ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 3, Issue 7, July 2015

Controlling of Fast dynamic DC/DC Buck Converter

P. Deepak Reddy[1], Dr.Basavaraja Banakara[2]

Associate Professor, Department of EEE, Lakireddy Bali Reddy College of Engineering, Mylavaram, India[1]

Professor & Chairman, E & E Department, University BDT College of Engineering (Constituent college of VTU) Davanagere, Karnataka[2]

Abstract: This paper presents, linear peak current mode controller for the control of DC/DC buck converter is designed and analyzed. Dynamic equations describing the buck converter are derived and linear peak current mode controller is designed. The buck converter, the voltage mode and current mode controller are modeled and are evaluated by computer simulations. The proposed technique has the advantages of reduced inductor current ripple, which in turn makes the DC load voltage to be stable and faster dynamic response. DC/DC buck Converter modeling, analysis, design criteria and Simulation results are presented. Simulation is done by using mathematical model of buck converter in MATLAB/SIMULINK environment.

Keywords: DC/DC Buck converter; voltage mode control (VMC); Current mode control (CMC); Linear peak current mode control (LPCMC);

I. INTRODUCTION

Power electronic converters are widely used in many industrial applications. The buck type DC/DC converters are employed in applications where the required output voltage is lower than the source voltage. The mathematical models of these converters are very important for engineers to study the system dynamic behavior. As DC/DC converters are nonlinear and time variant systems, the application of linear control techniques for the restraint of these converters are not desirable. The analysis of the system with time-varying models is very complicated. Moreover, such model consumes the vast simulation time because of the switching devices. In order to design a linear control system using classical linear control techniques, the small signal model is derived by linearization around a precise operating point from the state space average model [1]. To obtain a control method that has the best performances under any conditions is always in demand. Variations of system parameters and large signal transients such as those produced in the start up or against changes in the load, cannot be dealt with voltage control mode technique. In the paper, the generalized state-space averaging (GSSA) method is selected to analyze the buck converter in which this method is well known for analyzing the DC/DC converter [2] - [4].

In literature [5,6] voltage mode and current mode PWM control techniques are proposed. The main drawbacks in voltage follower approach of buck regulator are[5]

- Large current stresses on Semiconductor devices
- Demands more effort to attenuate the current ripple so as to have a satisfactory low electromagnetic interference (EMI) to the line.

The above drawbacks are alleviated with Current Mode Control. Current Mode Control was formerly introduced to the Power Electronics Ward in 1978 [6]. It was accepted as the most rugged way to control switching regulators. In literature [5] multiplier approach was first introduced under current mode control approach. However, due to the presence of inherent Oscillation Phenomenon for duty ratio is greater than the 0.5, noise immunity, complications in implementing, and system will be unstable.

After introduction of slope compensation technique and integrated control structure designed specifically for Carrier current mode control has led to a dramatic upswing in the application of this technique to new design. In literature [7, 8] carrier based current mode controllers are proposed for Quasi-steady-state property of CMC buck converter.

In this paper voltage mode controller (VMC) and current mode controller (CMC) under continuous conduction mode are designed for a buck converter based on the state space averaging technique. The stability of the system has been analyzed from the performance characteristics, which clearly shows that the current controlled converter is dynamic and efficient for various applications. In addition, the linear peak current control mode (LPCMC) is applied to regulate the output voltage of the system. This is because the LPCMC can provide a good dynamic response, robustness, and simple implementation. The results will show that simulations using the proposed model drastically reduce simulation time in comparison with the available software package.

The organization of this paper is as follows. Section II presents the modelling of buck converter. In Section III, the controllers dynamic model will be addressed. In Section IV, the simulation and results for the model comparison between the VMC & LPCMC are illustrated. Finally, Section V concludes and discusses the advantages of the proposed model for studies the system dynamic behaviour

II. MODELING OF BUCK CONVERTER

A. *Mathematical Modeling*

The topology of a buck converter is shown in Fig. 1 When the switch is on position 1 the circuit is connected to the

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526
INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 3, Issue 7, July 2015

dc input source resulting an output voltage across the load resistor. If the switch changes its position to position 0, the capacitor voltage will discharge through the load. Controlling switch position the output voltage can be maintained at a desired level lower than the input source voltage.

