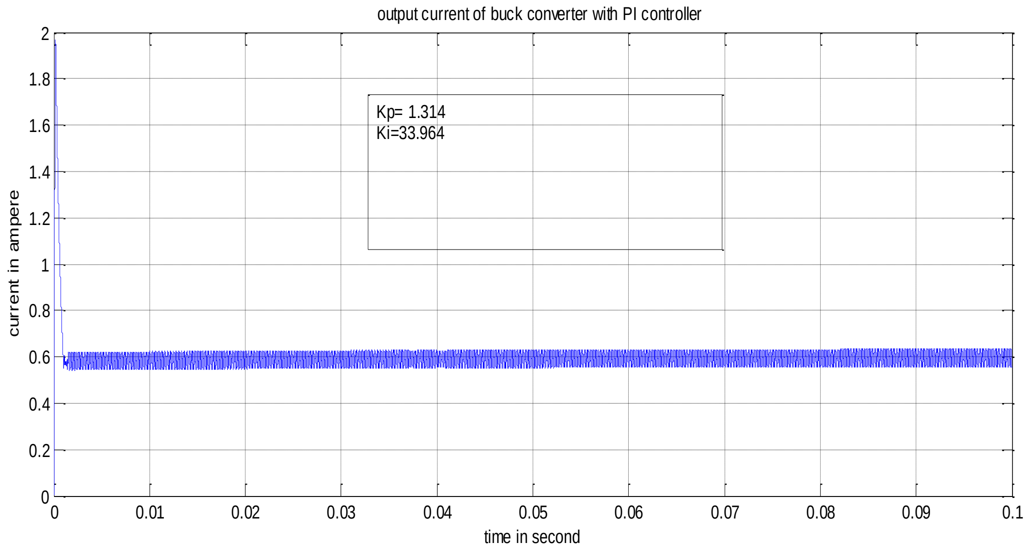


Fig 3.2.3 Output current with pi controller

From the response obtained in MATLAB/Simulink the overshoot of output voltage is 227% and rise time is 0.056 milliseconds .The settling time is 1.1 milliseconds. As overshoot is too high ,to minimise it another controller (PID) is used.

3.3 PID controller

A proportional-integral-derivative controller (PID controller) is a generic control loop feedback mechanism widely used in industrial control systems. A PID controller attempts to correct the error between a measured process variable and a desired set point.

The PID controller calculation (algorithm) involves three separate parameters; the Proportional, the Integral and Derivative values. The Proportional value determines the reaction to the current error, the Integral determines the reaction based on the sum of recent errors and the Derivative determines the reaction to the rate at which the error has been changing. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve or the power supply of a heating element. By "tuning" the three constants in the PID controller algorithm the PID can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set-point and the degree of system oscillation. Note that the use of the PID algorithm for control does not guarantee optimal control of the system.

3.3.1Proportional term

The proportional term makes a change to the output that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant Kp, called the proportional gain.

The proportional term is given by:

$P_{OUT} = K_P e(t)$(3.3)

Where

Pout: Proportional output

Kp: Proportional Gain, a tuning parameter

- e: Error = SP − PV
- t: Time or instantaneous time (the present)

A high proportional gain results in a large change in the output for a given change in the error. If the proportional gain is too high, the system can become unstable (See the section on Loop Tuning). In contrast, a small gain results in a small output response to a large input error, and a less responsive (or sensitive) controller. If the proportional gain is too low, the control action may be too small when responding to system disturbances. In the absence of disturbances pure proportional control will not settle at its target value, but will retain a steady state error that is a function of the proportional gain and the process gain. Despite the steady-state offset, both tuning theory and industrial practice indicate that it is the proportional term that should contribute the bulk of the output change.

3.3.2 Integral term

The contribution from the integral term is proportional to both the magnitude of the error and the duration of the error. Summing the instantaneous error over time (integrating the error) gives the accumulated offset that should have been corrected previously. The accumulated error is then multiplied by the integral gain and added to the controller output. The magnitude of the contribution of the integral term to the overall control action is determined by the integral gain, K_i.

The integral term is given by:

$$I_{OUT} = K_i \int_0^t e(\tau) d\tau \quad (3.4)$$

Where

Iout: Integral output

Ki: Integral Gain, a tuning parameter

Error = SP − PV

τ: Time in the past contributing to the integral response

The integral term (when added to the proportional term) accelerates the movement of the process towards set point and eliminates the residual steady-state error that occurs with a proportional only controller. However, since the integral term is responding to accumulated errors from the past, it can cause the present value to overshoot the setpoint value (cross over the set point and then create a deviation in the other direction). For further notes regarding integral gain tuning and controller stability, see the section on Loop Tuning.

3.3.3 Derivative term

The rate of change of the process error is calculated by determining the slope of the error over time (i.e. its first derivative with respect to time) and multiplying this rate of change by the derivative gain Kd. The magnitude of the contribution of the derivative term to the overall control action is determined the

$$D_{OUT} = K_d \frac{de}{dt} \qquad (3.5)$$

Where

Dout: Derivative output

Kd: Derivative Gain, a tuning parameter

e: Error = SP − PV

t: Time or instantaneous time (the present)

The derivative term slows the rate of change of the controller output and this effect is most noticeable close to the controller setpoint. Hence, derivative control is used to reduce the magnitude of the overshoot produced by the integral component and improve the combined controller-process stability. However, differentiation of a signal amplifies noise in the signal and thus this term in the controller is highly sensitive to noise in the error term, and can cause a process to become unstable if the noise and the derivative gain are sufficiently large. The output from the three terms, the proportional, the integral and the derivative terms are summed to calculate the output of the PID controller.

First estimation is the equivalent of the proportional action of a PID controller. The integral action of a PID controller can be thought of as gradually adjusting the output when it is almost right. Derivative action can be thought of as making smaller and smaller changes as one gets close to the right level and stopping when it is just right, rather than going too far. Making a change that is too large when the error is small is equivalent to a high gain controller and will lead to overshoot. If the controller were to repeatedly make changes That were too large and repeatedly overshoot the target, this control loop would be termed unstable and the output would oscillate around the setpoint in a either a constant, a growing or a decaying sinusoid. A human would not do this because we are adaptive controllers, learning from the process history, but PID controllers do not have the ability to learn and must be set up correctly. Selecting the correct gains for effective control is known as tuning the controller.

If a controller starts from a stable state at zero error (PV = SP), then further changes by the controller will be in response to changes in other measured or unmeasured inputs to the process that impact on the process, and hence on the PV. Variables that impact on the process other than the MV are known as disturbances and generally controllers are used to reject disturbances and/or implement set point changes.

In theory, a controller can be used to control any process which has a measurable output (PV), a known ideal value for that output (SP) and an input to the process (MV) that will affect the relevant PV. Controllers are used in industry to regulate temperature, pressure, flow rate, chemical composition, level in a tank containing fluid, speed and practically every other variable for which a measurement exists. Automobile cruise control is an example of a process outside of industry which utilizes automated control. Kp: Proportional Gain - Larger Kp typically means faster response since the larger the error, the larger the feedback to compensate. An excessively large proportional gain will lead to process instability. Ki: Integral Gain - Larger Ki implies steady state errors are eliminated quicker. The trade-off is larger overshoot: any negative error integrated during transient response must be integrated away by positive error before we reach steady state. Kd: Derivative Gain - Larger Kd decreases overshoot, but slows down transient response and may lead to instability.

3.3.4 **Loop tuning**

If the PID controller parameters (the gains of the proportional, integral and derivative terms) are chosen incorrectly, the controlled process input can be unstable, i.e. its output diverges, with or without oscillation, and is limited only by saturation or mechanical breakage. Tuning a control loop is the adjustment of its control parameters (gain/proportional band, integral gain/reset, derivative gain/rate) to the optimum values for the desired control response.

Some processes must not allow an overshoot of the process variable beyond the set point if, for example, this would be unsafe. Other processes must minimize the energy expended in reaching a new setpoint. Generally, stability of response (the reverse of instability) is required and the process must not oscillate for any conditions or set points.

Some processes have a degree of non-linearity and so parameters that work well at full-load conditions don't work when the process is starting up from no-load. This section describes some traditional manual methods for loop tuning.

There are several methods for tuning a PID loop. The most effective methods generally involve the development of some form of process model, and then choosing P, I, and D based on the dynamic model parameters. Manual "tune by feel" methods have proven time and again to be inefficient, inaccurate, and often dangerous.

