DESIGN AND IMPLEMENTATION OF A DISCRETE CONTROLLER FOR SOFT SWITCHING DC - DC CONVERTER

S.VIJAYALAKSHMI[1] Dr.T.SREE RENGA RAJA[2]

Mookambigai College of Engineering[1], Pudukkottai, Anna University of Technology[2], Tiruchirapalli
bksviji@gmail.com[1], renga_raja@rediffmail.com[2]

Abstract: In this paper, high efficiency Zero Voltage Switching buck converter with closed loop discrete PID controller is designed and simulated. The conventional buck converter generates switching losses at turn on and turns off. The efficiency of the buck converter can be improved by using resonant component. The only switch used in the converter is turn-ON at zero current and turn-OFF at zero voltage by means of the resonant component Inductor and Capacitor. The dynamic performance of the ZVS buck converter can be improved by the design of discrete PID PWM controller. A 10W / 400 KHz Soft switched Discrete PID PWM buck converter is simulated and analyzed using MATLAB / Simulink. Discrete PI Controller, Analog PI & PID Controller is also designed and simulated whose performance parameters are compared with the Discrete PID Controller is also illustrated.
Keywords: Buck converter, Zero Voltage Switching, Pulse Width Modulation, Analog to Digital Converter, Discrete PID controller, Digital to Analog Converter.

NOMENCLATURE

S1	Main switch.
D1	Main Diode.
L1	Main inductor.
C1	Main capacitor.
L2	Resonant inductor.
C2	Resonant capacitor.
D2	Auxiliary Diode.
f_r	Resonant frequency.
f_s	Switching frequency.
V_o	Output voltage.
V_s	Input voltage.
i_{L1}	Main inductor current
i_{L2}	Resonant inductor current
V_{c1}	Voltage across main capacitor.
V_{c2}	Voltage across resonant capacitor
k	Duty cycle
A,C	State coefficient matrix
B,D	Source coefficient matrix
ZVS	Zero Voltage Switching
ΔI	Input ripple current
ΔV_c	Output ripple voltage
PWM	Pulse Width Modulation

I. INTRODUCTION

Now a day's utilization of Switched Mode Power Supplies (SMPS) of nonlinear controller is inevitable. The main advantage of this method is greater efficiency because the switching device dissipates little power when it is outside of its active region. Other advantages include smaller size and lighter weight (from the elimination of low frequency transformers which have a high weight) and lower heat generation due to higher efficiency. In SMPS the role of digital controller is more important. The design of nonlinear digital controller offer many advantages over their analog counterpart. A disadvantages of the Analog Controller are difficulty in adjusting, Lack of flexibility to higher functions and system alteration, Low reliability. Some advantages of Digital Controller are 1) Digital components are less susceptible to aging and environmental variations. (2) They are less sensitive to noise. (3) Changing a controller does not require an alteration in the hardware. (4) They provide improved sensitivity to parameter variations." An important advantages offered by digital controller is in the flexibility of its modifying controller characteristics, simplicity in design, small drifting of system parameters and ease of operation. It also provides stability, fast response and minimal overshoot. Various nonlinear digital techniques [4 – 12] have been researched to achieve improved transient performance of the SMPS.

In general converters using hard switching at a high frequency, the switching loss increases in proportion to the switching frequency. Thus the soft switching technology, which uses resonance by an inductor and capacitor, reduces the switching losses considerably. This paper proposes an improved efficiency of Zero Voltage Switching buck converter and to implement the Discrete

Controller so that the circuit can give any required buck converter output voltage. Due to the controller, the circuit can withstand any change in the input voltage, Load resistance, filter capacitor and inductor and provide constant output voltage which is required. The soft switching can cut down the stress and loss produced at the switch [1 – 3].

This paper is subdivided as stated below. The section II of this article discusses about the block diagram of Discrete Controlled soft switching Buck converter, the section III gives the Design of Discrete controlled ZVS Buck Converter, section IV says the Discussion of the proposed Discrete Controller & its results, section V & VI gives the conclusion and references respectively.

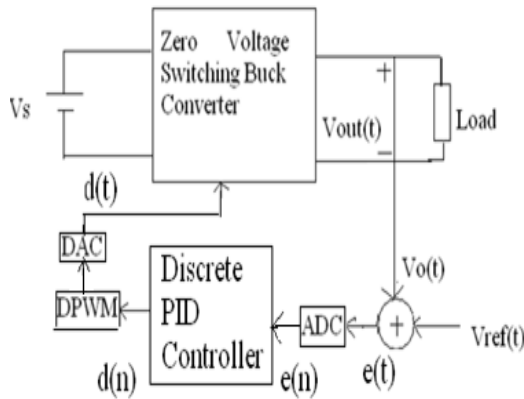## II. Block diagram of Discrete Controlled soft switching Buck Converter.

