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Performance Comparison of Various Control Algorithms for an Asynchronous Buck Converter

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Abstract: The control of power electronic circuits is a challenging field of research due to the requirements imposed by the applications. A controller design for a Buck converter which steps down a given dc value to a desired regulated dc value is the system taken into consideration in this study. The controller designed for Buck converter has to control rise time, peak overshoot, settling time, bandwidth which are affected by the load and line variations. Quarter Amplitude Decay (QAD), Internal Model Control (IMC) and Pole placement techniques are used to obtain the parameters of the PID controller. The performances of these tuning procedures are evaluated and the comparison is tabulated. It is found that the controller tuned by pole placement method gives less rise time and settling time with negligible overshoot. But transfer function of pole-placement base controller is quite complex and has high number coefficients which is difficult to realize in real time systems. QAD based PID controller has less rise time and settling time but it has peak over shoot which will produce voltage spikes in real time systems. Hence an IMC based PID controller which has acceptable rise time and settling time with no peak overshoot is realized in real form by using operational amplifiers. The performance is evaluated and tabulated under varying load and reference voltage conditions.

Key words: DC-DC converter, buck converter, quarter amplitude decay, internal model control, PID controller, pole-placement method

INTRODUCTION

Highly efficient buck DC-DC converters have numerous applications both in high voltage and low voltage domains such as DC motor drives, lighting systems, cellphones, PDAs etc. (Morroni *et al*., 2009). The desired output varies due to the line or load variations along with other factors like component degradation. A closed loop control is one of the solutions to counter the ill effects. The control algorithm can be of analog or digital, offline or online with each of the methods having their own advantages and disadvantages (Abiyev, 2001; Namnabat *et al*., 2007). Since DC-DC converters are inherently nonlinear structures, its average models are designed. The small signal models of the DC-DC converters are linearized model and are used by classical control methods (Morroni *et al*., 2009). However nonlinear control methods like Sliding Mode Control, Fuzzy Logic Controllers are also discussed in the literature (Kheirmand *et al*., 2008). The Nonlinear models are robust when compared to the linear counterpart (Shirazi *et al*., 2009). However, when designing or choosing a control strategy the complexity of the controller has to be taken into account (Zurita-Bustamante *et al*., 2011). Moreover modeling of the converter for designing a particular control system (Kelly and Rinne, 2005) also plays an important role and these models have to be simpler to analyze. Even though many techniques have been available to the design of PID controller parameters in literature (Khodabakhshian, 2007; Mohammadi *et al*., 2009), finding the optimum value of parameters is a very challenging one. In this study an analog offline control loop is designed using three methods and their performance in terms of rising time, settling time and peak overshoot is compared.

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Nomenclature	
C	Capacitor
DC	Direct current
F	Farad
QAD	Quarter amplitude decay
IMC	Internal model control
kW	Kilo watt
mW Milli Watt	
L	Inductor
PID	Proportional integral derivative
R	Resistor
W	Watt

BUCK CONVERTER MODEL

The regulated or unregulated dc source is used as the input of the dc-dc converter. The purpose of the dc-dc converter is to give a constant dc voltage to the load irrespective of changes in line, load and temperature. Usually asynchronous buck converter is used where the output is high compared to diode reference voltage (Mariethoz *et al*., 2010).

The circuit model of Buck converter is shown in Fig. 1.

The working principle of Buck converter can be explained in two modes. In the first mode when the transistor is ON and the current passes through L, C and R. In the second mode, the transistor is OFF and the diode is ON in which the stored energy in the inductor is responsible for obtaining the continuous current flow. Before the inductor current reaches zero, the next cycle starts.