The choice of method will depend largely on whether or not the loop can be taken "offline" for tuning, and the response time of the system. If the system can be taken offline, the best tuning method often involves subjecting the system to a step change in input, measuring the output as a function of time, and using this response to determine the control parameters

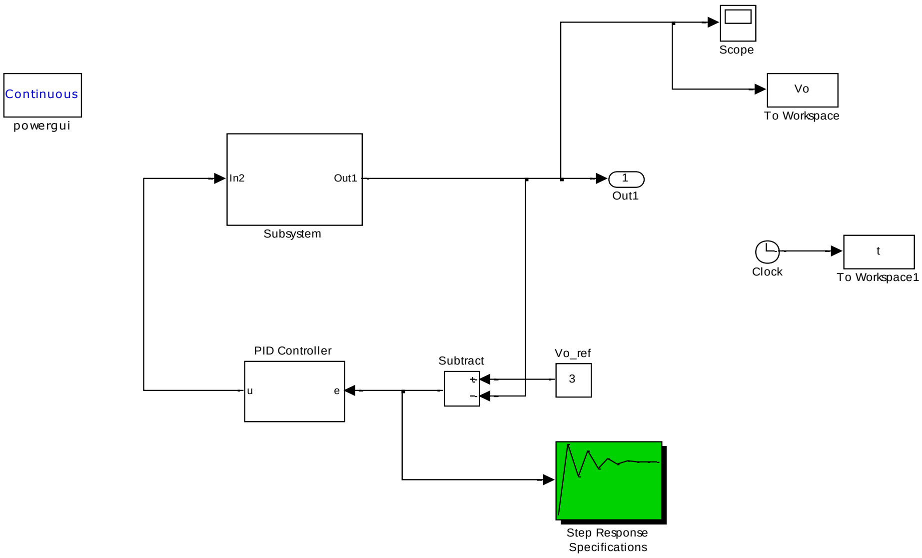
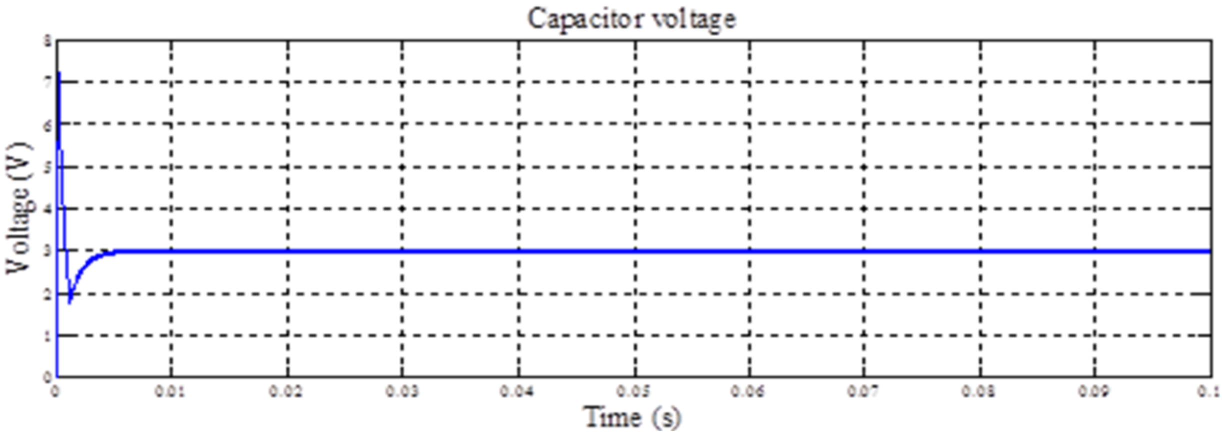
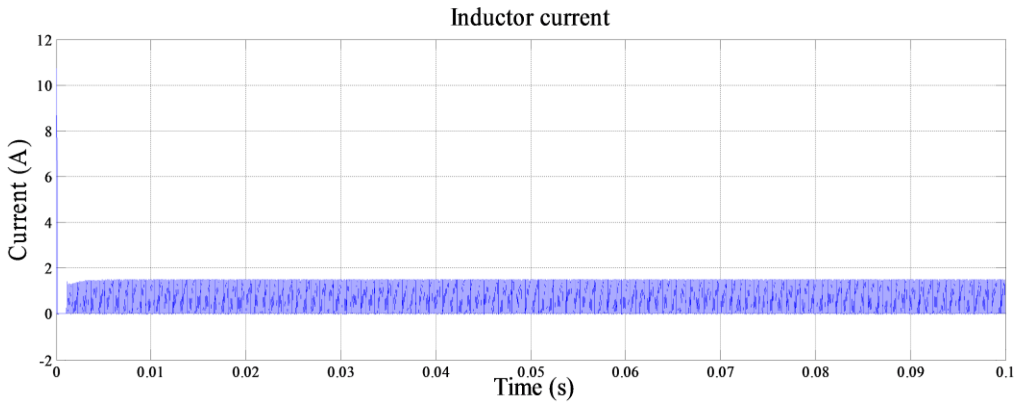


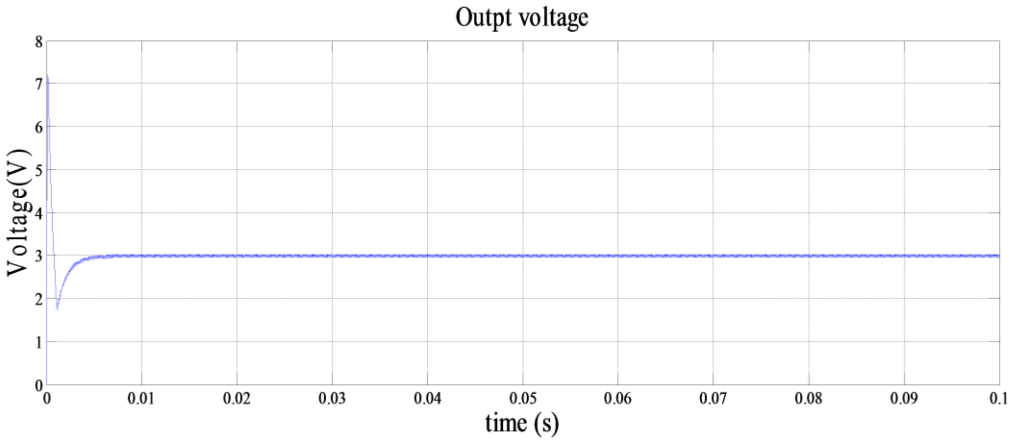
Fig.3.3.1 MATLAB/Simulink model of Buck Converter with PID controller

(a)





(b)



(c)

Fig 3.3.2. Buck converter responses with PID controller

(a) Capacitor voltage
(b) Inductor current
(c) Output voltage

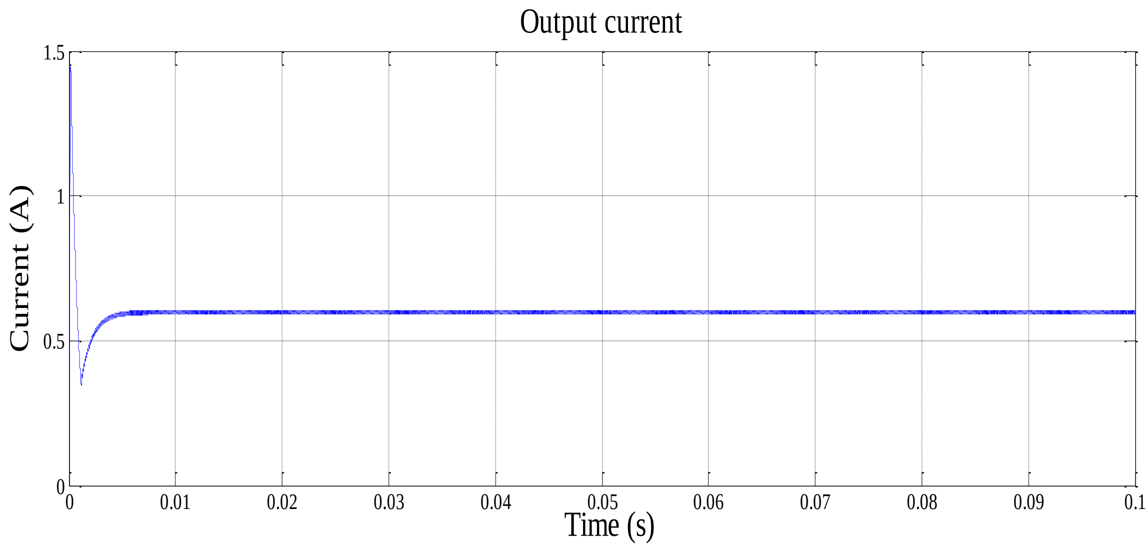


Fig3.3.3 Output current

From the response obtained in MATLAB/Simulink the overshoot of output volage is 213% and rise time is 0.047 milliseconds .The settling time is 0.6 milliseconds.As overshoot is too high ,to minimise it another controller (SMPID) is used.

3.4 SLIDING MODE PID CONTROLLER

Sliding mode control (SMC) for DC/DC converters is a topic that has been covered in numerous publications during the last decade. Originating from the control engineering field sliding mode techniques are well described and many advanced implementations are possible. For most DC/DC applications, low controller complexity is desirable (to reduce cost and simplify design and implementation), and generally, simple control schemes such as PD or PID voltage-mode are preferable. The sliding mode PID voltage controller is particularly useful, due to its high performance and simple implementation. To increase the applicability of the solution, proper modelling tools are needed so that the closed-loop control system performance can be predicted, analysed and optimized.