Fig. 1. Block diagram of Discrete controlled Zero Voltage switching Buck Converter.

Fig.1. Shows a Discrete Controlled Soft switching buck converter. It consists of Soft switching Buck converter, Analog to Digital converter, discrete PID controller, Pulse Width Modulator and Digital to Analog converter. The output of the ZVS Buck converter is compared with the reference voltage in a comparator whose output is an error signal. The analog error signal is converted into a digital signal by means of Analog to Digital Converter. The Digital error output is corrected by Discrete PID controller. The discrete control output is converted into Digital Pulse width signal by DPWM block. The digital PWM pulse is again converted into analog PWM pulse by Digital to Analog Converter. Finally the analog PWM pulse is given to the ZVS Buck Converter. Whatever variations occur in input voltage, required output voltage changes, Load resistance variations and circuit component variations the discrete controller accordingly control the error and provide the regulated output. Hence the robustness of the circuit is very high.

III. Design of Discrete controlled ZVS Buck Converter

A. Buck Converter:

Fig. 2. Shows a schematic diagram of Conventional Buck Converter. The average output voltage V_o, is less than the input voltage V_s. It requires only one switch and it is the simplest one, whose efficiency is more than 90%. The buck converter component L1 and C1 can be calculated by using [15] the value of L1 & C1 is

$$L1 = \frac{V_s k (1-k)}{f \Delta I} \qquad (1)$$

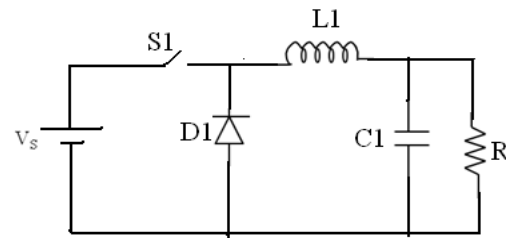$$C1 = \frac{V_s k (1-k)}{8 L f^2 \Delta V_c} \qquad (2)$$

Fig. 2. Schematic diagram of Buck Converter.

B. Zero Voltage Switching Buck Converter :

The switches of a ZVS converter turn ON and turn OFF at zero voltage. Fig. 3. Shows the proposed converter with Zero Voltage Switching. In this circuit inductor L2, Diode D2 and capacitor C2 for accomplishing the soft switching of S1. The capacitor C2 is connected in parallel with the switch S1 to achieve ZVS. The internal switch capacitance C_j is added with the capacitor C2, and it affects the resonant frequency only, thereby contributing no power dissipation in the switch. If the switch is implemented with MOSFET S1 and an anti parallel diode D2 as shown in Fig. 3., the voltage across C2 is clamped by D2, and the switch is operated in a half-wave configuration. The resonant component of L2 & C2 can be calculated by using [15].

$$Z = \sqrt{L2/C2} = \frac{V_s}{I_o} \qquad (3)$$
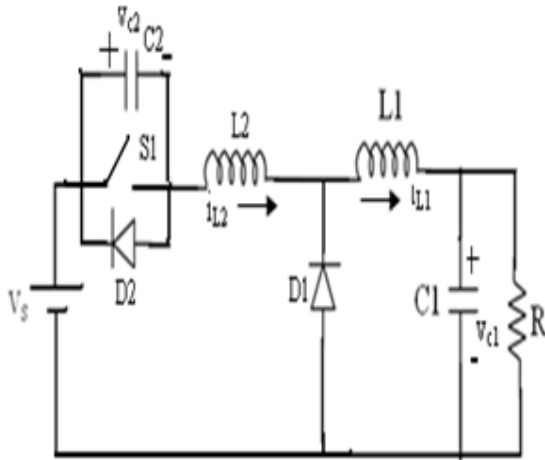
$$fr - \frac{1}{2\pi\sqrt{L2C2}} \qquad (4)$$