The dynamic and output equations of the circuit for ON period are as follows (Batarseh, 2004; Kazimierczuk, 2008):

$$v_{in} = r_L i_L + L\frac{di_L}{dt} + v_c \quad (1)$$

The Eq. 1 can be written as:

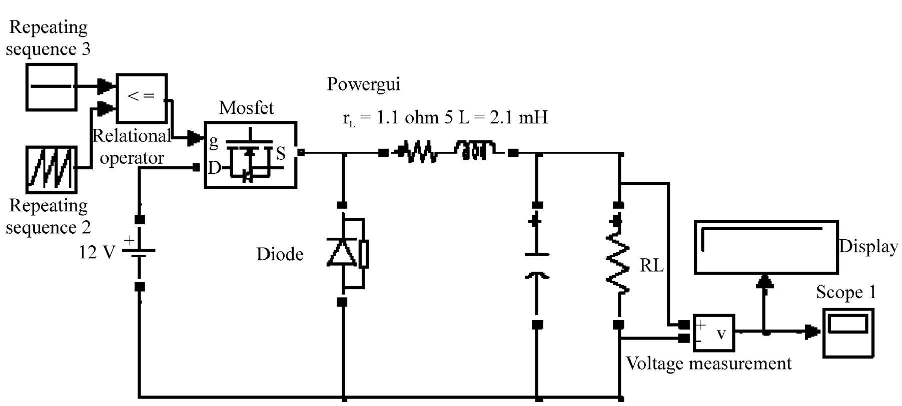

Fig. 1: Circuit diagram for buck converter

$$\frac{di_L}{dt} = -\frac{r_L}{L}i_L - \frac{v_c}{L} + \frac{v_{in}}{L} \quad (2)$$

The current equation is as follows:

$$i_L = C\frac{dv_C}{dt} + \frac{v_C}{R} \quad (3)$$

The Eq. 3 can be written as:

$$\frac{dv_C}{dt} = \frac{i_L}{C} - \frac{v_C}{RC} \quad (4)$$

Therefore:

$$V_{out} = VC \quad (5)$$

The dynamic output equation of the circuit for OFF period is as follows:

$$\frac{di_l}{dt} = \frac{r_L}{L}i_L - \frac{v_C}{L} \quad (6)$$

The current equation is given below:

$$\frac{dv_C}{dt} = \frac{i_L}{C} - \frac{v_C}{RC} \quad (7)$$

$$V_{out} = VC \quad (8)$$

It will be convenient to put these equations in the following form,

During ON time:

$$\overset{\circ}{x} = A_1 x + b_1 v_{in} \quad (9)$$

$$V_{out} = q_1 x \quad (10)$$

During OFF time:

$$\overset{\circ}{x} = A_2x + b_2v_{in} \tag{11}$$

$$V_{out} = q_2x \tag{12}$$

Where:

$$\overset{\circ}{x} = \begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_c}{dt} \end{bmatrix} \tag{13}$$

$$A_1 = A_2 = \begin{bmatrix} -\frac{r_L}{L} & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \tag{14}$$

$$b_1 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \tag{15}$$

$$b_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{16}$$

$$q_1 = q_2\ [0\ 1]x \tag{17}$$

Equation 10 and 12 are referred to as the output equations. Equation 11 and 13 are referred to as the dynamic equations or the state equations of the converter for each of the sub periods of the switching period.

The state space model of the asynchronous buck converter is given by Eq. 11-14, which is linear and time invariant. This is because the state and output matrices A1, A2, b1, b2 etc. are functions of time. Therefore it is necessary to linearize the system Eq. 5, 6. To find the transfer functions of the converter, the following equations are used:

$$A = A_1D + A_2\ (1\text{-}D) \tag{18}$$

$$b = b_1D + b_2\ (1\text{-}D) \tag{19}$$

$$q = q_1D + q_2\ (1\text{-}D) \tag{20}$$

$$f = [A_1 = A_2)\ X + (b_2\text{-}b_2)\ v_{in}] \tag{21}$$

$$X = \text{-}AG^1\ b\ v_{in} \tag{22}$$

From the above Eq. 18-19, transfer function of the converter is obtained:

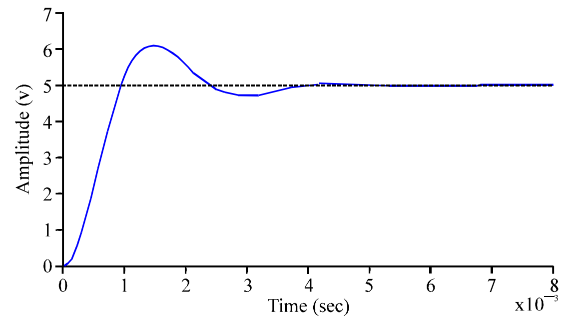

Fig. 2: Open loop response of the buck converter

Table 1: Buck converter parameters

Parameters	Symbol	Value
Voltage source (V)	V_{in}	12.0
Output voltage (V)	V_{out}	5.0
Filter capacitance (μF)	C	100.0
Converter inductance (mH)	L	2.1
Load resistance (Ω)	R	6.8
Inductor resistance (Ω)	r_L	1.1
Duty ratio	Δ	0.48

$$\frac{v_{out}(s)}{\delta\ (s)} = q(sI\text{-}A)^{-1}f \tag{23}$$

By substituting the values of q, A and f, the obtained transfer function of the Buck Converter is given below:

$$\frac{v_{out}(s)}{\delta\ (s)} = \frac{v_{in}}{LCs^2 + s\left[\frac{L}{R} + r_LC\right] + \left[1 + \frac{r_L}{R}\right]} \tag{24}$$

Table 1 shows the parameters of the Buck converter under consideration and the response in open loop is shown in Fig. 2.

CONTROLLERS FOR BUCK CONVERTER

PID controller is considered for the dc-dc converter with the objective of reducing the peak overshoot, rise time and settling time. The dc-dc converter is also given disturbance in form of varying load. PID controller performs Proportional, Integral and Derivative actions on the error signal. The parameters of the controller are obtained by applying various design techniques in such a way that the system will meet the desired transient and steady state performance. The closed loop Buck converter is shown in Fig. 3.

The design of PID controller is done by three methods.

Internal model control (IMC) PID tuning procedure: In this method, controller is designed by fixing the controller

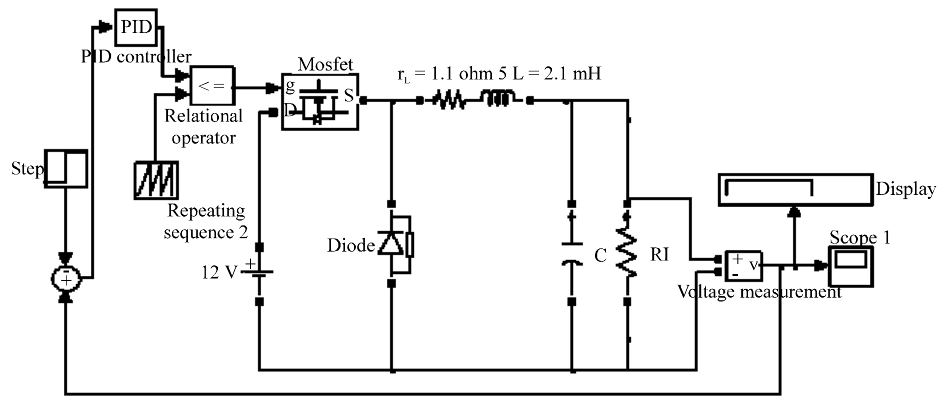

Fig. 3: SIMULINK realization of Buck converter with a PID controller

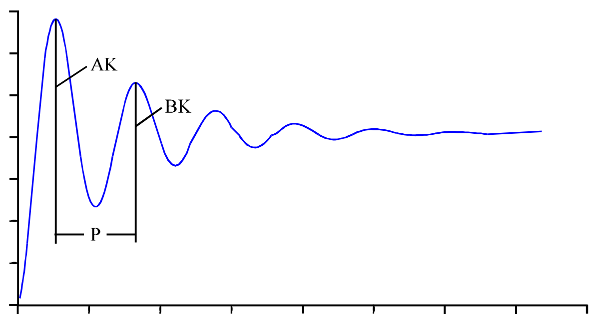

Fig. 4: Measurement step

transfer function to be the inverse of the converter transfer function. If complete knowledge about the process (as encapsulated in the process model) being controlled is known, then perfect control can be done. For the given converter transfer function, the control procedure is developed in MATLAB and the values obtained are K_p = 0.0968, K_i = 268.5679 and K_D = 4.8545e-5