Designing of Sliding mode is based on three conditions.

Existence Condition.

Reaching Condition.

Stability Condition.

Existence conditions.

The trajectory is required either to slide or switch after reaching the switching function.

The existence condition for SMC

$$\lim_{\sigma\to 0^+} \frac{d\sigma}{dt} < 0 \quad (3.6)$$

$$\lim_{\sigma\to 0^-} \frac{d\sigma}{dt} > 0 \quad (3.7)$$

Reaching conditions.

Design the switching function in such a way that our initial equilibrium point will reach the switching trajectory.

System: $dx = f(x,t,u)$

$$u = \begin{Bmatrix} u^+ \ for \ \ \sigma(x) > 0 \\ u^- \ for \ \ \sigma(x) < 0 \end{Bmatrix} \quad (3.8)$$

Sufficient reaching condition

$$X^+ \ \varepsilon \ \ \sigma(x) < 0$$

$$X^- \ \varepsilon \ \ \sigma(x) > 0$$

u = Scalar discontinuous function

X = steady state representative point

+ = positive surface

- = negative surface

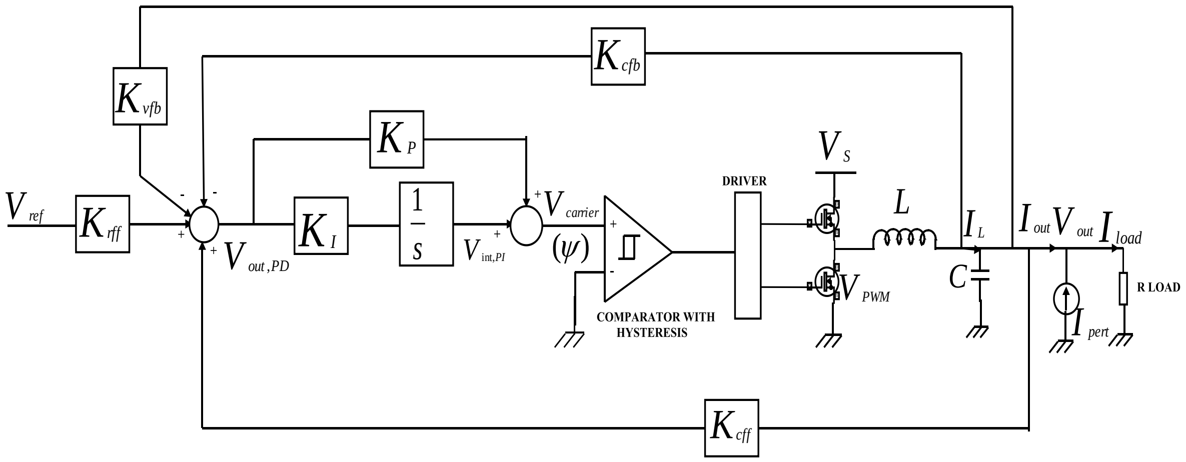


Fig3.4.1 Derived model of a sliding mode PID voltage-mode control system for a buck converter[23].

To simplify analysis the PID compensator is considered as cascaded PD and PI compensators. For the PD compensated buck converter output voltage, following relationship is found

$$V_{out,PD}(s) = -V_{out}(s).\frac{R_D}{R_{PI}}(1 + sR_DC_D) + V_{ref}.\frac{R_{rff}}{R_{PI}} \quad (3.9)$$

Using the basic description of a capacitor and Kirchoff's current law leads to

$$V_{out,PD} = -V_{out}.\frac{R_{PI}}{R_D} - \frac{R_{PI}}{R_D}\frac{R_DC_D}{C}.\left[I_L - I_{load} + I_{pert}\right] + V_{ref}.\frac{R_{rff}}{R_{PI}} \quad (3.10)$$

This suggests that the PD compensated buck converter output voltage feedback system is functionally equivalent to a full state-feedback control system with ideal output current feed-forward compensation (as illustrated in above figure) – the output current is fed back with equal gain but opposite polarity compared to the inductor current. Using the constants given in Table 1, this can be rewritten to:

$$V_{out,PD} = -KV_{vfb}.V_{out} - K_{cfb}.I_L + K_{cff}.(I_L - I_{pert}) \quad (3.11)$$

The PI part of the compensator introduces an extra state to the system, the output of the integrator part, $v_{int,PI}$ is chosen for this state. The relationship between input and output of the PI compensator is:

$$V_{carrier}(s) = V_{out,PD}.\frac{1+sR_{PI}C_{PI}}{sR_{PI}C_{PI}} = V_{out,PD}.\left(1+\frac{1}{s}.\frac{1}{R_{PI}C_{PI}}\right)(3.12)$$

The integrator output is then given by:

$$v_{int,PI} = V_{out,PI}.\frac{1}{s.R_{PI}C_{PI}}(3.13)$$

This leads to the following state equation for $v_{int,PI}$

$$\dot{v}_{int,PI} = K_1.[-K_{vfb}.V_{out-}K_{cfb}.I_L + K_{cff}.I_{out} + K_{rff}.V_{ref}](3.14)$$

The found expressions for the constants in the PID controller equivalent model are listed in Table 2

Parameter		Expression
Output voltage feedback gain	K_{vfb}	$\frac{R_{PI}}{R_D}$
Inductor current feedback gain	K_{cfb}	$\frac{R_{PI}C_D}{C}$
Output current feed-forward gain	K_{cff}	$\frac{R_{PI}C_D}{C}$
Reference summation gain	K_{rff}	$\frac{R_{PI}}{R_{rff}}$
PI compensator proportional gain	K_P	1
PI compensator integral gain	K_I	$\frac{1}{R_{PI}C_{PI}}$

Table 3.1 Gains in PID controller equivalent model [23]

To demonstrate the performance of the proposed dc-dc buck converter using sliding mode PID controller in MATLAB/Simulink with the parameters as given in Table 3. A constant voltage source of 30 V is input to the converter with R load having the value R =1KΩ, . The complete model consists of a voltage source, a linear load, a voltage source PWM converter.

COMPONENTs	**PARAMETERs**	**VALUE IN PROTOTYPE**
Output inductor	L	10 µH
Output capacitance	C	0.99 µF
Inductor/switch series R	R_S	100 mΩ
Total time delay	t_d	60 ns
PID component	R_d	10 kΩ
PID component	C_d	180 pF
PID component	R_{PI}	1 kΩ
PID component	C_{PI}	10 nF
Ref. injection resistor	R_{RFF}	1kΩ

Table 3.2 SMC PID buck prototype design parameters[23]

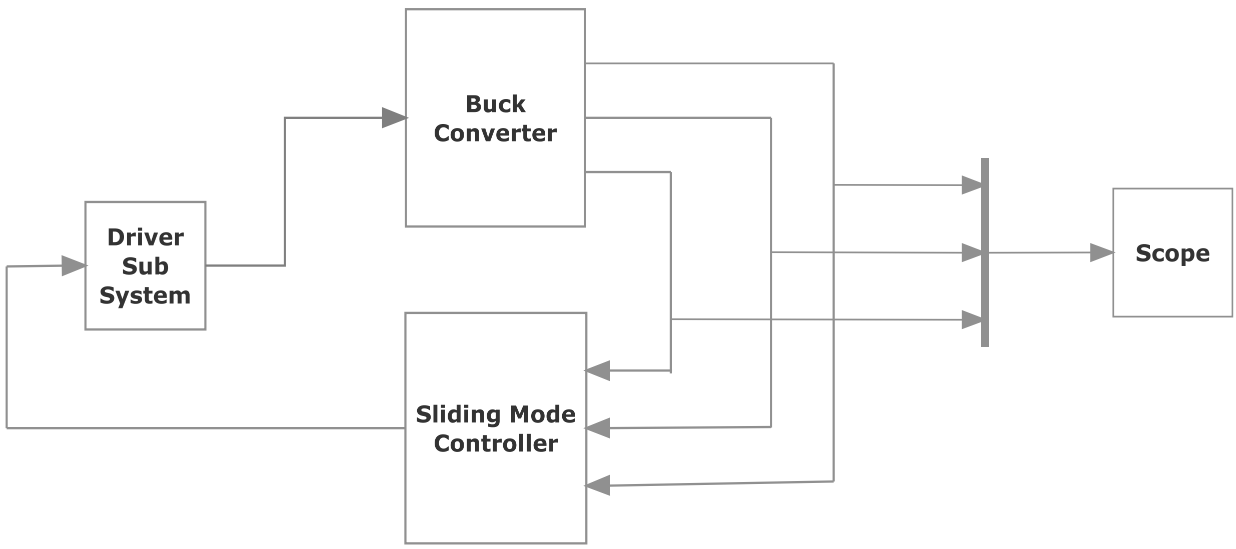


Fig3.4.2 Block diagram of sliding mode PID voltage-mode control system for a buck converter.