Fig. 3. Schematic diagram of Zero Voltage Switching Buck Converter

Table I. Design parameters of ZVS Buck Converter

S. No.	Parameter	Value
1	Output power P_o	10 W
2	Input Voltage V_s	12 V
3	Switching frequency f_r	400 KHz
4	Sampling frequency f_s	1 MHz
5	Input ripple current ΔI	0.6 A
6	Output ripple voltage ΔV_c	20 mV
7	Main Inductor L_1	12µH
8	Main Capacitor C_1	10µF
9	Resonant Inductor L_2	2.4µH
10	Resonant Capacitor C_2	66.3nF

The efficiency of the conventional buck converter and ZVS buck converter can be calculated by

$$Efficiency = \frac{Output\ Power}{Output\ Power + Losses} \qquad (5)$$

Table 2 Losses occur in ZVS Buck Converter at V_s =12V, R=10Ω, & f_s=400 KHz.

Losses due to	Losses (mW) Hard Switched	Losses (mW) Soft Switched
ESR of the main capacitor	0.5491	1.204
ESR of the main inductor	7.526	16.5
ESR of the resonant capacitor	--	10.62
ESR of the resonant inductor	--	13.1
Conduction Loss of the MOSFET	0.5956	0.9763
Switching Loss of the MOSFET	62.14	--
Freewheeling diode conduction losses	112.6	118.5
Total losses	183.4	160.9

Table 2 shows the Losses of various components in the hard switched (Buck Converter) & soft switched (ZVS Buck Converter). Though other losses in the various components are greater in soft switched converter, it has no switching losses in the MOSFET. In general switching losses in the power semiconductor is more than other losses. Hence total losses in the Hard switched is greater than that of Soft switched converter.

Table 3 Calculated Efficiency of Buck Converter and ZVS Buck Converter.

Buck Converter						ZVS Buck Converter					
R	I_o	V_o	P_o	Losses	η (%)	R	I_o	V_o	P_o	Losses	η (%)
2.5	1.78	4.45	7.93	0.7706	91.14	2.5	1.353	3.38	4.59	0.2931	92.12
5	0.9	4.49	4.04	0.3664	91.68	5	0.982	4.911	4.824	0.2867	94.38
7.5	0.60	4.50	2.70	0.3177	91.71	7.5	0.794	5.959	4.735	0.2073	95.8
10	0.45	4.51	2.03	0.1834	91.76	10	0.677	6.773	4.522	0.1608	96.57
12.5	0.361	4.51	1.62	0.1494	91.8	12.5	0.594	7.422	4.406	0.1254	97.23
15	0.31	4.65	1.44	0.1292	91.86	15	0.528	0.726	4.188	0.0997	97.67

Load Resistance (R), Output current (I_o), Output voltage (V_o), Output power (P_o), Losses an Efficiency (η (%)) of Buck Converter and ZVS Buck Converter.

Equation (5) is used to find efficiency of the Buck Converter and ZVS Buck Converter. Table 3 Shows the various values of Load Resistance (R), Output Power, Losses, corresponding efficiency of the Buck Converter and ZVS Buck Converter. For every load resistance the efficiency of the ZVS Buck converter is greater than that of the conventional Buck converter.
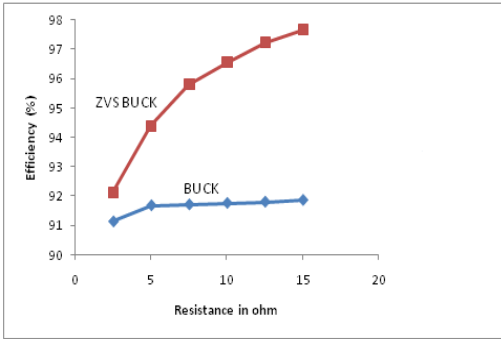

Fig. 4. Efficiency comparison at 400 KHz.

By using Table 3 there is a response curve between Load Resistance (R) and % efficiency (% η) of the conventional Buck Converter and ZVS Buck Converter are shown in Fig. 4. From the Fig. 4. Efficiency of the ZVS Buck Converter is improved by 5% than the schematic Buck Converter.

C. State Variable modeling of ZVS Buck Converter:

The state-space averaging is an approximate technique that can be applied to describe the input and output relation of a ZVS Buck Converter. All state variables are subscribed $\dot{x}$'s and all sources are subscribed u's.

