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Subramanian Vijayalakshmi, Thangasamy Sree Renga Raja

Time domain based Digital PWM controller for DC-DC converter

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Original scientific paper

Discrete Pulse Width Modulated controller for buck converter is described. The key building blocks are Analog to Digital converter, compensator, and digital pulse width modulator is introduced to meet the requirement of perfect output voltage regulation, high-speed dynamic response, and programmability. The discrete controller method bypasses errors related to the conversion from the continuous to the discrete domain based on the time domain method. The simulation results are proven with experiment conducted. Analog controller is also designed for a buck converter whose controller parameters are compared with the Discrete PID controller is illustrated.

Key words: Buck Converter, Data Acquisition Cable, Discrete PID controller, Lab VIEW

Digitalni pulsno-širinski regulator za istosmjerne pretvarače temeljen na vremenskoj domeni. Opisan je diskretni pulsno-širinsko modulirani regulator za silazni upravljač. Osnovni dijelovi su analogno-digitalni pretvornik, kompenzator, a predložen je i diskretni pulsno-širinski modulator kako bi se što bolje upravljalo izlaznim naponom i imao što brži dinamički odziv. Diskretni regulator nadilazi pogreške povezane s prelaskom iz kontinuirane u diskretnu domenu. Simulacijski rezultati su potvrđeni eksperimentom. Projektiran je i analogni regulator za silazni upravljač te je napravljena usporedba s diskretnim PID regulatorom.

Ključne riječi: silazni pretvarač, prikupljanje podataka, diskretni PID regulator, Lab VIEW

1 INTRODUCTION

Switched mode Electronic control DC-DC converters convert one level of DC voltage to another level by varying the duty cycle of the converter. These converters are smaller in size, more power efficient provides an efficiency of 75% to 98% therefore, they are used extensively in computer peripherals, personal computers, communication, medical electronics and adapters of consumer electronic devices to provide different levels of DC voltages.

DC-DC converters are time varying, nonlinear dynamic systems. Buck converter is known as step – down converter. The advantages of a Buck converter are highly efficient, simple to design mostly due to not having a transformer, puts minimal stress on the switch, and requires a relatively small output filter for low output ripple. The switching devices and passive components such as inductors and capacitors arise nonlinearities in the converters. As a result, the linear control techniques cannot be directly applied to analyze. Hence the design of feedback compensation using linear control techniques is needed for nonlinearities.

The analog PID control scheme has been used successfully in many industrial control systems. Digital controllers are often superior in performance and lower in price than their analog counterparts. They are extremely flexible, easily handle nonlinear control equations involving complicated computations or logical operations. A very much wider class of control laws can be used in digital controllers than in analog controllers. Digital controllers are capable of performing complex computations with constant accuracy at high speed and can have almost any desired degree of computational accuracy alternatively with little increase in cost.

In order to attain tight voltage regulation, robustness, fast switching transient and improved transient characteristic, Discrete PID controller is introduced. Digital controller offers many advantages than analog controller. Digital controller has low component ageing, low cost, zero drift characteristic, high reliability and controllability than other controllers. Many literatures are developing a digital controller for DC-DC converter [1]-[6]. Few of them are discussed now.

For high regulation and accuracy application, the introduction of single-phase and multi-phase controlled digital dither in digitally controlled PWM converters, which increases the effective resolution of DPWM modules [1]. Digital dither is to generate average duty levels by varying the duty cycle by an LSB over a few switching periods.

It also introduces ac ripple which is superimposed by the switching action of a converter. Another type of digital controller for buck converter, consider about the two quantizers namely A/D converter and DPWM. These quantizers can cause undesirable limit-cycle oscillations. In the static and dynamic model, existence of DC solution is examined and finds the solution to obtain no limit-cycle oscillation [2].

Time domain design of digital compensators for buck converter is determined by the first few samples of the step response of the compensator [3]. The controller is carried out in the time domain which bypasses errors from continuous to discrete domain discretization. To control high frequency low power buck converter, digital PID controller with hybrid Δ-Σ DPWM is introduced [4]. Δ-Σ DPWM includes DCM phase shift and a 2-bit counter- comparator in hardware architecture. It is available on FPGA board.

When fast transient response is needed, large load changes are expected, improved transient response and rise time are required, Auto-tuning PID scheme is developed for buck converter [5]. This controller continuously adjusts the controller gain by applying an easily interpretable heuristic rule. Digital controller is also implemented using IC for high frequency buck converter [6]. This controller has high noise immunity, small size, low power consumption and low- power compensator with lookup tables. Various converter configurations can be redesigned without the need for external passive components.

In the proposed discrete PID controller is designed for buck converter. The controller design takes two steps 1) Design an analog controller of a continuous time domain for the buck converter. 2) Approximate the behaviour of an analog controller with a digital one that is convert continuous domain into discrete domain. In the discrete domain, the controller that compensates the error signal and track the accurate output. It is easy to design for all types of converters. It does not produce any limit cycle oscillation, for any resolution of DPWM, the controller act accordingly and prove its robustness and stability. Performance is very good. In the proposed controller, controller parameter like rise time, settling time and peak overshoot is very low. It does not have steady state error and ripple voltage. Any uncertainty like the variations in input voltage and load, it continuously tracks the output and prove its enhanced robustness. Any component variations up to certain limits, do not affect the output voltage provided digital compensator rectifies the error, accordingly varies the duty cycle of the converter and produces the constant output voltage. The change in the required voltage does not take much time to attain the same as the output voltage.

To implement a discrete PID controller in buck converter, three specific blocks are needed as shown in Fig. 1.