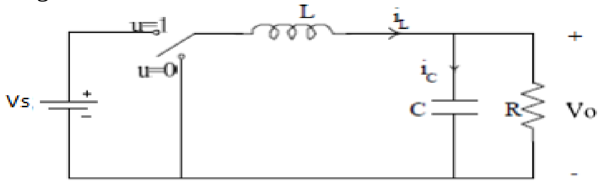

Fig.1 Buck converter

Therefore, the dynamic equation for the converter designed with the R Load for the circuit topology in is, For continuous conduction mode, The output of the circuit for ON period is,

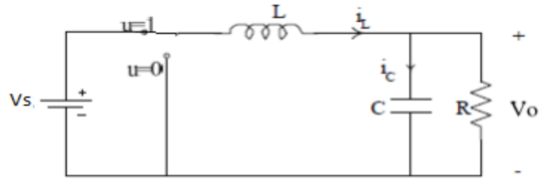

Fig.2 Buck converter for ON period

$$V_s = L\frac{di_L}{dt} + V_0 \qquad (1)$$

$$L\frac{di_L}{dt} = \frac{V_s}{L} - \frac{V_0}{L} \qquad (2)$$

$$i_L = i_c + i_0 \qquad (3)$$

$$C\frac{dV_0}{dt} + \frac{V_0}{R} - i_L = 0 \qquad (4)$$

$$\frac{dV_c}{dt} = \frac{i_L}{C} + \frac{V_0}{RC} \qquad (5)$$

The output of the circuit for OFF period is:

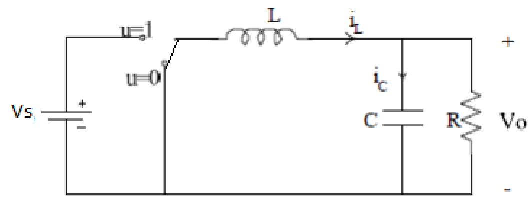

Fig.3 Buck converter for OFF period

$$L\frac{di_L}{dt} + V_0 = 0 \qquad (6)$$

$$\frac{di_L}{dt} = \frac{V_0}{L} \qquad (7)$$

$$-c\frac{dV_c}{dt} - \frac{V_0}{R} + i_L = 0 \qquad (8)$$

$$\frac{dV_c}{dt} = \frac{i_L}{C} - \frac{V_0}{RC} \qquad (9)$$

With reference to these equations, the state space averaging technique is performed for better analysis.

$$L\frac{di_L}{dt} = uV_s - V_0 \qquad (10)$$

$$C\frac{dV_0}{dt} = i_L - i_0 \qquad (11)$$

$$u = \begin{cases} 0 \text{ if switch is at position } 0 \\ 1 \text{ if switch is at position } 1 \end{cases} \qquad (12)$$

Where i_L is the inductor current, V_o or V_c is the output capacitor voltage, V_S is the constant external input voltage source, L is the inductance, C is the capacitance of the output filter and R is the output load resistance. u is the control input taking discrete values of 0 and 1 which represents the switch position. It is assumed here that the inductor current will have a nonzero value due to load variations which is known as the continuous conduction mode (CCM).

Rewriting Equations (10) and (11) in the form of state equations by taking the inductor current and output capacitor voltage as the states of the system, the following state equations are obtained.

$$\frac{di_L}{dt} = \frac{V_s}{L}u - \frac{V_0}{L} \qquad (13)$$

$$\frac{dV_0}{dt} = \frac{i_L}{C} - \frac{V_0}{RC} \qquad (14)$$

$$\text{Where} \quad i_0 = \frac{V_0}{R} \qquad (15)$$

The block diagram of the buck converter using state Equations (12) and (13) is shown in Fig. 4.

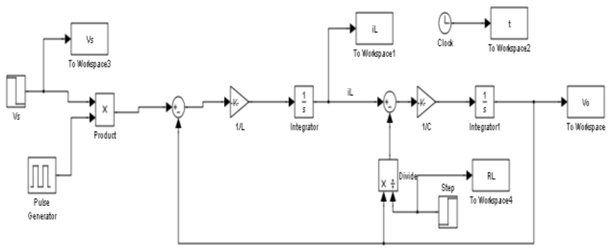

Fig.4 Block diagram of Buck converter

B. State Space Modeling

The state space averaging is an approximation technique, which helps in continuous time signal frequency analysis apart from the switching frequency analysis for higher switching frequencies. Though the original system is linear, the resulting system will be non-linear therefore, this averaging technique gives an ease in representation of transfer functions.