RESULTS

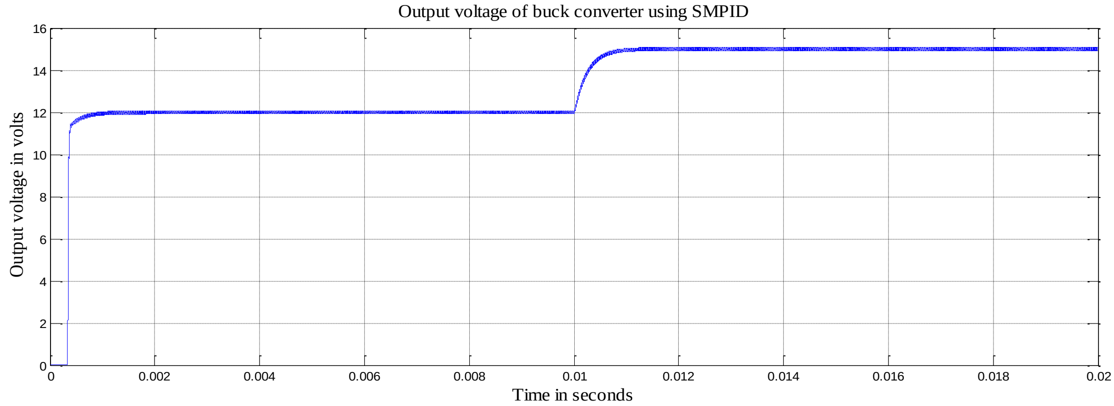


Fig 3.4.3.Output voltage with SMPID controller

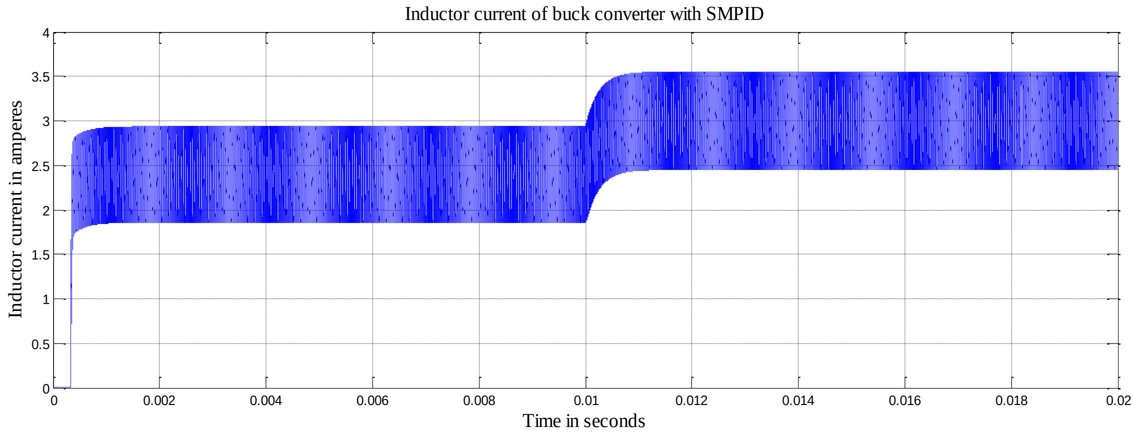


Fig 3.4.4 Inductor current with SMPID controller

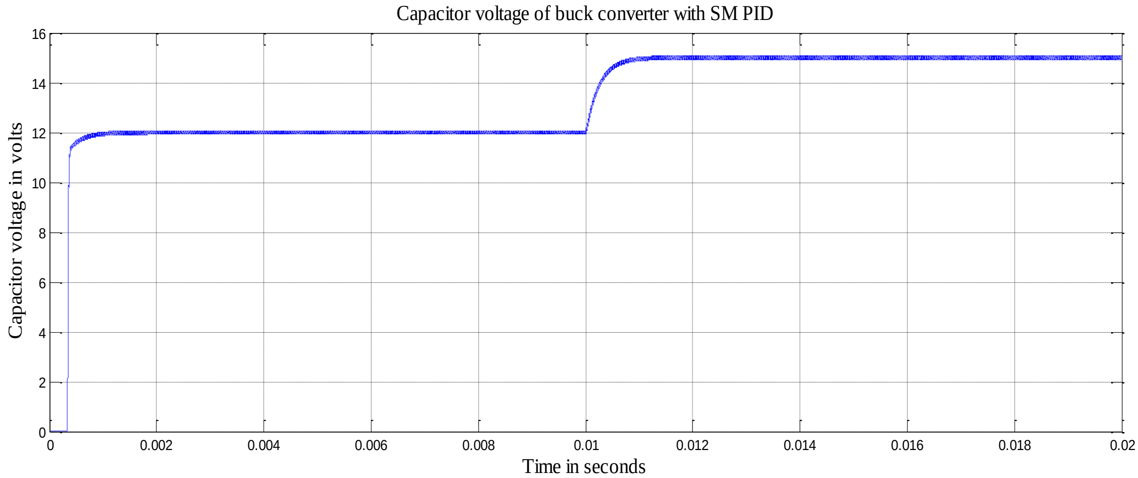


Fig3.4.5Capacitor voltage with SMPID controller

From the response obtained in MATLAB/Simulink the overshoot of output volage is 0.08% and rise time is 0.01 milliseconds .The settling time is 0.01

milliseconds.SMPID is best suitable to obtain the desired values among PI,PID and SMPID controllers.

RESULTS AND DISCUSSIONS:

Parameter	**Without controller**	**With PI controller**	**With PID controller**	**With sliding mode PID controller**
% Overshoot	73.3	227	213	0.08
Rise time(in ms)	0.162	0.056	0.047	0.01
Settling time(in ms)	18	1.1	0.6	0.01

Table 3.3

3.5 Summary

The time response analysis of the dc-dc buck converter are done by observing their damping nature of oscillatory transient signals mainly the output voltage in terms of various parameters like time required to settle to a steady state desired value from the initial high transient values, the maximum value that the output voltage attains during the transient period and the duration after which the desired output value is reached for the first time. These objectives are satisfied by measuring the rise time, settling time and overshoot from the graphical results obtained from the simulation. Same approach is repeated for all the controller topologies implemented with dc-dc buck converter discussed and the results are given in a tabular manner for better clarity.

It is seen that the SMPID controller meets our demand of controlling the output voltage of dc-dc buck converter in a smooth manner without much more chattering in the transient period by decreasing the rate of transition between the states of high frequency oscillation and low frequency steady state value and thereby shows a sharp decrease in rise time and settling time. The implementation of SMPID controller also reduces the unwanted peak of output voltage during the transient period almost to zero and therefore reduces the chances of damage due to sudden rise of voltage in modern day power electronic devices having a very narrow tolerance zone to meet the requirements ultrafast performance.

4.1 Design Concept

The project design constraints on power efficiency, lower cost, and less reduce space and components used. For higher power application, power supplies that need to provide higher current not suitable use to the chip since the current is too high for handled and it might cause IC damage. And therefore it may cause instability condition when the load or input voltage changing may cause system at risk. Dynamic power losses are due to the switching behavior of the selected pass devices (MOSFETs, Power Transistors, IGBTs, etc.). These losses include turn-on and turn-off switching losses and switch transition losses. Since an increasing of power electronics circuits in many applications such used in automobiles to laptops which use an integrated circuit (IC) and form in smaller size. The lower system cost improvement of power supply show in designing of power supplies using analogue techniques requires components to be oversized to compensate for component variation and component drift. Using analog circuitry to implement system control functions is not always cost-effective or flexible. Losses in an electric or power electronics circuits come from many source, in this project the losses such a resistive losses in the controllable switch, capacitive losses due to charging of the controllable gates and parasitic capacitances, short circuit current through the controllable switch especially current flow during switch open and voltage drop across when switch is closed and the parasitic losses of filter in an inductor and capacitor. More that, in order to regulate the output voltage, the duty cycle to the buck converter is set by a feedback control loop, but to associate the controller design to buck converter power elements, it may cause inefficient in power conversion. To ensure the systemstability and for improving transient output response, the more complex proportional integral derivative (PID) controller can be implemented.

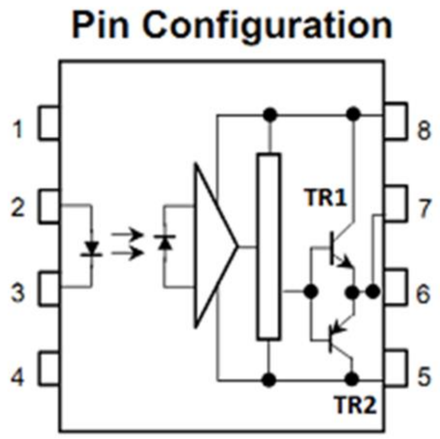
4.2 Components Review

4.2.1 Bridge rectifier

In order to produces unregulated dc supply voltage up to 15Vdc from main supply of 240Vac, this silicon bridge rectifier is used to the circuit. The cost of this component is cheap with the features maximum average forward output current.

4.2.2Opto-isolator IC (TLP 250)

The opto-isolator is used to convert the voltage mode (output voltage) read from Buck converter to an appropriate value of gate pulse of 50KHz,5Vto perform closed loop feedback conversion system in order to maintain output voltage at desired level. The data sheet is given in the appendix A.