The state equation method as follows

$$\dot{x} = Ax + Bu \qquad (6)$$
$$y = Cx + Du \qquad (7)$$

The state equation method is applied to Fig. 3. ZVS Buck Converter. Where

$$\dot{x} = \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{c1} \\ v_{c2} \end{bmatrix} \qquad (8)$$

$$A = \begin{pmatrix} 0 & 0 & \frac{k-1}{L2} & \frac{-k}{L1+L2} \\ 0 & 0 & 0 & \frac{-k}{L1+L2} \\ \frac{1-k}{C2} & 0 & 0 & 0 \\ 0 & \frac{d}{C1} & 0 & \frac{-k}{RC2} \end{pmatrix} \qquad (9)$$

$$B = \begin{pmatrix} \frac{k}{L1+L} + \frac{1-k}{L1} \\ \frac{k}{L1+1} \\ 0 \\ 0 \end{pmatrix} \qquad (10)$$

$$C = [\,0\ 1\,] \ ; \ D = [0] \qquad (11)$$

By using equation (9),(10) & (11) the transfer function of the ZVS Buck Converter is calculated from [17]

$$tf = \frac{7.276*10^{-12}s^3 + 2.896*10^9 s^2 + 28s + 6.227*10^{21}}{s^4 + 1.667*10^4 s^3 + 2.151*10^{12}s^2 + 3.584*10^{16}s + 2.595*10^{21}} \qquad (12)$$

D. Analog to Digital Converter:

It is a device that converts a continuous quantity to a discrete time digital representation. Fig. 5. shows an error signal e(t) is converted into Discrete sample signal by an Analog to Digital Converter. The A/D conversion process involves deriving samples of the analog signal at discrete instants of time separated by sampling period T (1μS) sec and the quantization interval is 1/128.
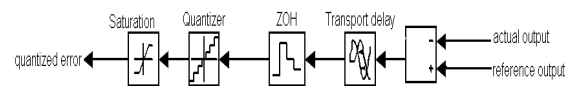

Fig. 5. Analog to Digital Converter

E. Discrete PID Controller:

PID controller is versatile enough to control wide variety of industrial processes. The common practice is to interface a PID controller to the process and adjust the parameters of the

controller online, by trial – and – error, to obtain acceptable performance. The control Algorithm to design discrete PID controller as follows:
Obtain experimentally the dynamic characteristics of the process.
1. Based on dynamic characteristics of a process, tuning rules have been developed by Ziegler-Nichols method, refer Table 4.

Table 4. Ziegler–Nichols tuning formulae.

Type of Controller	K_p	T_i	T_d
P	$0.5K_{cr}$	∞	0
PI	$0.45K_{cr}$	$1/1.2P_{cr}$	0
PID	$0.6K_{cr}$	$0.5P_{cr}$	$0.125P_{cr}$

2. Equation describing the Analog PID controller is as follows:

$$u(t) = Kc\left[e(t) + \frac{1}{Ti}\int_0^t e(t)dt + Td\frac{de(t)}{dt}\right] \tag{13}$$

$$U(s) = Kc\left[1 + \frac{1}{Tis} + Td(s)\right]E(s) \tag{14}$$

By using Ziegler – Nichols Tuning formulae obtain control parameters K_p, T_i, & $T_{d..}$ The value of K_p, T_i, & T_d for ZVS Buck Converter whose plant model transfer function (12) is $K_{p=}$ 0.001, $T_{i=}$2.14e-5, & T_d=5.36e-6 where $K_c=K_p$.

Now
$$U(s) = 0.001\left[1 + \frac{1}{2.14\ast10^{-5}s} + 5.36\ast10^{-6}s\right]E(s) \tag{15}$$

The actual discrete transfer function of the form as

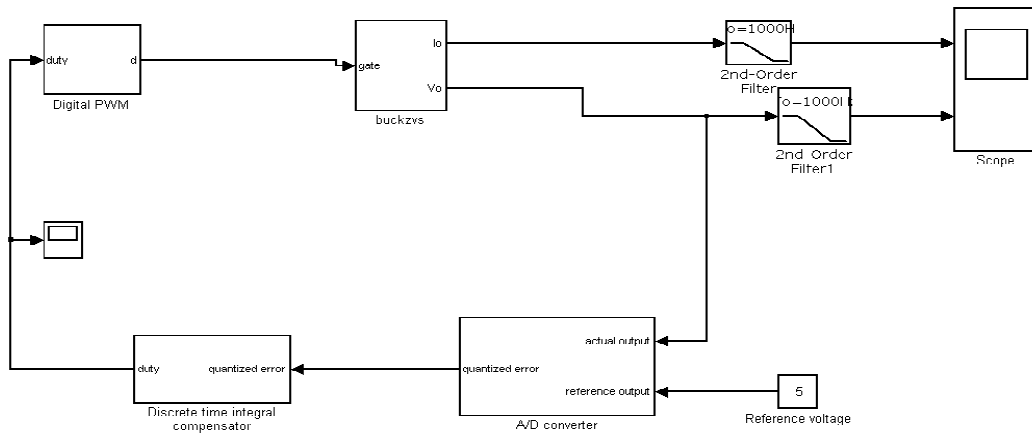$$U(z) = \frac{h0\,z^n + h1\,z^{n-1} + \ldots + hn}{z^n + a1z^{n-1} + \ldots + an} \tag{16}$$