Thus from the dynamic equations, the state space equation for the entire switching cycle T is given below, For Continuous mode, In state space form

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_c}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C} & \frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_s \qquad (16)$$

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526
INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 3, Issue 7, July 2015

$$V_0 = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix} \tag{17}$$

In state space form

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_c}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_s \tag{18}$$

$$V_0 = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix} \tag{19}$$

III. CONTROLLERS FOR BUCK CONVERTER

In order to overcome the switching losses due to unregulated power supply and core losses affecting the high frequency operation, controllers are widely used so that, regulated output voltage with maximum power can be obtained. Hence, linear and non-linear controllers are designed independently and the converter stability has been analyzed

A. Voltage mode controller

The voltage feedback arrangement is known as voltage-mode control when applied to DC/DC converters. Voltage-mode control (VMC) is widely used because it is easy to design and implement, and has good community to disturbances at the references input. VMC only contains single feedback loop from the output voltage.

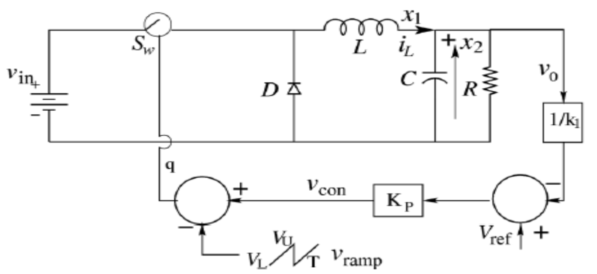

Fig.5 Voltage mode controlled DC/DC buck converter

The voltage mode controlled buck converter circuit is shown in Fig. 5. It consists of a controlled switch S_w (MOSFET), an uncontrolled switch diode D (diode), an inductor L, a capacitor C, and a load resistance R. The circuit shown in Fig. 5 is a nonsmooth dynamical system described by two sets of differential equations:

$$\frac{di_L}{dt} = \begin{cases} \frac{V_{in} - V_0}{L}, S_w \text{ is conducting} \\ \frac{-V_0}{L}, S_w \text{ is blocking} \end{cases} \tag{20}$$

$$\frac{dv_0}{dt} = \frac{i_L - \frac{V_0}{R}}{C} \tag{21}$$

The switch is controlled by analog PWM feedback logic. This is achieved by obtaining a control voltage V_{con} as function of the output capacitor voltage V_c and a reference signal V_{ref} in the form,

$$V_{con} = k_p \left(V_{ref} - \frac{V_0}{k_1} \right) \tag{22}$$

Where, k_p is the gain of proportional controller and k_1 is the factor of reduction of the output voltageV_0. An externally generated saw-tooth voltage defined as $V_{ramp}(t)$ is used to determine the switching instants.

$$V_{ramp}(t) = V_L + (V_U - V_L) F\left(\frac{t}{T_s}\right) \tag{23}$$

Where T_s is the time period and V_U and V_L are upper and lower threshold voltages respectively. Here F(x) denotes the fractional part of x: F(x) = x mod 1. In voltage mode control, the controlled voltage V_{con} is then compared with the periodic saw-tooth wave V_{ramp}, to generate the switching signal q Є [1, 0] is described by

If $\quad V_{ramp} < V_{con};\ q = 1$
If $\quad V_{ramp} > V_{con};\ q = 0$

The inductor current increases while the switch S_w is on i.e q=1 and falls while the switch S is off i.e. q=0.

If the current reaches zero value before the next clock cycle, the operation is said to be in DCM, else it is in CCM. The state equation that describes the dynamics of the buck converter can be written as

$$\frac{dx}{dt} = \begin{cases} A_1 x + B_1 U;\ (k_p x_1 - V_{ref}) < V_{ramp,} \\ A_1 x + B_1 U;\ (k_p x_1 - V_{ref}) > V_{ramp,} \end{cases}$$