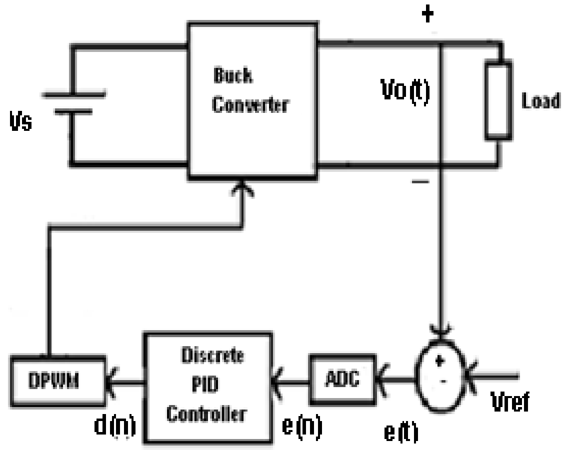


Fig. 1. Digitally controlled buck converter.

i) The ADC used to sample the error voltage ii) the discrete PID controller that compensates the error signal iii) In order to reduce the lower order harmonics in the duty cycle, implement the Pulse Width Modulator (PWM). The combination of DAC and PWM is known as a Digital Pulse Width Modulator (DPWM). DPWM converts the sampled, compensated error signal into the gate drive signals, which drives the MOSFET switch.

The design of PID controller is usually supported by simulation tools Matlab Simulink and LabVIEW control design. In this paper, a simulation study of a PID controller for Buck converter is conducted and the hardware of a buck discrete PID controller is constructed using LabVIEW. It is possible to speed up programming considerably in LabVIEW, it is easy to implement through the use of sub virtual instruments Vis [7] – [9]. This LabVIEW has built-in ADC and DAC. The output of the controller is compared with triangular wave carriers and is adopted as a PWM switching signal generating part. The switching frequency is set at 400 KHz.

2 DESIGN OF BUCK CONVERTER

For Buck converter of Fig. 2 operates in Continuous Conduction Mode, the relationship between the input voltage (V_s) and the output voltage (V_o) is given as [10]:

$$d = \frac{V_o}{V_s} = \frac{\mathrm{T_{ON}}}{\mathrm{T_S}} \tag{1}$$

where d is the duty-cycle, T_{ON} is conducting time of the switch and T_s is the switching period. The switching period Ts can be expressed as [10]:

$$Ts = \frac{I_L V_s}{V_o(V_s - V_o)} \tag{2}$$

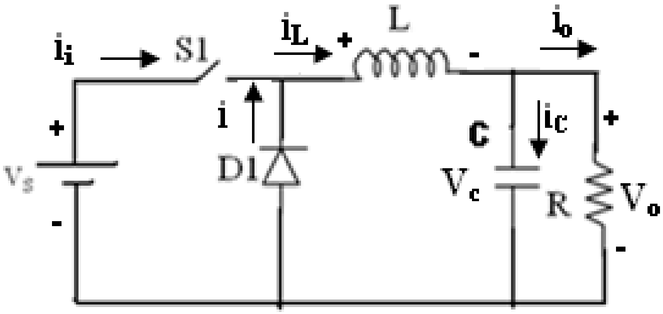


Fig. 2. Power stage of Buck converter

Table 1. Design parameters of Buck converter

Parameter	**Buck**
Output power P_o	10 W
Input Voltage V_s	12 V
Switching frequency f_r	400 kHz
Ripple current ΔI	0.6 A
Ripple voltage ΔV_c	20 mV
Inductor L	12μH
Capacitor C	10μF
Load resistor R	2.5Ω

where ΔI is the ripple current, L is the inductance of the circuit.

The value of L can be determined as [10]

$$Lf_s\,\mathrm{I}_L \;=\; V_s\,d(1-d) \tag{3}$$

The capacitor C is then determined by the allowed voltage ripple ΔV_c. The ripple voltage is given as [10]

$$\mathrm{V_c} = \frac{V_s d(1-d)}{\mathrm{8LC\ f_s}^{\ 2}} \tag{4}$$

The value of capacitance depends on the change in the load. The design parameter of the buck converter is shown in Table 1.

3 ANALOG TO DIGITAL CONVERTER

The device that performs the sampling, quantization, and coding is an A/D converter. For sampling, the Zero – order hold is widely used in practice which increases the stability margin, decreases the instability than the higher-order hold. To avoid aliasing, we choose the sampling frequency high enough as $f_s > 2f_r$. The difference between adjacent levels or the quantization step in terms of the range of the signal is

$$q = \frac{R}{2^{b+1}}$$

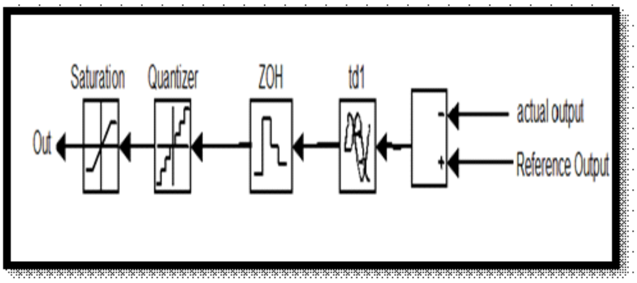


Fig. 3. Block Diagram representation of Analog to Digital Converter

where q is quantization steps, R is an amplitude range. If the input signal has a range of 2V, then the quantization step size is equal to

$$q = \frac{2}{2^{b+1}} = 2 - b$$

In quantization, a word length of 7 bits, an input signal can be resolved to one part in 2-7, or 1 in 128. With the availability of converters with resolution 7 bits, the quantization errors do not pose a serious threat in the computer control of processes. It may be noted that the quantized discrete-time signal and the coded signal carry exactly the same information. Block diagram representation of Analog to Digital converter is shown in Figure 3.

4 DIGITAL PWM

The Digital Pulse Width Modulator also serves as a D/A converter. The quantizer and saturation block combindly works as a digital to analog converter. The digital error signal $e(n)$ at the A/D output is obtained by quantization of analog error voltage e(t), while the duty cycle d at the DPWM output is obtained by quantization of the duty cycle command k. The characteristic of a quantizer having a continuously varying input x and an output $y = Q(x)$. The range of x is divided into the binary of width q, where q is the “quantization level,” or the value of the quantizer’s least significant bit (LSB). For x in the kth bin, the output y equals the kth discrete output value ($y = kq$). We choose the quantization interval (q) is 1/1024. The quantized signal is converted into an analog signal by the device of saturation. Fig. 4 shows the Discrete PWM pulse generator.