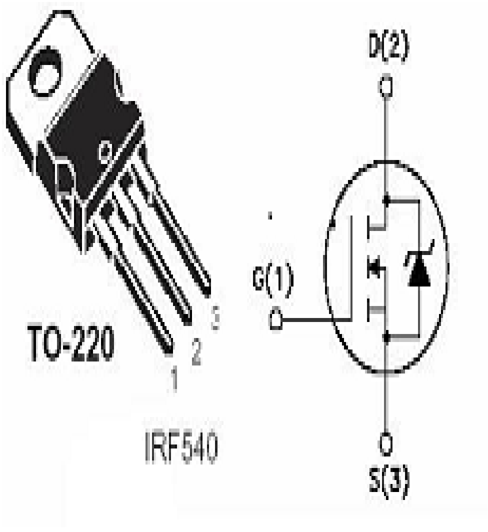


1. NC
2. Anode
3. Cathode
4. NC
5. Ground
6. V_o(OUTPUT)
7. V_o(OUTPUT
8. V_{CC}

Fig.4.1 Pin Configuration of TLP 250

4.2.3 MOSFET

SMPS MOSFET has limitations operation in terms of voltage, current and power dissipation. The power absorbed by the gate drive circuitry should not significantly affect the overall efficiency. The power MOSFET current rating is related with the heat dissipated in the devices. This rating will be take in consideration for designing appropriate circuit to protect power MOSFET against high voltage and current, thus cause heat generation. While considering protection of power MOSFET against over voltage, a distinction has to be made between slowly varying over voltage and short time surge. It is about 100Vdc the minimum rating of drain to source breakdown voltage. Gate voltage must be 10-25V higher than the drain voltage. Being a high side switch, such gate voltage would have to be higher than the rail voltage, which is frequently the higher voltage available in the system. The data sheet is given in the appendix B.



1. Gate
2. Drain
3. Source

Fig.4.2 Pin Configuration of IRF 540

4.2.4 Capacitor

The capacitor is chosen with minimum loss because switched power regulators are usually used in high current-performance power supplies. Loss occurs because of its internal series resistance and inductance. Commonly capacitors for switched regulators are chosen based on the equivalent series resistance (ESR).

The capacitance of the capacitor (C) is given by

$$C = \frac{(1-D)}{16Lf^2} \qquad (4.1)$$

4.2.5 Inductor

The function on inductor is to store energy and the value is selected to maintain a continuous current mode (CCM) operation as a rated of load (5 Ω) is decided for this Buck converter. In CCM, current flow continuously in inductor during the entire switching cycle and output inductance selected to limit the peak to peak ripple current flowing. The factors tobe considered in selecting the inductor are its peak to peak ripple current (CCM), maximum dc or peak current (not overheat) and maximum operating frequency (maximum core loss is not exceeded, resulting in overheating or saturation).

The inductance of the inductor (L) is given by

$$L = \frac{(1-k)R}{2f} \qquad (4.2)$$

4.2.6 PIC microcontroller

The microcontroller selected to control the closed –loop feedback conversion power was the 40-pin PDPIP package of the PIC30F4011. The pin configuration is given in Fig 5.3. A primary benefit of this microcontroller is the flexibility of the many I/O pins to accommodate analog to digital signals other than easy to firm the program.

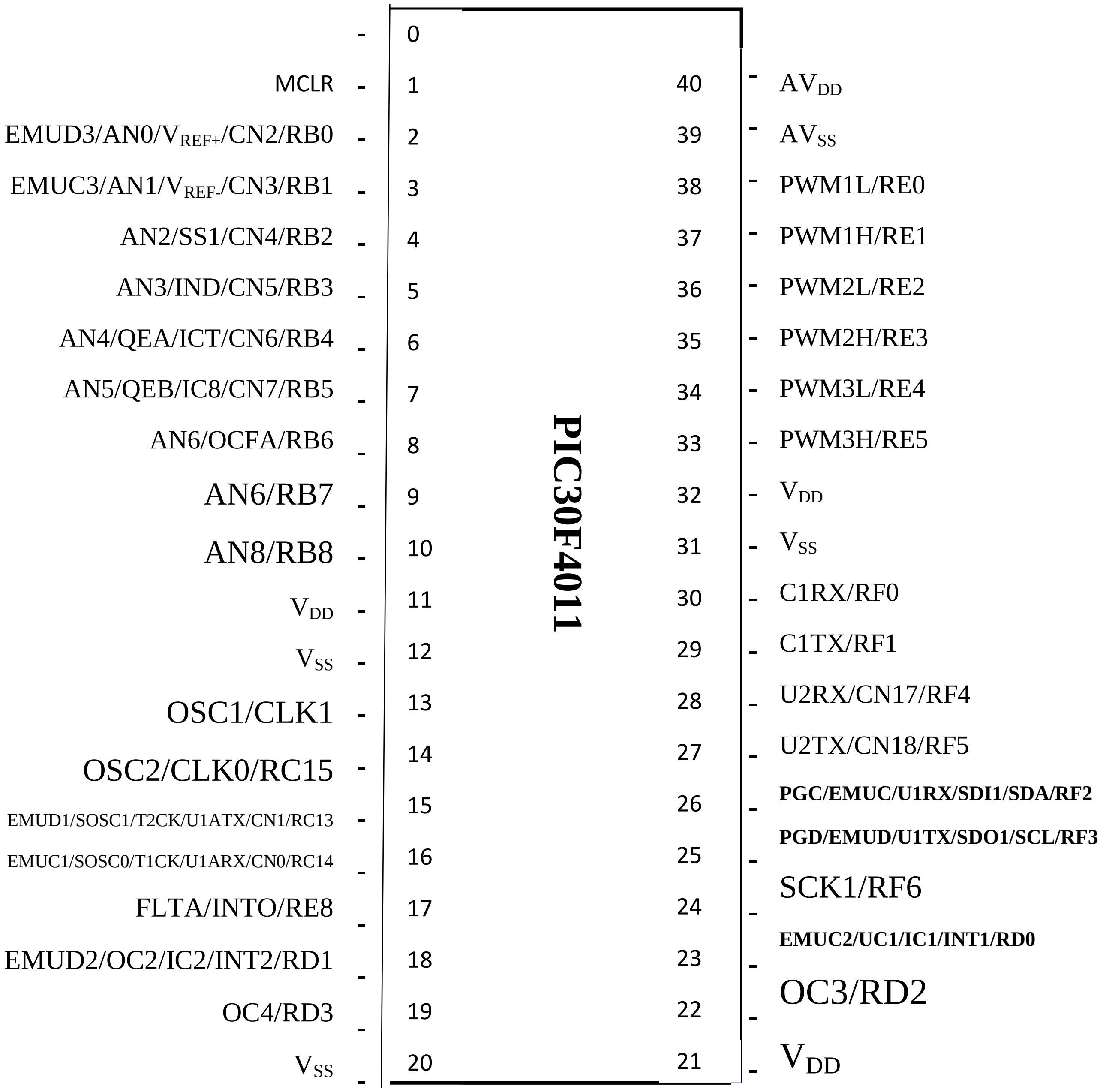


Fig. 4.3 Pin configuration of PIC30F4011

4.3 PID BASED MICROCONTROLLER

This Buck system is closed loop feedback system, in order to simulate or to firm the program for controller, the basic such Proportional Error Gain (P-Gain) which this parameter produces a correction factor that is proportional to the magnitude of the output voltage error, an integral error gain (I-Gain) which this parameter uses the cumulative voltage error to generate a correction factor that eliminates any residual error due to limitations in offset voltages and measurement resolution an Derivative error gain (D-Gain) which this parameters produces a correction factor that is proportional to the rate of change of the output error voltage, which helps the system respond quickly to changes in the system conditions. Feed forward gain – this parameter produces a correction factor that is computed based on the magnitude of the input voltage, inductor current and circuit attributes such an inductor and capacitor value. Thistermallow the control loop to be protective rather than reactive. In other words, when the input voltage changes, feed forward gain responds so that the control loop does not have to wait until the output voltage changes before making the appropriate gain correction. Using the PID algorithm, the proportional,integral and derivative error of the actual versus the desired output voltage is combined to control the PWM duty cycle. The PID algorithm will be used in voltage mode control loops. The PID software is typically small, but its execution rate is very high, often hundreds of thousands of iterations per second. This highiteration raterequires the PID software routine be as efficient as possible to minimize performance. The PID control-loop is interrupt-driven by the ADC on a fixed-time basis. Any system function that can be executed in the “idle loop” should be, in order to reduce the unnecessary workload within the PID control software. Functions such as voltage ramp up/down, error detection, feed-forward calculations and communication support routines are candidates for the idle loop. Any other interrupt-driven processes, such as communication, must beat lower priority than the PID loop.