Equation (15) represents Analog PID controller transfer function. The equation (13) can be converted into discrete PID form [15], it becomes

$$U(z) = \frac{0.1174z^2 - 0.02139z + 0.009743}{z^2 - 1} \tag{17}$$

The equation (17) is converted into poles & zeros form as

$$U(z) = \frac{(z - 0.9122)(z - 0.3098)}{(z+1)(z-1)} \tag{18}$$
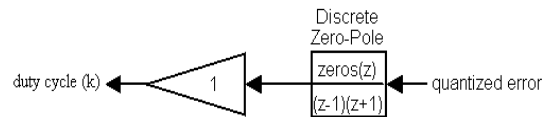

Fig. 6. Discrete PID Controller

F. Digital PWM:
The output of the discrete time Integral Controller is converted into Analog form by means of quantizer, whose quantization interval is 1/1024. The Output of the saturation is in digital form which is one of the input of the comparator is compared with the carrier signal (400 KHz). The comparator output (d) is the PWM pulses. This PWM output pulse is the gate pulse of the ZVS buck converter switch.
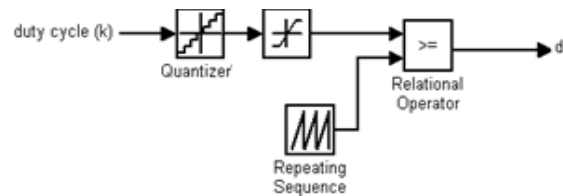

Fig. 7. Discrete PWM Pulse generator

Fig. 8. Matlab/Simulink diagram of Discrete Controlled ZVS Buck Converter

Fig. 8. Shows the overall Matlab / Simulink diagram of Discrete Controlled ZVS Buck Converter, whose output voltage response is shown in Fig. 9. Fig. 10, 11, 12 shows the output voltage response of the Discrete PI controller, Analog PID controller and Analog PI controller respectively.
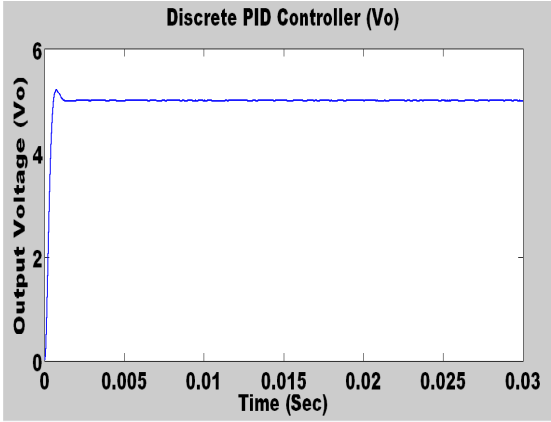

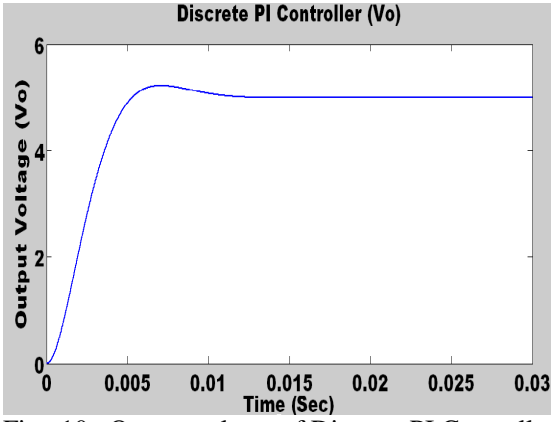Fig. 9. Output voltage of Discrete PID Controller.