The gating signals are generated by an analog error corrected signal is compared with the high frequency carrier signal (400 KHz). The frequency of the carrier signal determines the fundamental frequency of the output voltage (d).

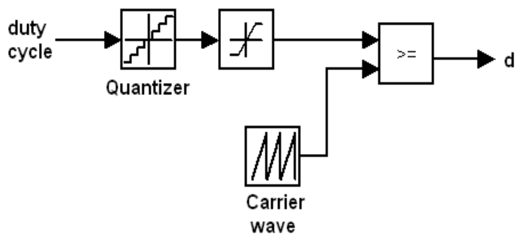


Fig. 4. Discrete PWM pulse generator

5 DESIGN OF DISCRETE PID CONTROLLER

Proportional plus Integral plus Derivative controller is the widely used one in the design of continuous – time control system. The step to design a digital controller is

1. Design an analog controller of a continuous time controller for the plant (buck converter)
2. Approximate the behavior of the analog controller with a digital one. The digital controller which consists of an A/D converter driving an $H(z)$ (discrete-time system) followed by D/A conversion. This combination is called a digital filter. The control algorithm to design a discrete PID controller is as follows.

i. Find the dynamic characteristics and transfer function $G(s)$ of the buck converter by open loop.

5.1 State Variable modelling of Buck Converter

The state-space averaging is an approximate technique that can be applied to describe the input and the output relation of a buck converter. All state variables are subscribed$\dot{x}$'s and all sources are subscribed as u's [11].

The state equation method as follows

$$\dot{x} = A_1 x + B_1 u \tag{5}$$

$$\dot{x} = A_2 x + B_2 u \tag{6}$$

where x is a state vector, u is a source vector, A_1, A_2, B_1, B_2 are the state coefficient matrices. Replacing the (5) and (6) two sets of equation by a single equivalent one

$$\dot{x} = Ax + Bu \tag{7}$$

where

$$A = dA_1 + (1-d)\,A_2 \tag{8}$$

$$B = dB_1 + (1-d)\,B_2 \tag{9}$$

where d is the duty cycle. State model of the buck converter is derived and is discussed below.

Higher power densities are possible only for continuous conduction mode (CCM) of operation. But for continuous current mode of operation, stability problem occurs. This can be easily solved by pole-zero cancellation method. Diode D and MOSFET S are always in a complementary state, when S-ON, D-OFF and vice versa. Two modes of operations are possible, corresponding state equations are

Mode 1 : S is ON and D is OFF

$$\dot{x} = A_1 x + B_1 V_s \tag{10}$$

where

$$x = \begin{bmatrix} i_L \\ \mathrm{V}_C \end{bmatrix} \tag{11}$$

where i_L is the current through the inductor, and V_C is the voltage across the capacitor [11].

Mode 2 : S is OFF and D is ON

$$\dot{x} = A_2 x + B_2 V_s \tag{12}$$

where

$$A_1 = A_2 \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C} & \frac{-1}{RC} \end{bmatrix} \tag{13}$$

$$B1 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \tag{14}$$

$$B2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{15}$$

Substitute (13) in (8) can get

$$A = \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C} & \frac{-1}{RC} \end{bmatrix}. \tag{16}$$

Similarly applying (14) and (15) in (9) can get

$$B = \begin{bmatrix} \frac{k}{L} \\ 0 \end{bmatrix} \tag{17}$$

$$Y = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ \mathrm{V}_C \end{bmatrix} \tag{18}$$

Find the transfer function $G(s)$ of the buck converter. Conversion of state space equation (7) and (18) into transfer function [12] can obtain

$$G(S) = \frac{-7.2766{*}10^{-12}\mathrm{s} + 3.472{*}10^{9}}{s^2 + 40000s + 8.33{*}10^{9}} \tag{19}$$

ii. According to the dynamic characteristic and the transfer function of the converter, the analog PID controller

Table 2. Ziegler-Nichols tuning formulae

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

has been designed using Ziegler and Nichols tuning formulae shown in Table 2.

PID controller has the advantages of both PD & PI controller. PD controller improving system stability and increasing system bandwidth, it is a special case of phase-lead controller. PI controller reduces steady-state error is a special case of the phase-lag controller. Hence PID controller is also called as phase lag - lead controller.

The equation describing the Analog PID controller is as follows [13]:

$$u\,(t) = \; K_p[e\,(t) + \; \frac{1}{T_i}\int_0^t e\,(t)\,dt + T_d\frac{de(t)}{dt}] \tag{20}$$

where K_p is the controller gain, T_i is the integral time and T_d is the derivative time.

iii. Find the characteristic equation

$$1 + G(s)H(s) = 0 \tag{21}$$

where $G(s)$ is the transfer function of the converter and H(s) is the unity feedback gain.

iv. From the characteristic equation, find the PID controller parameter K_p, T_i and T_d using Ziegler – Nichols Table 2. For buck converter $K_P = 0.2$, $T_i = 2.89 * 10 - 5$, and $T_d = 7.23 * 10 - 6$.

v. Find the Laplace transform of equations (20)

$$U\,(s) = \; K_c[1 + \; \frac{K_I}{s} + K_D s]\; E(s) \tag{22}$$

where $K_c = K_p$, $K_I = \frac{K_P}{T_I}$ and $K_D = K_p T_D$.

vi. Convert Analog PID controller (20) into the Discrete PID controller, for that Euler's forward, Euler's backward and Trapezoidal methods are available. Here we implement Trapezoidal method. It is also called as Tustin method or Bilinear-Transformation method. This Tustin method tracks the analog controller output more accurately at the sample times and approximate to the analog integration are better than other methods. Trapezoidal approximation to the integral in equation gives [14]