Where $x = [x_1\ x_2]^T = [v\ i]^T$ is the state vector and A's and B's are the system matrices. The state matrices and the input vectors of the converter are given by

$$A_1 = A_2 = \begin{bmatrix} \frac{-1}{RC} & \frac{1}{C} \\ \frac{-1}{L} & 0 \end{bmatrix}, \quad B_1 = \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix}$$

$$B_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \quad U = V_{in}\ 0$$

The switching hyper surface (h) can be written as

$$h = x_1 - v_{ref} - \frac{V_{ramp}}{k_p} = 0, k_p \neq 0 \tag{24}$$

For discontinuous conduction mode, inductor current reaches zero before the next clock cycle. In this case, the state equation of the converter can be written as

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} \frac{-1}{RC} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{25}$$

However, VMC have a few disadvantages. Any change in input voltage will alter the gain and influence the system dynamics behaviour. VMC cannot correct any disturbance immediately until it is detected at the output since the disturbances are delayed in phase by the inductor and capacitor prior to the output.

B. Current mode controller

Another control scheme that is widely used for DC/DC converters is current mode control. Current-mode controlled dc-dc converters usually have two feedback loops: a current feedback loop and a voltage feedback loop. The inductor current is used as a feedback state.

DOI 10.17148/IJIREEICE.2015.3712

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526
INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 3, Issue 7, July 2015

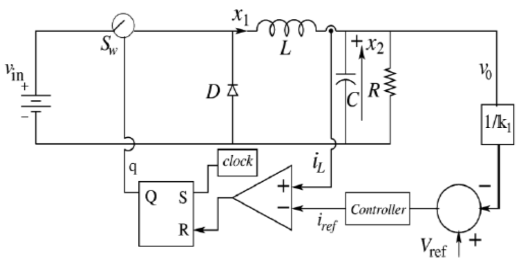

Fig.6 Current-mode controlled DC/DC buck converter

A current mode controlled dc-dc buck converter circuit is shown in Fig. 6. At the beginning of a switching cycle, the clock signal sets the flip-flop (q=1), turning on the (MOSFET) switch. The switch current, which is equal to the inductor current during this interval, increases linearly. The inductor current i_L is compared with the control signal i_{ref} from the controller. When i_L , is slightly greater than i_{ref} , the output of the comparator goes high and resets the flip-flop (q=0), thereby turning off the switch. The switch will be turned on again by the next clock signal and the same process repeated.

The buck converter circuit operates at continuous conduction mode (CCM). Depending on the state of the switch, there are two circuit configurations, which are described by the following differential equations:

$$\frac{di_L}{dt} = \begin{cases} \frac{V_{in} - V_0}{L}, S_w \text{ is conducting} \\ \frac{-V_0}{L}, S_w \text{ is blocking} \end{cases} \qquad (26)$$

and

$$\frac{dv_0}{dt} = \frac{i_L - \frac{V_0}{R}}{C} \qquad (27)$$

If the switch position is expressed with the switching function q , then

$$q = \begin{cases} 1, S_w \text{ closed} \\ 0, S_w \text{ opened} \end{cases} \qquad (28)$$

The control input signal is proportional to reference current i_{ref}. The reference current i_{ref} is a function of output of the controller to regulate the output voltage. The control voltage can be defined as,

for P controller

$$V_{con} = k_p \left(V_{ref} - \frac{V_0}{k_1} \right) \qquad (29)$$

for PI controller.

$$V_{con} = k_p \left(V_{ref} - \frac{V_0}{k_1} \right) + k_1 \int \left(V_{ref} - \frac{V_0}{k_1} \right) dt \quad (30)$$

Hence the reference current can be written as $i_{ref} = \frac{V_{con}}{R_f}$, where R_f is a proportionality factor. The voltage waveforms are scaled to equivalent current waveforms by the proportionality factor R_f.

The state equation that describes the dynamics of the buck converter can be written as

$$\frac{dx}{dt} = \begin{cases} A_1 x + B_1; \quad \text{when S is closed,} \\ A_1 x + B_1 U; \text{when S is opened,} \end{cases} \qquad (31)$$

Where $x=[x_1\ x_2]^T = [v\ i]^T$ is the state vector and A's and B's are the system matrices.

The state matrices and the input vectors for the ON and OFF periods are

$$A_1 = A_2 = \begin{bmatrix} \frac{-1}{RC} & \frac{1}{C} \\ \frac{-1}{L} & 0 \end{bmatrix}, \quad B_1 = \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix}, \quad B_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix},$$

$$U = V_{in}\ 0$$

There are two types of current mode control(CMC) strategies. In both, the switch is turned on at the beginning of every clock period. In peak current mode control, the inductor current is compared with a reference current signal with a compensation ramp, and the switch is turned off when the two become equal. In the average current mode control, the inductor current is compared with a ramp waveform, and the switch is tuned off when $i_L < i_{ref}$. It is turned on again at the next clock instant. Here a brief overview of peak current mode control scheme is described.