4.3.1 Voltage –mode control

Voltage-mode control is the methods of control based on analog switch-mode power supply (SMPS) control techniques. In voltage mode, the difference between desired and actual output voltage (error) controls the time that the supply voltage is applied across the inductor, which indirectly controls current flow in the inductor. Varying the duty cycle essentially adjusts the input voltage drive to the Buck's LC components which directly effects. Voltage-mode can provide more stability in a noisy environment and over a wide operating range.

4.4 PIC Microcontroller Tools Development

4.4.1Picbasic pro compiler (pbp)

PICBASIC PRO™ Compiler is the easiest way to program the fast and powerful Microchip Technology PIC microcontrollers (PIC30F4011). PICBASIC PRO converts BASIC programs into files that can be programmed directly into a PIC MCU. The BASIC language is much easier to read and write than the quirky Microchip assemblylanguage. PBP compiler produces code that may be programmed into a wide variety of PIC microcontroller having from 8 up to 84 pins and various on-chipfeatures including A/D converters, hardware timers and serialports. The PIC30F4011 use Harvard technology to allow rapid erasing and reprogramming for program debugging. The PIC30F4011 devices also contain between 64 and 1024 bytes ofnon-volatile data memory that can be used to store program and data and other parameters even when the power is turned off.

4.4.2 Window interface software

Mplab is actually Integrated Development Environment (IDE) with In Circuit Debugging (ICD) capability designed specifically for PICBASIC PRO compiler. This software is easy to set up and capable to identify, correct the compilation and assembler an error. The controller algorithm programming writtenin Mplab..

4.4.3 Programming Adapters and mplabs U2 pic programmer

The melabs U2 PIC Programmer is driven and powered from a single USB port on computer. Then adapters connect the programmer's 40-pin expansion header to allow programming of PIC microcontrollers in DIP, PLCC or surface mount packages.

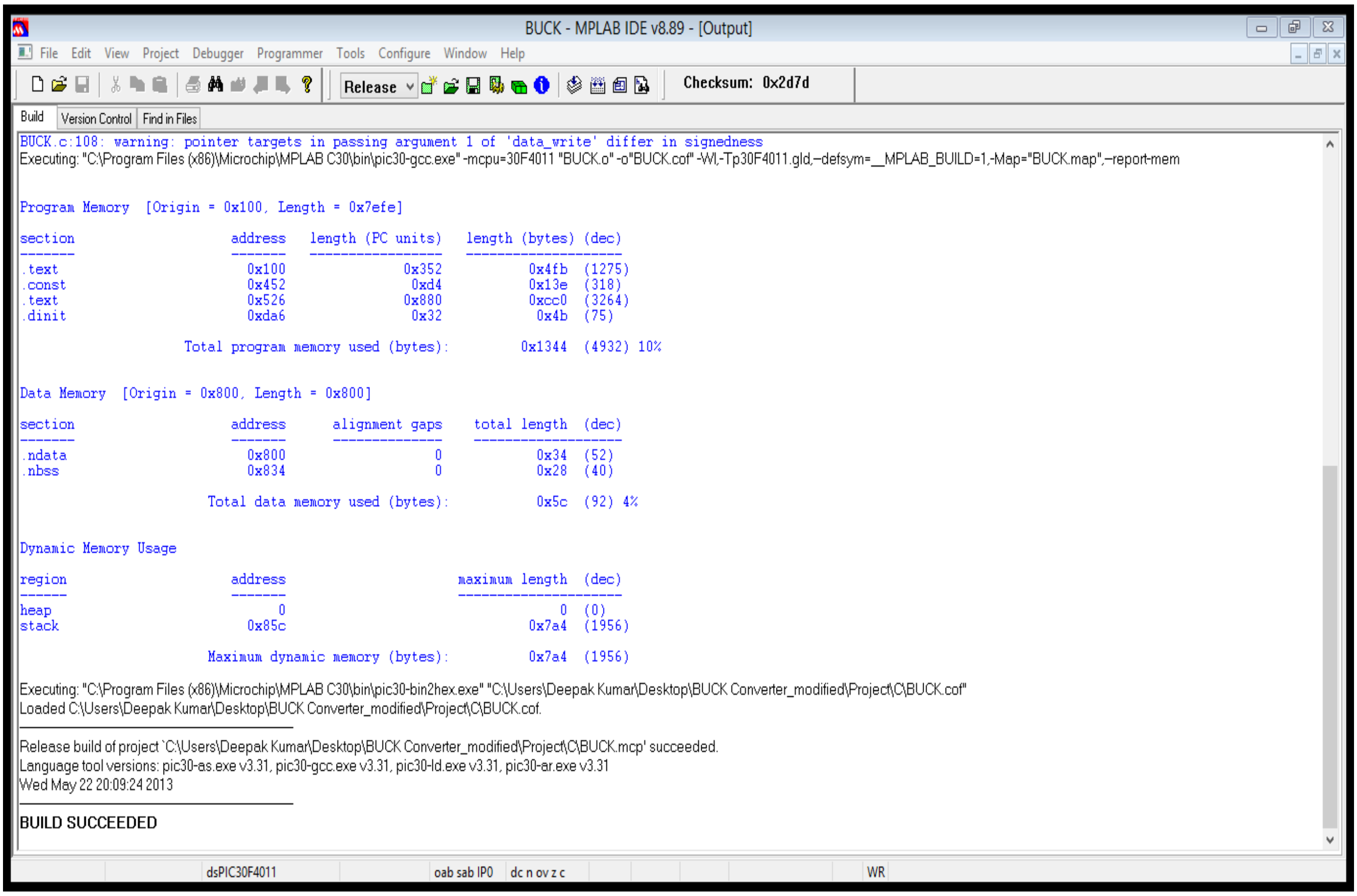


Figure 4.4: Mp lab SCREENSHOTS

METHODOLOGY

4.5 Introduction

This chapter explains about hardware development such as equipments, procedures and method design for Buck converter including controller technique used in closed-loop feedback system. This chapter also explains about the software interface and the complete operation of the Buck converter. Before looking at the details of all methods below, it is good to begin with brief review of the problem that is considered in this Buck converter. The changing of voltage from input supply will be consider as problem need to against by apply feedback controller in order to maintain an output from Buck converter.

4.5.2 Hardware Development

4.5.3 Circuit function

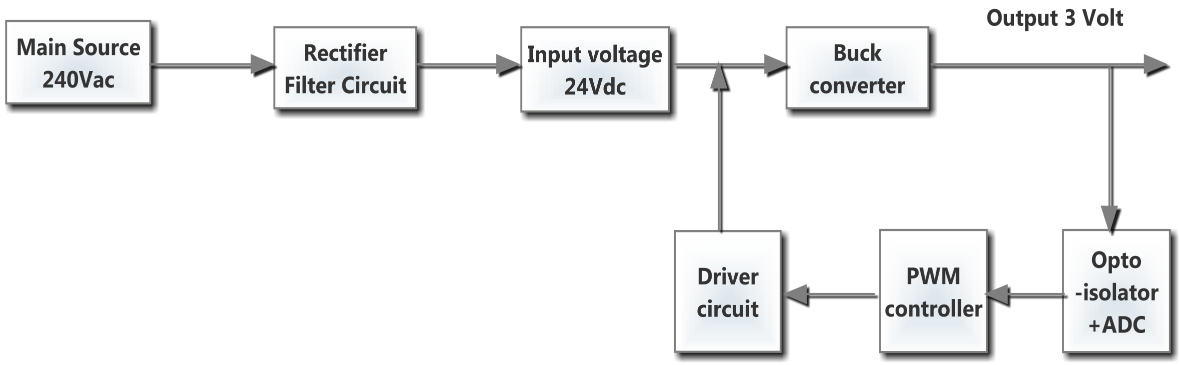


Figure 4.5:Design flow for Microcontroller Based Buck PID system

In the hardware part, the circuit is design to step down dc – to – dc voltage. The circuit included parts of Buck components such as controllable switch (IRF540), inductor and capacitor, PIC30F4011microcontroller, optoisolator (TLP250), and other basic components. Rectifier and filter circuit is design to obtain voltage up to 15Vdc from main source. The voltage obtained will be step down by Buck converter to 3Vdc. In order to maintain output voltage, controller will be operated infeedback circuit. The complete circuit for the system is shown in APPENDIX I. PIC30F4011 is used to control SMPSMOSFET switching duty cycle which is connected to Buck converter circuit.PIC30F4011has 40 pins. Since the PWM that will be apply to Buck converter is varied in order to maintain the output voltage, the HPWM function pin at RC2/CCP1/P1A need to set in order to generate the PWM signal from the microcontroller. The 20MHz crystal oscillator is used for PIC30F4011 microcontroller internal clock.

4.5.4 Basic Buck converter circuit operation

Figure 4.5 show the full Buck converter equivalent circuit. For determining the output voltage of Buck converter, the inductor current and inductor voltage should be examined first. Observations made during controllable switch closed and switch open.