Let $n(t)$ be the integral of $e(t)$, then the value of the integral of $t = (K + 1)T$ is equal to the value at KT plus the area added from KT to $(K + 1)T$.

$$N[(K + 1)T] = n(KT) + \int_{KT}^{(K+1)T} e\,(\tau)\,d\tau \tag{23}$$

Using Trapezoidal rule, $e(t)$ is the area curve from $t = KT$ to $t = (K + 1)T$ is approximated as

$$\frac{e\,[(K + 1)\,T] + \; e(KT)}{2}\; x\,T \tag{24}$$

therefore

$$N\{(K+1)T\} = n(KT) + \frac{T}{2}\;\{e\,[(K + 1)\,T] + e\,(KT)\} \tag{25}$$

Taking the z-transform, we obtain

$$zN(z) = N(z) + \frac{1}{2}[zE\,(z) + \; E\,(z)] \tag{26}$$

thus

$$\frac{N(z)}{E(z)} = \frac{T}{2}\left[\frac{z + 1}{z - 1}\right] \tag{27}$$

hence equation (27) is the transfer function of a discrete Integrator.

Trapezoidal approximation to differentiation. Derivative of $e(t)$ at $t = KT$ is $n(KT)$, then

$$n\,(KT)\,\frac{e\,(KT) - \; e[(K - 1)\,T]}{T} \tag{28}$$

thus

$$\frac{N(z)}{E(z)} = \frac{(z - 1)}{Tz} \tag{29}$$

Now discrete PID controller transfer function becomes

$$U(z) = \left[K_P + K_I\frac{Ts}{2}\frac{z + 1}{z - 1} + K_D\frac{z - 1}{Tz}\right]E(z) \tag{30}$$

$$U(z) = \left[\frac{\left(K_P + K_I\frac{Ts}{2}\frac{2Kd}{Ts}\right)z^2 + (K_I T_s + \frac{4K_D}{T_s}}{z^2 - 1}\right]E(z) \tag{31}$$

In the designed buck converter

$$\mathrm{U}\,(\mathrm{z}) = \frac{3.094z^2 - 5.7752\mathrm{z} + 2.694}{(z + 1)\;(z - 1)} \tag{32}$$

vii. a) Any closed loop pole outside the unit circle makes the system unstable. b) If a simple pole lies at $z = -1$, then the system becomes critically stable. C) Any multiple closed-loop pole on the unit circle makes the system unstable. d) Closed loop zeros do not affect the stability and therefore may be located anywhere in the z

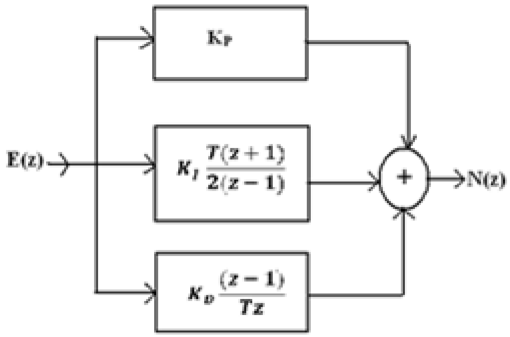


Fig. 5. Discrete PID controller

plane. Hence in the design of z-plane, to cancel the undesirable poles and zeros of the controller and new open-loop poles and zeros are added as more advantageous locations to satisfy the design specifications [15].

By using the pole-zero cancellation technique, cancel the pole at $z = -1$ and makes the system to be stable. Now $U(z)$ becomes

$$U\left(z\right)=\frac{\left(z-a\right)\left(z-b\right)}{z\ \left(z-1\right)} \tag{33}$$

In the designed buck converter

$$U\left(z\right)=\frac{\left(z-0.9492\right)\left(z-0.9174\right)}{\mathrm{z}(z-1)} \tag{34}$$

The discrete PID controller block diagram is shown in Fig.5.

Tustin method maps the imaginary axis in the s-plane to the unit circle on the z-plane, the right half of the s-plane to the exterior of the unit circle of the z-plane and left half of the s-plane to the interior of the unit circle in the z-plane [15]. Mapping between the S-plane and Z-plane using Tustin's method is shown in Fig. 6.

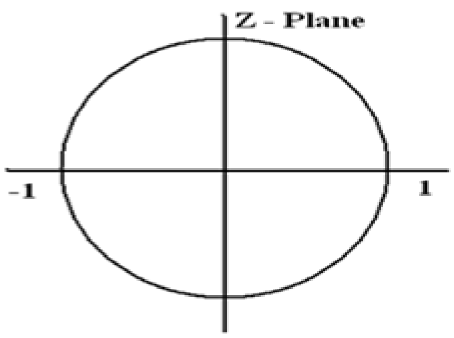


Fig. 6. Mapping between the S-plane and Z-plane using Tustin's method

6 SIMULATION AND EXPERIMENTAL RESULTS

6.1 Simulation results

Simulink model of a digitally controlled buck converter is shown in Fig. 7. The Converter parameters are: V_s = 12V, V_{ref} = 5V, $f = 400$ kHz, $R = 2.5\Omega$, $L = 12\mu$H and $C = 10\mu$F. The given reference voltage is compared with the actual output and the error is converted into Digital form by means of A/D Converter in the subsystem block.