C. Current Mode Control with Compensating Ramp

Fig. 6 shows the waveform of inductor current of a switching converter operating in continuous conduction mode (CCM). The inductor current changes with a slope m_1 during the first subinterval, and a slope $-m_2$ during the second subinterval. The peak inductor current is controlled and the controlled method is therefore called peak current-mode control. The current mode controller is unstable whenever the steady-state duty cycle is greater than 0.5, resulting in sub-harmonic oscillation.

To avoid this stability problem, the control scheme is usually modified by adding an external ramp to the sensed inductor current waveform. Let the slope of compensating ramp is m_a. When $m_a \geq 0.5m_2$,then the controller is stable for all duty cycles. The relationship between the ramp, inductor and reference current is given in**,**

$$i_a dT_s + i_L dT_s = i_{ref} \qquad (32)$$

Then, the control equation is given by

$$i_L - \left(i_{ref} - m_a \frac{t}{T_s} \right) \qquad (33)$$

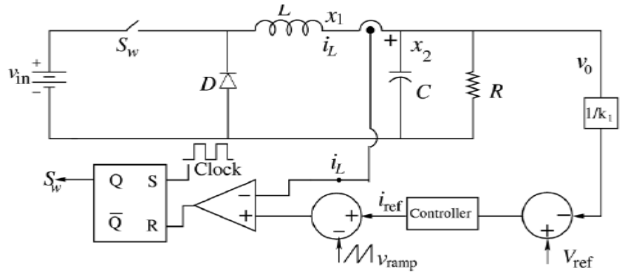

Fig.7 Peak current mode control

Advantages of peak current mode control include Control of the peak inductor current, inherent peak current limiting and sharing, good dynamic performance, first order transfer function. Some of the main drawbacks of this control are the limited duty ratio, increased output impedance, sub-harmonic oscillation, noise sensitivity.

These problems are rectified by means of an artificial ramp signal either subtracted from the control signal or added to the inductor-current signal.

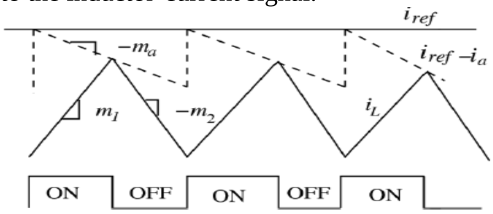

Fig.8 Inductor Current waveform with compensating ramp

IV. Simulation Results

The response of the buck converter in the voltage mode and current mode controller for various gain parameters has been obtained using the MATLAB/Simulink and shown in Fig. 9 & 10.

V. Conclusion

DC/DC buck converters with voltage mode control and peak current mode controllers are simulated in this paper. The simulation results show the validity of the peak current mode controlled buck converter model and the robustness of this control technique against changes in the load or variations in the input voltage. Therefore the LPCMC control method shows better dynamics for changes in input voltage and load compared to the PWM voltage-mode method. It can be seen that the LPCMC control method can well regulate the output voltage even in large range of load and line variation.