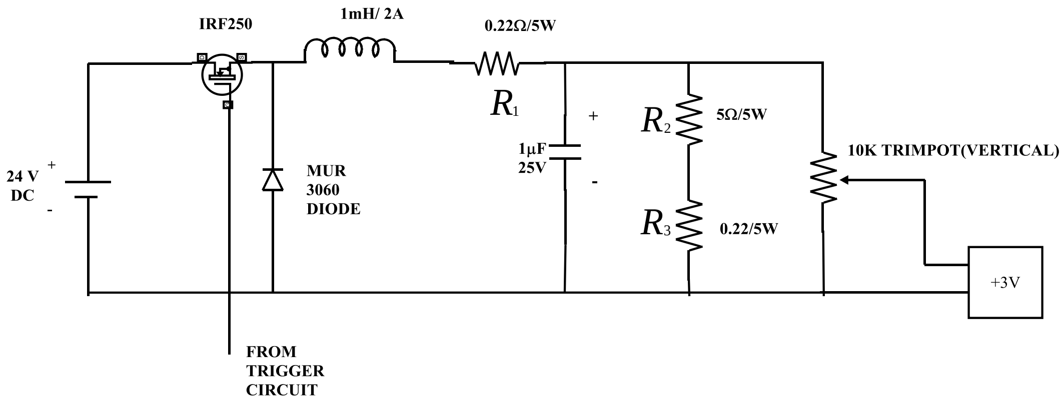


Fig4.6 buck converter

Refer on Figure 4.6, when the duty cycle is in ON state, diode become as reversed biased and the inductor will deliver current and switch conducts inductor current. With the voltage (Vin - Vo) across the inductor, the current rises linearly (current changes, ΔiL). The current through the inductor increase, as the source voltage would be greater then the outputvoltage and capacitor current may be in either direction depending on the inductor current and load current. When the current in inductor increase, the energy stored also increased. In this state, the inductor acquires energy. Capacitor will provides smooth out of inductor current changes into a stable voltage at output voltage and it's big enough such that V out doesn't change significantly during one switching cycle.

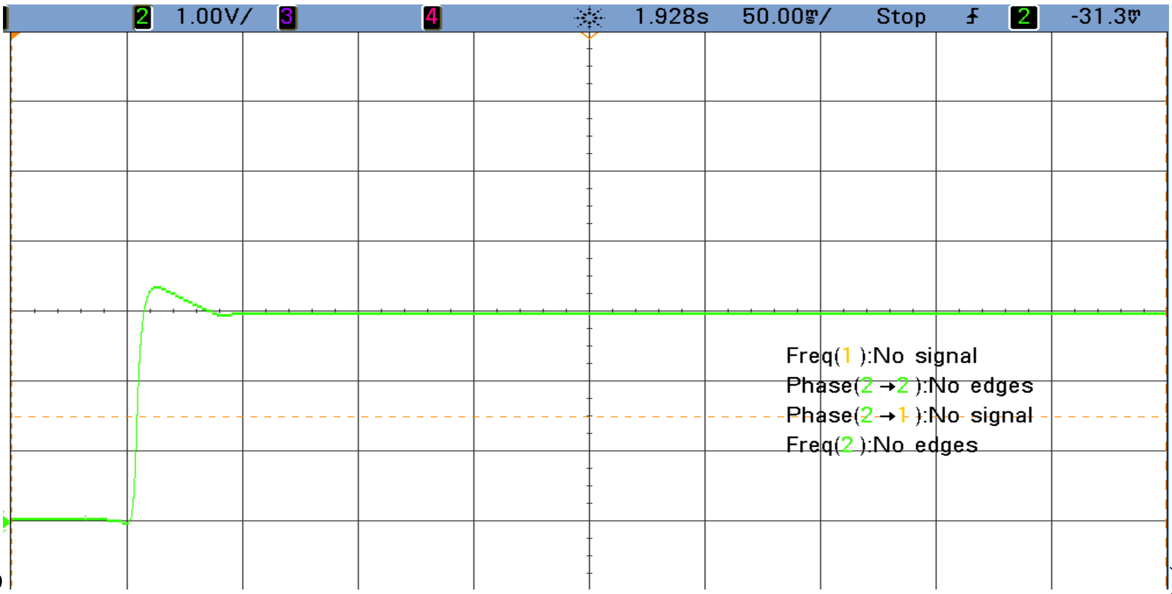
InOFF state of duty cycle, the diode is ON and the inductor will maintains current to load. Because of inductive energy storage, iL will continues to flow. While inductor releases current storage, it will flow to the load and provides voltage to the circuit. The diode isforward biased. The current flow through the diode which is inductor voltage is equal with negative output voltage. The model is shown in fig 4.7

Fig 4.7 model of buck converter with microcontroller

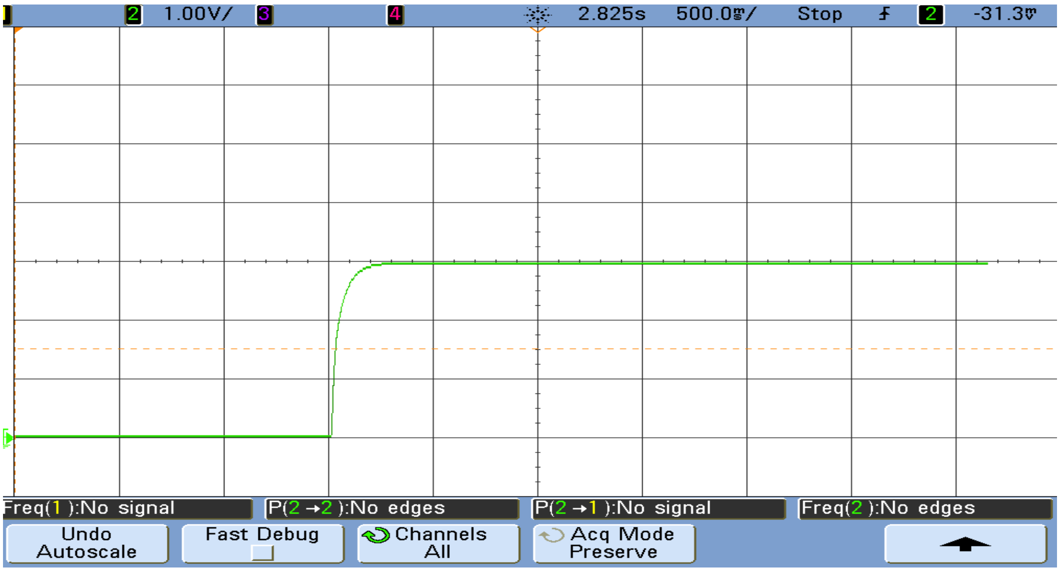
The output voltage is obtained using DSO in open loop and closed loop mode with microcontroller controlled in PID logic.

a)

b



)



c)

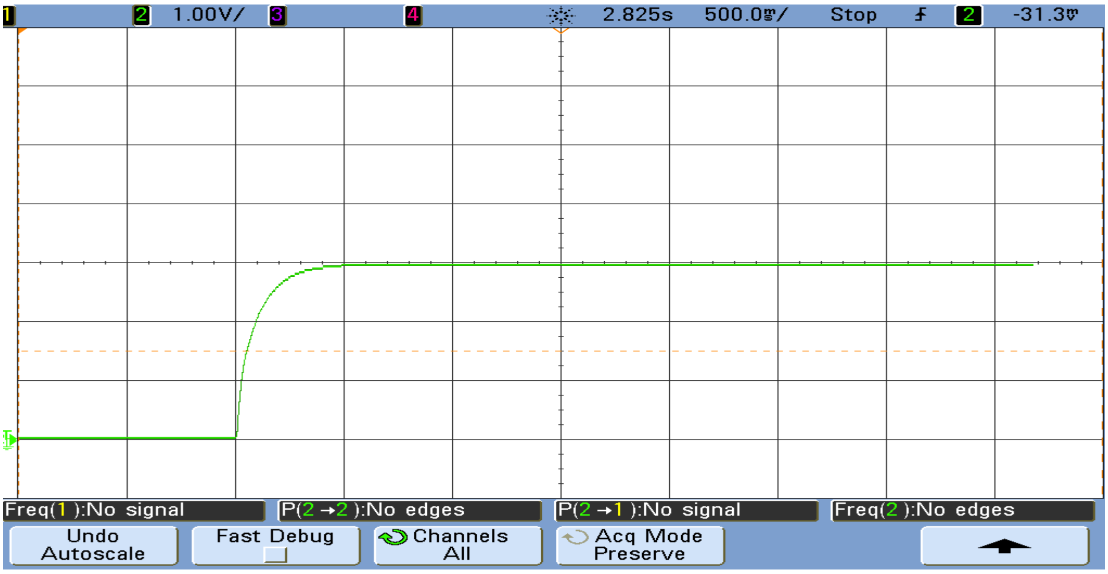


Fig 4.8. Responses of buck converter obtained from microcontroller implemented PID controller.

a)output voltage in open loop

b)output voltage in closed loop

c)capacitor voltage in closed loop

4.6 RESULTS AND DISCUSSIONS

Parameter	With microcontroller Implemented PID controller	With PID controller	With sliding mode PID controller
% Overshoot	0	213	0.08
Rise time(in ms)	0.027	0.047	0.01
Settling time(in ms)	0.35	0.6	0.01

Table 4.1

It is observed that the output voltage has overshoot 0f around 6% with a settling time of around 420 microseconds in open loop. But in closed loop when it is controlled by microcontroller with PID as base, overshoot reduces to zero and settling time falls to around 350 microseconds.