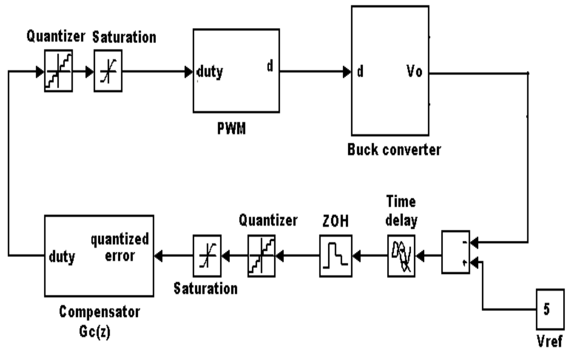
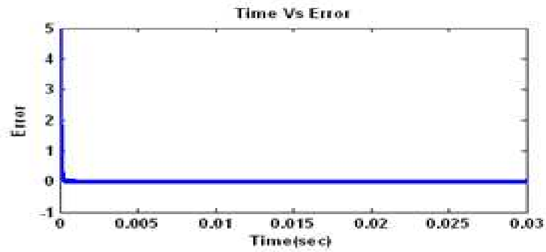


Fig. 7. Matlab/Simulink diagram of a Discrete Controlled DC-DC Converter

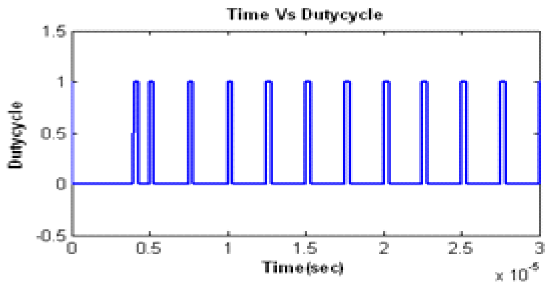
The quantized error is corrected by Discrete Time Integral compensator subsystem block. The corrected signal is converted into digital PWM pulses by DPWM, finally PWM pulses are given to MOSFET switch in DC-DC converter. The simulation is carried out by quantized error from analog to digital converter is shown in Fig. 8(a). The PWM pulse from DPWM is shown in Fig. 8(b). Simulation is also carried out by output voltage and output current with the reference voltage 5V and the input voltage of 12V of the buck converter is shown in Fig. 9. The simulation result proves that the output voltage does not have any overshoot, rise time, settling time, ripple voltage and steady state error.

The output voltage and output response to the change in input voltage is shown in Fig. 10. The designed input voltage is 12V, it increased by 40V. The changes in the input voltage do not make any variations in the output voltage that is the controller adopt the variations in the parameters, nullify the error produced by the variations and continuously track the reference voltage, produces the reference as the output voltage. This proves the robustness of the controller.

The simulation is carried out by varying the load resistance from 5Ω to 2.5Ω. The actual designed resistance is 2.5Ω, but the high resistance does not affect the output voltage and the varying resistance at 0.025 s does not make any effect on the output voltage is shown. The simulation is also carried out by varying the output with the variation in



(a) Error



(b) PWM pulses

Fig. 8. Simulation results on Discrete PID Controlled buck converter

the reference voltage is shown in Fig. 12. From 0 to 0.03 s the reference voltage is 5V, the corresponding output voltage is also 5V, reference voltage has been changed to 8V from 0.03 s to 0.05 s, the corresponding output voltage is also changed to 8V. The controller does not take any time to vary the output voltage from 5V to 8V as shown. The controller adopts the change in reference, vary the duty cycle of the converter and produce the reference as the output voltage within a fraction of millisecond as shown. Figure 13 shows the output voltage response of the discrete and analog controllers. From the fig analog controllers have large rise time, settling time and peak overshoot. The digital PI controller may have less rise and settling time than analog controller but it has more peak overshoot than all the controllers. Only digital PID controller does not have any rise time, settling time, peak overshoot, and steady state error, ripple voltage.

Comparison between the controllers are given in Table 3 based on the state space model and identified model of the converter. It is found that the Discrete PID controller that are extracted based on the identification produce better dynamic results in closed loop response than the other controllers. The important advantages of the proposed method are the fact that it is carried out in the time domain (and hence bypasses few errors due to the s to z transformation) and that it is does not involve a trial and error procedure. The variations in different component parameters and the controller output voltage response is given in Table 4. Table 4 and simulation results prove that the stability of the

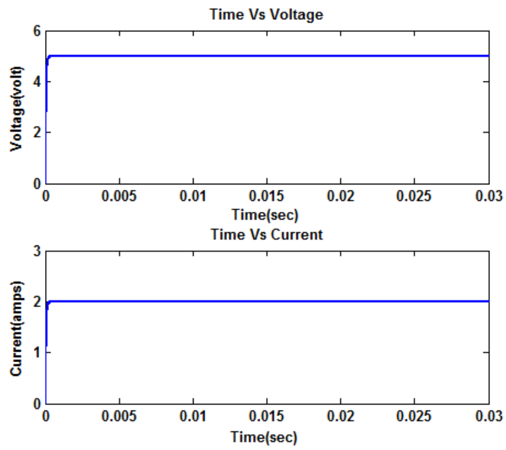


Fig. 9. Output response of discrete PID controlled buck converter with the reference voltage of 5V.

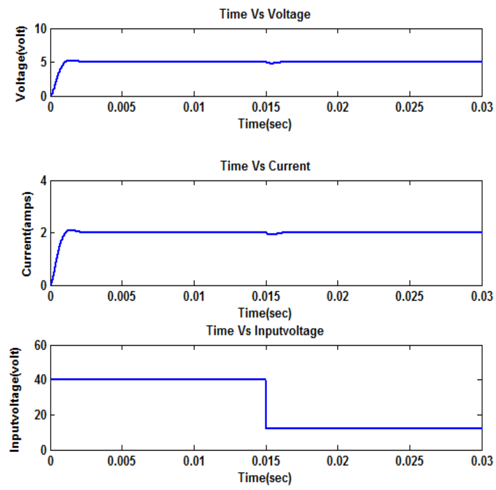


Fig. 10. Output response of discrete controlled buck converter with the change in input voltage of 40V to 12V.

controller that the variations in the component and input voltage do not affect the output voltage.