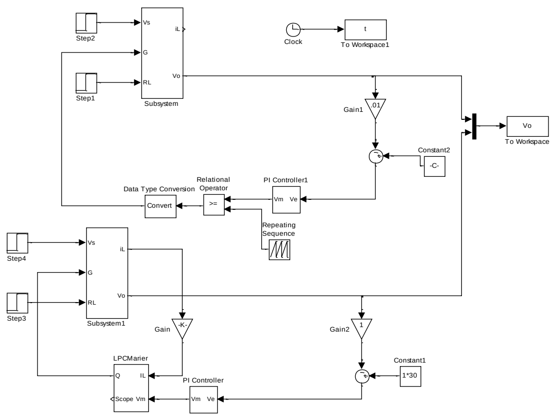

Fig.9 Closed loop simulink model VCM & LPCMC of buck converter

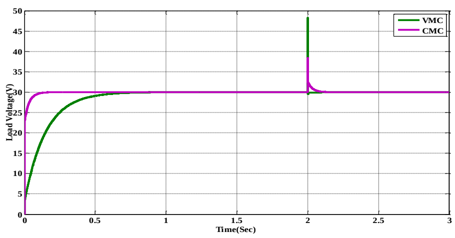

Fig.10 Waveforms of output response for changing the load

References

[1] J. Forsyth, "Modeling and Control of DC-DC Converters," Power Engineering Journal, Vol. 12, No. 5, 1998, pp. 229-236.
[2] Emadi, "Modeling and Analysis of Multiconverter DC Power Electronic Systems Using the Generalized State-Space Averaging Method," IEEE Tran. on Indus. Elect., vol. 51 no. 3, 2004, pp. 661 668.
[3] A. Emadi, M. Ehsani, and J.M. Miller, "Vehicular Electric Power Systems: Land, Sea, Air, and Space Vehicles," Marcel Dekker, Inc., 2004.
[4] J. Mahdavi, A. Emadi, M.D. Bellar and M. Ehsani, "Analysis of Power Electronic Converters Using the Generalized State-Space Averaging Approach," IEEE Tran. on Circuit and Systems., vol. 44, 1997, pp.767- 770.
[5] Zheren Lai, Keyue Ma Smedly, "A Family of Continuous Conduction- Mode power-Factor-Correction Controllers based on the general pulse- width modulator", IEEE Trans. On power electronics, Vol.13, no.3, May 1998,pp.501-510
[6] Robert Mammano "Switching Power Supply topology, Voltage Mode Vs Current Mode", Unitrode Design note. DN-62
[7] J.P.Gegner and C.Q.Lee,' Linear peak current mode control: A simple active power factor correction control technique for continuous conduction mode", in Proc. IEEE PESC'96 Conf., 1996, pp.196-202.
[8] D.Maksimovic, Y.Jang, and R.Erikson, "Non-linear carrier control for high power factor boost rectifiers", Proc. IEEE APEC'95 Conf., 1995, pp.635-641.
[9] Souvik Chattopadhayay, V. Ramanarayanan, and V. Jayashankar, "A Predictive Switching Modulator for Current Mode Control of High Power Factor Boost rectifiers", IEEE Trans. On Power Electronics, vol. 18, No.1, Jan. 2003

BIOGRAPHIES

Deepak Reddy.P was born in 1981. Received B.Tech degree in electrical and electronics engineering from JNTU, Hyderabad, india in 2002, and he received the M.Tech degree from vellore institute of technology, vellore, india in 2005, and he is pursuing Ph.D. on "Modeling and Analysis of Control Techniques for DC-DC Buck converter" from GITAM University, Hyderabad. He worked as a Asst.Prof.,in at SVITS, Mahaboobnagar, Currently he is working as an Associate Professor in Dept. of EEE in Lakireddy Bali Reddy college of Engineering, Mylavaram, india. His areas of interest include power electronics and drives, ac–dc converter with power factor correction, SMPS and Active power filters for Harmonic compensation, dc-dc converters. He presented 5 publications in international journals. He is a Life member of ISTE, Life member of IETE.

D. Basavaraja Banakara was born in 1970. He obtained his B.E (EEE) degree from Gulbarga University and M.E from Karnataka University, India and he is completed his Doctoral program from National Institute of Technology, Warangal, India. He worked as a Lecturer in VEC Bellary, Associate Professor at SSJ Engineering College Mahaboobnagar, Professor at SR Engineering College Ananthasagar, Waranagal, Principal at Padmasri Dr.BV Raju Institute of Technology, Narasapur, AP, India, Professor & Director for Academic Registration at KL University, Guntur, Professor & HOD at GITAM University, Hyderabad campus & Presently he is working as Professor & Chairman, E & E Department University BDT College of Engineering (Constituent college of VTU) Davanagere, Karnataka, India.His areas of interest include power electronics and drives, Power Quality, Micro-grids, High voltage Engineering and EMTP applications. He presented 45 publications in national & international journals as well as in conferences. Dr.Basavaraja is a Senior Member of IEEE, Life member of ISTE, Fellow of IACSIT, Member of IAENG, Fellow IEI, and Executive Committee Member for ISTE Andhra Pradesh Section. He is reviewer, board member for technical journals and conference publication in national and international level.

 DOI 10.17148/IJIREEICE.2015.3712