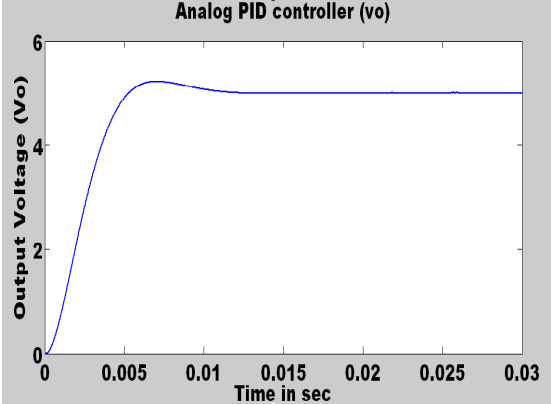Fig. 10. Output voltage of Discrete PI Controller.

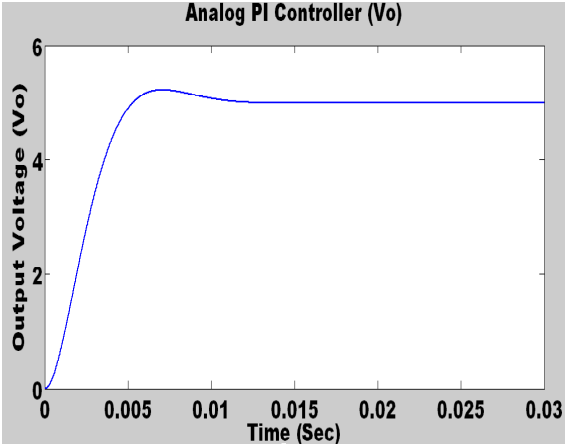Fig. 11. Output voltage of Analog PID Controller.

Fig. 12. Output Voltage of Analog PI Controller.

Table 5 Comparison of the Performance Parameters of Discrete and Analog controlled ZVS Buck Converters

Controller	Settling Time (ms)	Peak Overshoot (%)	Rise Time (ms)	Steady State Error (V)	Output Ripple Voltage (V)
Discrete PID Controller	1.25	4.25	0.6	0	0
Discrete PI Controller	1.4	4.8	0.51	0.03	0.008
Analog PID Controller	12.2	4.33	5.3	0.215	0
Analog PI Controller	10.8	4.31	5.2	0.0029	0

Table 6 Performance of the Discrete PID Controller with the variations of the different parameters.

Output Response for Load variations					Output Response for Input Voltage variations		
R(Ω)	L(µH)	C(µF)	Reference Voltage(V)	Output Voltage(V)	V_s	Reference Voltage(V)	Output Voltage(V)
2.5	-	-	5	5	10	5	5
5	10	-	5	5	14	5	5
15	14	12	5	5	8	5	5
25	15	8	5	5	6	5	5
40	12	12	5	5	16	5	5
60	17	15	5	5	18	5	5

IV. Discussion

The ZVS Buck converter has High Efficiency than the conventional Buck Converter is tabulated in Table 3. The ZVS Buck Converter with Discrete PID controller and many other controllers are designed and simulated. The output voltage performance of the Discrete PID and PI Controller and Analog PID & PI Controller are shown in fig. 9, 10, 11 & 12 respectively. The performance parameters of the Discrete PID controller are better than all other Controllers are illustrated in Table 5. Discrete PID Controller has less settling time, less Peak overshoot, less rise time and has no steady state error and ripple voltage. The response of the system is much faster also. Table 6 shows the response of the system with all possible variations of Input voltage, Load resistance, main inductance and main capacitance. It also provides good regulation even though the Input voltage varied from 2V to 30V instead of fixed 12V. From the simulation we understood that if the input voltage is increased from 12 V, proportionately maximum overshoot is decreased. The designed Discrete PID controller can withstand all the variations in Load resistance, Input voltage, and Inductance and Capacitance values. Hence it proves that the controller is a robust one. From the circuit we can obtain the require output voltage in the range of 1 V to 11 V with the given input voltage of 12 V.

V. Conclusions

This paper presents a simple method for design and implementation of a non-linear discrete PID controller. It is shown that duty cycle can be selected based on the input error signal value to achieve significantly improved dynamic response. The implementation includes an ADC, DAC, and Discrete PID Controller, which is well suitable for high frequency SMPS controllers. Simulation results are presented for 10W/400KHz, 12V to 5V point of load. The response of the system is much faster and it works well for all the possible values of the duty cycle and the change in the load resistance, inductance, capacitance and Input voltage. In future we can change the load from resistive to Inductive or motor load. This controller circuit can be implemented to control different Special machines like Brushless DC motor, Switched reluctance motor etc.

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