6.2 Hardware implementation

The buck converter with a discrete controller can be implemented using LabVIEW is shown in Figure 14. The design parameters are given in Table 5. LabVIEW is (Laboratory Virtual Instrumentation Engineering Workbench) used as a controller platform for implementing any closed loop system. LabVIEW is powerful flexible and reliable instrumentation and analysis software, it creates hardware and software products that control computer technology to help

Table 4. Variations in different parameters and performance of the discrete PID controller

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

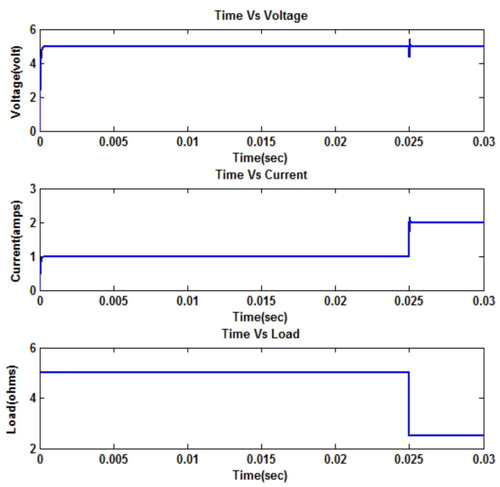


Fig. 11. Output response of discrete PID controlled buck converter with the change in load resistance of 5Ω to 2.5Ω.

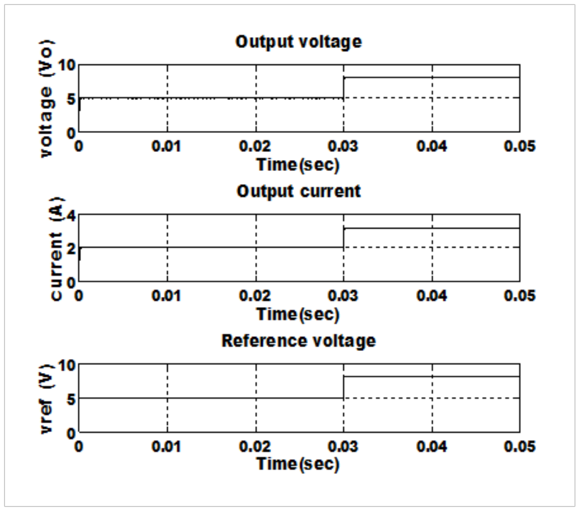


Fig. 12. Output response of discrete PID controlled buck converter with the reference voltage of 5V to 8V.

Table 3. Comparison of the Controller for Buck Converter

Controller	Settling Time (ms)	Peak Overshoot (%)	Rise Time (ms)	Steady State Error (V)	Output Ripple Voltage (V)
Discrete PID	1	0	1	0.00398	0
Discrete PI	12	5	2	0.01	0
Analog PID	25	4.3	11	0.0001	0.05
Analog PI	23	4.6	10	0.01	0.08
Sliding mode	1.3	2.5	0.07	0	0

engineers and scientists take measurements, control processes, analyze and store data. This has three main parts: the block diagram, the front panel, and the icon/connector. The front panel is the interactive user interface of a VI – a window through which the user interacts with the source code. The front panel opens through which we pass inputs to the executing program and receive outputs when we run a VI. The front panel is necessary for viewing the program outputs. Figure 15 shows a front panel of control circuit. The block diagram consists of executable icons (called nodes) connected (or wired) together is shown in Figure 16. NI 6009 Data Acquisition cable (DAQ) is used as an interfacing circuit. It provides the extraordinary ability to simultaneously stream analog inputs and outputs at up to 3.2 MS/s and digital I/O up to 10 MHz. DAQ combines signal connectors, signal conditioning, and A/D converters in each measurement module. Output from the DAQ is processed with carrier frequencies which produce PWM gate pulses.

The experimental output voltage waveform with the reference voltage is shown in Figure 17. The given reference voltage is 7.0 V, the output voltage response is 7.03V. The output voltage response to the variation in input volt-

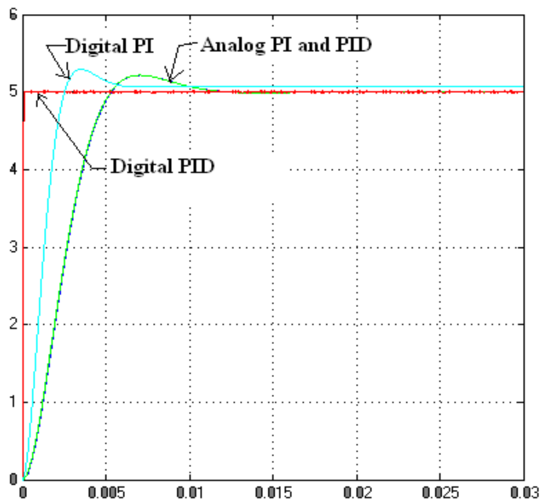


Fig. 13. Output voltage response of Analog PID, PI and Discrete PID, PI controller for discrete controlled buck converter

age is shown in Figure 18. In spite of variations in the input voltage from 12V to 10V, the controller tracks the reference voltage of 5V and produces reference voltage as the output voltage of 5.02V. Similarly the input voltage is increased from 12V to 15V, the output voltage is again 5.06V is shown in Fig. 19. Therefore the increase or decrease in input voltage does not vary the output voltage. The gate pulse waveform from the DPWM circuit and the output voltage response is shown in Fig. 20 and Fig. 21. The reference voltage of Fig. 20 and Fig. 21 is 5V and 7V respectively. According to the reference voltage the duty cycle of the gate waveform is varied as shown. For 5V reference the duty cycle of the gate pulse is 41.6% and 7V it is 56.6%. The frequency of the PWM gate pulse is almost equal to the carrier frequency of 400 KHz. Therefore if the reference voltage is varied the controller accordingly varies the duty cycle of the switch and produces the reference as the output voltage. The simulation & experimental results confirm the feasibility of the proposed design method. This method can thus be a good applicant for an alternative approach to the design of digital compensators for PWM DC-DC converters. The simulation and experimental results prove the enhanced robustness, voltage regulation and good dynamic characteristic of the discrete PID controlled buck converter.