Quarter amplitude decay (QAD) PID tuning procedure: In this procedure, proportional gain alone is used randomly to achieve a quarter amplitude decay response and the tuning rules are used to extract data from this response. The initial proportional gain Kp is selected such that the stable system is obtained. The response is observed for the step input.

Ratio $R_k = B_k/A_k$, is computed and if R_k = 0.25, then measure the period P between the first and second peaks in Fig. 4. and the values of K_i and K_d are calculated using Table 2.

Table 2: PID tuning for damped oscillation data

Controller structure	Performance criterion	Proportional gain (K_p)	Integral time constant, τ_i	Derivative time constant, τ_d
PID	¼ decay	K_p	P/1.5	P/6

If R_k<<0.25 then increase K_p and if R_k>>0.25 then decrease K_p and the procedure is repeated. The coding is developed in MATLAB and the values obtained are K_p = 0.75, K_i = 1.236e3 and K_d = 1.146e-4.

Pole placement: The closed loop response of Buck converter for pole-placement is obtained by means of MATLAB SISO tool with the help of Buck converter transfer function. The location of new poles is obtained by trial and error method. By using Pole placement method, the closed loop poles are obtained as -997.19±2130.3j.

The controller transfer function is given below:

$$G_c(s) = \frac{1.1446(s^2+1994s+5.532*10^6)}{s(s+1.121*10^4)} \quad (25)$$

PERFORMANCE COMPARISON

The performance comparison of the controllers designed for DC-DC converter are made in terms of peak overshoot, rise time, settling time and robustness to load/input variations.

Table 3 gives the details about the step response of PID controller tuned by various techniques for the DC-DC converter designed without any disturbances. The combined time response for all the controllers is shown in Fig. 5.

HARDWARE IMPLEMENTATION

By observing the above graphs, IMC based PID controller has rise time of 1ms and settling time of less than 2 m sec with no peak overshoot. So it is concluded as a best controller for implementation in hardware design. The PID controller whose values are obtained by IMC method is realized using operational amplifiers. The error signal is obtained after subtracting the output voltage from the reference voltage and is given to PID controller. The output of controller is a control voltage. The output pulses obtained by comparing the control voltage with the Saw tooth waveform of switching frequency 1 kHz are given to MOSFET through IRF 2110.The experimental setup is shown in Fig. 6.

Table 3: Response without any disturbances

Measuring factors	Quarter amplitude decay PID controller	Internal model control (IMC)	Pole-placement method
Rise time	0.17 (msec)	0.793 (msec)	0.612 (msec)
Amplitude	5V	5V	5V
Settling time	1.35(msec)	1.41(msec)	1.05 (msec)
Peak overshoot (%)	16.6	0	1.11e-3