4.7 CONCLUSIONS

The time response analysis of the dc-dc buck converter are done by observing their damping nature of oscillatory transient signals mainly the output voltage in terms of various parameters like time required to settle to a steady state desired value from the initial high transient values, the maximum value that the output voltage attains during the transient period and the duration after which the desired output value is reached for the first time. These objectives are satisfied by measuring the rise time, settling time and overshoot from the graphical results obtained from the simulation. Same approach is repeated for all the controller topologies implemented with dc-dc buck converter discussed and the results are given in a tabular manner for better clarity.

It is seen that the SMPID controller meets our demand of controlling the output voltage of dc-dc buck converter in a smooth manner without much more chattering in the transient period by decreasing the rate of transition between the states of high frequency oscillation and low frequency steady state value and thereby shows a sharp decrease in rise time and settling time. The implementation of SMPID controller also reduces the unwanted peak of output voltage during the transient period almost to zero and therefore reduces the chances of damage due to sudden rise of voltage in modern day power electronic devices having a very narrow tolerance zone to meet the requirements ultrafast performance.

FUTURE SCOPE :

- Design and implementation of SMC and SMPID with microcontroller in the designed buck converter for voltage mode control and to observe the chattering during transient state.

REFERENCES:

[1] M. H. Rashid, "*Power Electronics, Circuits, Devices And Applications*," 2nd ed. Englewood Cliffs, NJ: Prentice Hall, 1993.

[2] R. W. Erickson, "*Fundamentals of Power Electronics*" Norwell, MA: Kluwer-Academic.1999

[3] Mohan, Undeland, Riobbins, *Power Electronics Converters Applications and Design*, 3rd edition, Wiley India (P.) Ltd.

[4] R.D Middlebrook and S Cuk , "A general unified approach to modelling switching Converter Power stages," in *Proc. IEEE PESC Rec.*, pp. 18–34, 1976.

[5] A.J. Forsyth and S.V. Mollow, "Modelling and control of dc-dc converters," *IEE power engineering journal*, vol. 12, no. 5, pp. 229–236, Oct. 1998.

[6] V.S.C Raviraj and P.C. Sen, "Comparative Study of proportional-integral, Sliding-mode, and fuzzy logic controllers for power converters," *IEEE transaction on Industry applications*, vol. 33, no. 2, pp. 518-524, Mar. /Apr. 1997.

[7] Kapat, S.; Krein, P.T.; , "Formulation of PID control for dc-dc converters based on capacitor current: A geometric context," *Control and Modelling for Power Electronics (COMPEL), 2010 IEEE 12th Workshop on* , vol., no., pp.1-6, 28-30 June 2010

[8] R. Anandanatarajan, P. Ramesh Babu, *Control System Engineering,* 3rd edition, SciTech Publications (India) Pvt. Ltd.

[9] Stanislaw H. Zak,*Systems and Control*, Oxford University Press, New York, 2003.

[10] Juing-Huei Su; Jiann-Jong Chen; Dong-Shiuh Wu; , "Learning feedback controller design of switching converters via MATLAB/SIMULINK," *Education, IEEE Transactions on* , vol.45, no.4, pp. 307- 315, Nov 2002.

[11] Escobar, G.; Ortega, R.; Sira-Ramirez, H.; Vilain, J.P.; Zein, I.; , "An experimental comparison of several nonlinear controllers for power converters," *Decision and Control, 1997., Proceedings of the 36th IEEE Conference on* , vol.1, no., pp.227-228 vol.1, 10-12 Dec 1999.

[12] Ang, S.S.; , "A practice-oriented course in switching converters," Education, IEEE Transactions on , vol.39, no.1, pp.14-18, Feb 1996.

[13] Fliess, M.; , "Generalized controller canonical form for linear and nonlinear dynamics," *Automatic Control, IEEE Transactions on* , vol.35, no.9, pp.994-1001, Sep 1990.

[14] Siew-Chong Tan; Lai, Y.M.; Tse, C.K.; Cheung, M.K.H.; , "An adaptive sliding mode controller for buck converter in continuous conduction mode," *Applied Power Electronics Conference and Exposition, 2004. APEC '04. Nineteenth Annual IEEE* , vol.3, no., pp. 1395- 1400 Vol.3, 2004

[15] Shoei-Chuen Lin; Ching-Chih Tsai; , "Adaptive voltage regulation of PWM buck DC-DC converters using back stepping sliding mode control," *Control Applications, 2004. Proceedings of the 2004 IEEE International Conference on* , vol.2, no., pp. 1382- 1387 Vol.2, 2-4 Sept. 2004

[16] Algreer, Maher; Armstrong, Matthew; Giaouris, Damian; , "Adaptive control of a switch mode dc-dc power converter using a Recursive FIR predictor," *Power Electronics, Machines and Drives (PEMD 2010), 5th IET International Conference on* , vol., no., pp.1-6, 19-21 April 2010

[17] Jafari, M.; Malekjamshidi, Z.; , "Design, Simulation and implementation of an adaptive controller on base of artificial neural networks for a resonant DC-DC converter," *Power Electronics and Drive Systems (PEDS), 2011 IEEE Ninth International Conference on* , vol., no., pp.1043-1046, 5-8 Dec. 2011

[18] Zhou Wei; Liu Bao-bin; , "Analysis and design of DC-DC buck converter with nonlinear adaptive control," *Computer Science & Education (ICCSE), 2012 7th International Conference on* , vol., no., pp.1036-1038, 14-17 July 2012

[19] Mattavelli, P.; Rossetto, L.; Spiazzi, G.; , "Small-signal analysis of DC-DC converters with sliding mode control ," *Applied Power Electronics Conference and Exposition, 1995. APEC '95. Conference Proceedings 1995., Tenth Annual* , vol., no.0, pp.153-159 vol.1, 5-9 Mar 1995

[20] Siew-Chong Tan; Lai, Y.M.; Cheung, M.K.H.; Tse, C.K.; , "On the practical design of a sliding mode voltage controlled buck converter," *Power Electronics, IEEE Transactions on* , vol.20, no.2, pp. 425-437, March 2005

[21] Fossas, E.; Olm, J.M.; , "Generation of signals in a buck converter with sliding mode control ," *Circuits and Systems, 1994. ISCAS '94., 1994 IEEE International Symposium on* , vol.6, no., pp.157-160 vol.6, 30 May-2 Jun 1994

[22] Hongmei Li; Xiao Ye; , "Sliding-mode PID control of DC-DC converter," *Industrial Electronics and Applications (ICIEA), 2010 the 5th IEEE Conference on* , vol., no., pp.730-734, 15-17 June 2010.

[23] Mikkel C. W. Høyerby ;Michael A. E. Andersen ,"Accurate Sliding-Mode Control System Modeling for Buck Converters"to be presented at PESC2007, June 2007

[24] V. Utkin, J. Guldner, J. Shi, "Sliding Model Control in Electromechanical Systems", CRC Press, 1999

[25] Chung-HsienTso, Jiiin-Chuan Wu, "A Ripple Controlled Buck Regulator With Fixed Output Frequency", IEEE Power Electronics Letters, vol. 1, no. 3, September 2003

[26] SørenPoulsen, Michael A. E. Andersen, "Simple PWM modulator with excellent dynamic behaviour", proc. of APEC 2004, February 2004, Anaheim, USA, pp 486-492

[27] SørenPoulsen, "Global loop integrating modulator", WO2004100356-A2, patent application

[28] M. C. W. Høyerby, M. A. E. Andersen, "Ultra-Fast Tracking Power Supply with 4th order Output Filter and Fixed-Frequency Hysteretic Control", to be published

[29] M. C. W. Høyerby, M. A. E. Andersen, "A small-signal model of the hysteretic comparator in linearcarrier self-oscillating switch-mode controllers", proc. of NORPIE 2006, Lund, Sweden, June 2006

[30] Gene W. Wester, "Describing-function analysis of a ripple regulator with slew-rate limits and time delays", proc. of PESC 1990, June 1990, pp 341-346

[31] O. Rafael, S. Daniel, K. Charif, "Simple Hysteresis Describing Technique to Control a Non-Active Power Compensator", proc. of PESC 2005, June 2005, pp 1732-1737

[32] Thomas H. Lee, "The Design of CMOS Radio-Frequency Integrated Circuits", 2nd edition, Cambridge University Press, 2004, pp 617-620

[33] E. Fossas, J. P. Olm, "Generation of Signals in a Buck Converter with Sliding Mode Control", proc. Of ISCAS '94, May 2004, pp 157-160

[34] M. C. W. Høyerby, M. A. E. Andersen, "A Comparative Study of Analog Voltage-mode Control Methods for Ultra-fast Tracking Power Supplies", to be presented at PESC2007, June