7 CONCLUSION

This paper presents a simple method for the design and implementation of a Discrete PID controller for Buck converter. It is shown that the proportional, integral and differential gains of a PID controller can be selected based on the input error signal value to significantly improve the dynamic response of the Buck converter. The implementation includes LabVIEW based digital compensator which is well suited for practising high-frequency SMPS controllers. The discrete PID controller is implemented in buck converter and its dynamic characteristics are experimentally verified. Simulation and experimental results are presented for a 12V-to-5V point-of-load Buck converter to show the improved dynamic response under non-linear control.

Table 5. Experimental values

Description	Experimental values
fr	400 KHz
Vs	12 V
L	12μH
C	10 μF
R	2.5 Ω
S	IRF840
D	1N4001
DAQ	NI 6009

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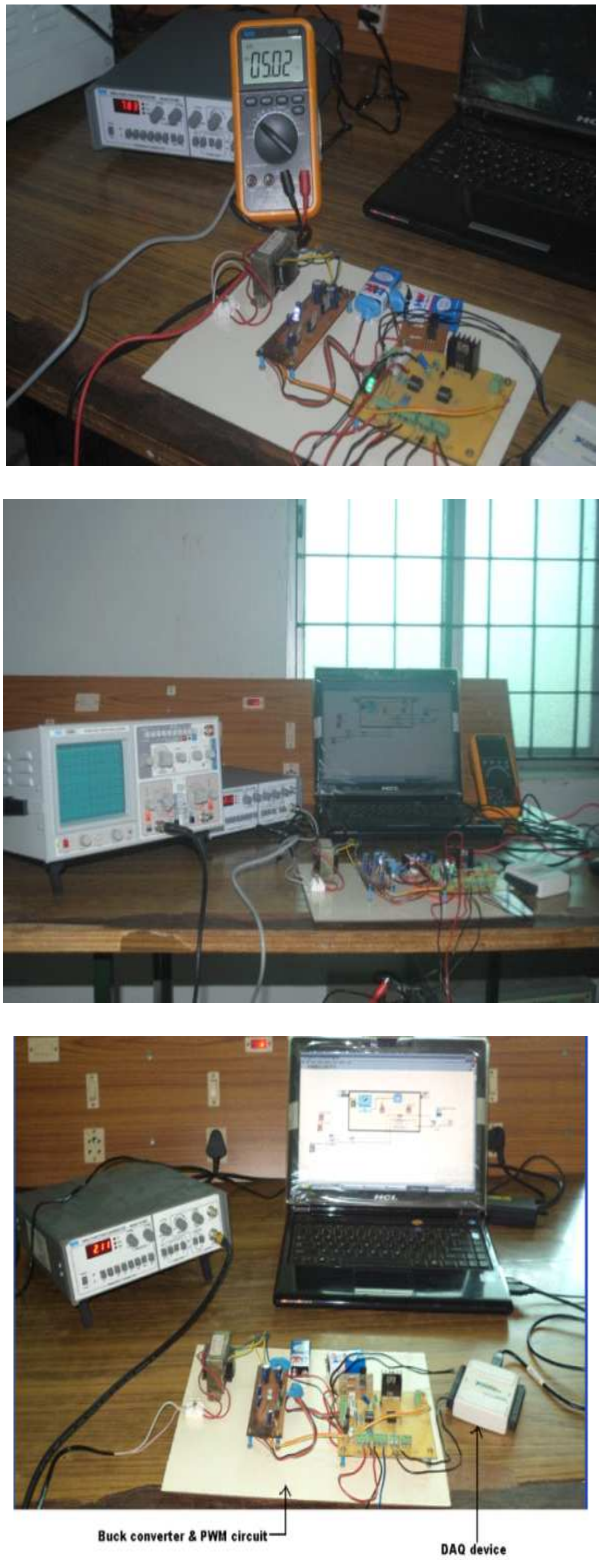

Fig. 14. Overall Experimental setup of the Buck discrete controller using LabVIEW

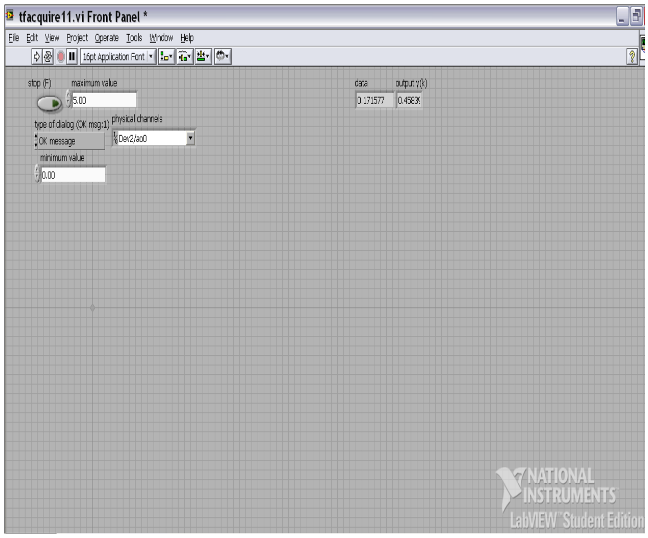

Fig. 15. Front panel of the control circuit

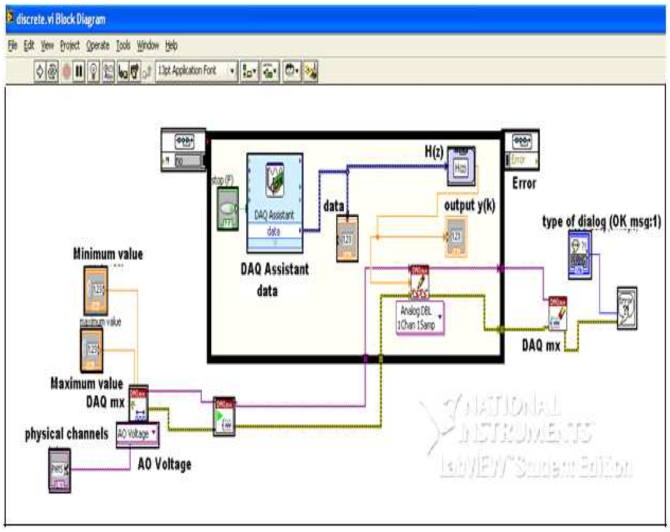

Fig. 16. Block diagram of the Discrete controller circuit using LabVIEW

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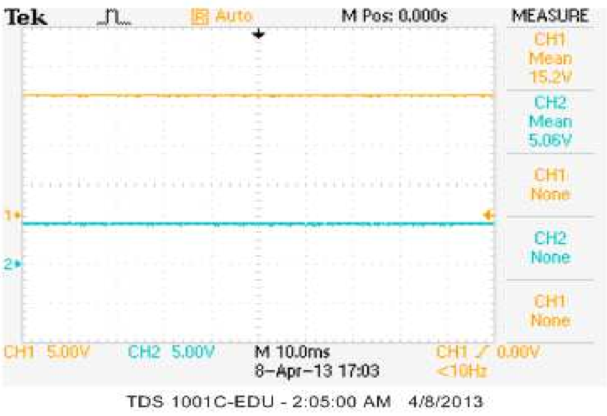

Fig. 19. The output voltage response of variation in input voltage from 12 V to 15V with the reference voltage of 5V. (CH1 – input voltage 15.2V, CH2 – Output voltage 5.06V)

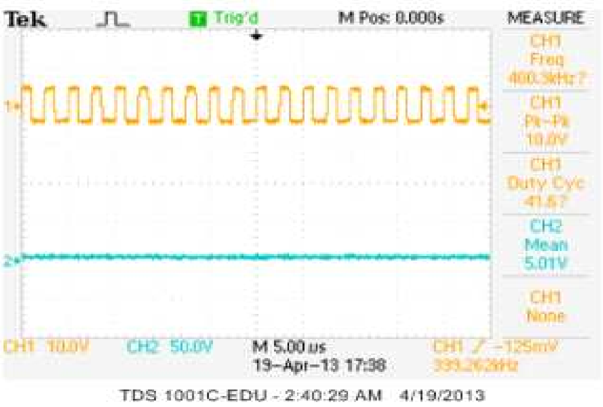

Fig. 20. Gate pulse waveform and output voltage with the reference voltage of 5V and the input voltage of 12V. (CH1 – Gate pulse waveform duty cycle 41.6%, CH2 – Output voltage 5.01V).

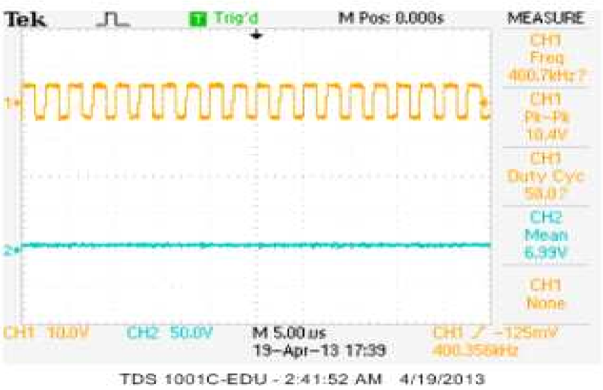

Fig. 21. Gate pulse waveform and the output voltage with the reference voltage of 7V and the input voltage of 12V. (CH1 – Gate pulse waveform duty cycle 58%, CH2 – output voltage 6.99V).

Fig. 17. Output voltage response to the reference voltage of 7V and the input voltage of 12V. (CH1 – reference voltage 7.0V, CH2 – Output voltage 7.03V).

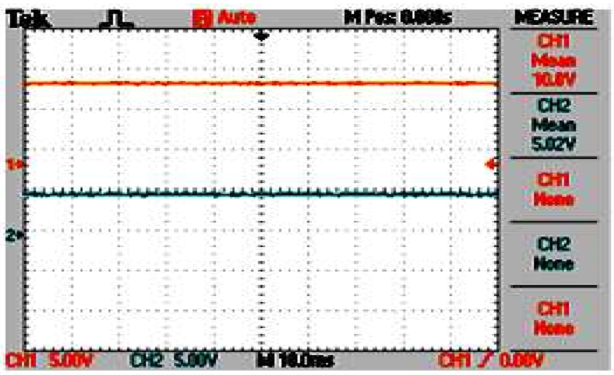

Fig. 18. The output voltage response of variation in input voltage from 12 V to 10V with the reference voltage of 5V. (CH1 – input voltage 10.0V, CH2 – Output voltage 5.02V)

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S. Vijayalakshmi received AMIE degree in Electronics & Communication Engineering from Institution of Engineers (India), Kolkatta in 1992, Master of Science degree in Information Technology from Bharathidasan University, Tiruchirapalli, and Master of degree in Power Electronics and Drives from Anna University, Chennai in 2007. Her research interests are Discrete controller for DC-DC converter.

T. Sree Renga Raja is working as an Assistant Professor in the Department of Electrical and ElectronicsEngineering, Anna University, BIT Campus, Tiruchirapalli, Tamil Nadu, India. He obtained B.E (Electrical and Electronics Engineering) degree from Manonmaniam Sundaranar University, Tirunelveli in 1998, M. E (Power Systems) from Annamalai University, Chidambaram in 1999 and Ph.D from Anna University, Chennai in 2007. He has published many papers in the field of PowerSystem Engineering. His area of interest includes Power system optimization, Renewable Energy Applications, Energy Conservation Management and Insulation Engineering.

AUTHORS' ADDRESSES

Subramanian Vijayalakshmi, M.E.
Department of Electrical and Electronics Egineering
Saranathan College of Engineering
Panchapur, Tiruchirappalli 600 012, India
email: bksviji@gmail.com

Asst. Prof. Thangasamy Sree Renga Raja, Ph.D.
Department of Electrical and Electronics Engineering
Anna University, BIT Campus
Tiruchirappalli, Tamil Nadu 600024, India
email: renga_ raja@rediffmail.com

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