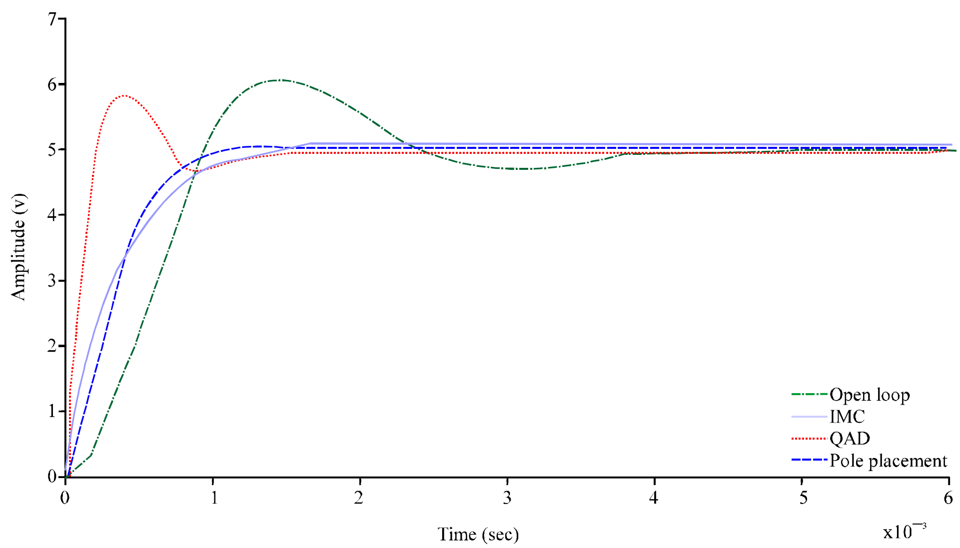

Fig. 5: Buck converter comparison graphs

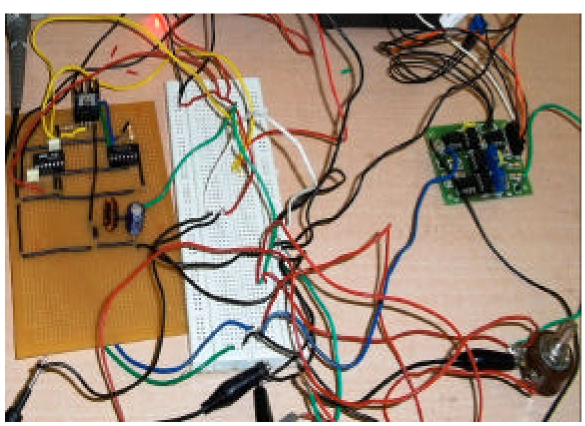

Fig. 6: Hardware implementation of a closed loop of buck converter

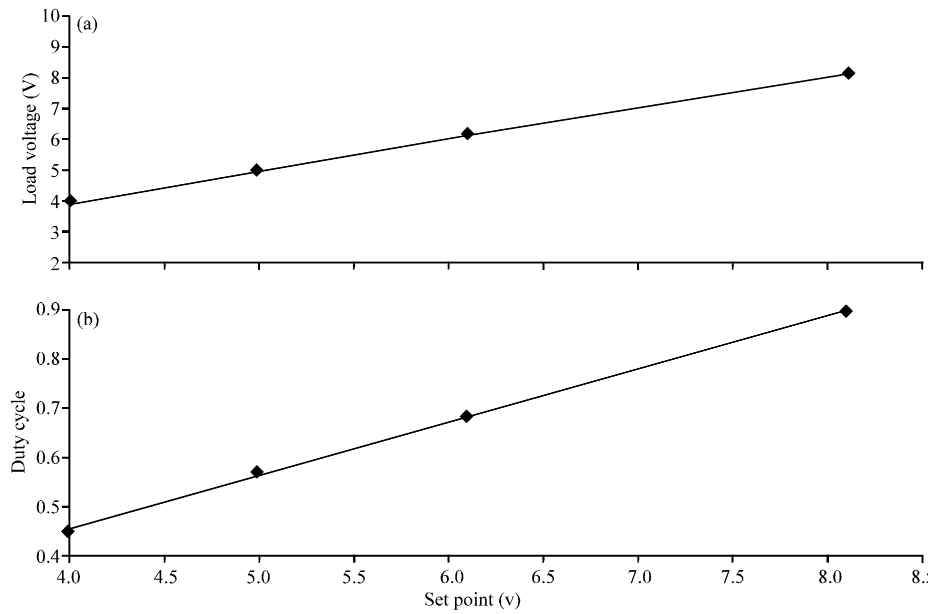

Fig. 7(a-b): Set point tracking vs (a) Load voltage and (b) Duty cycle

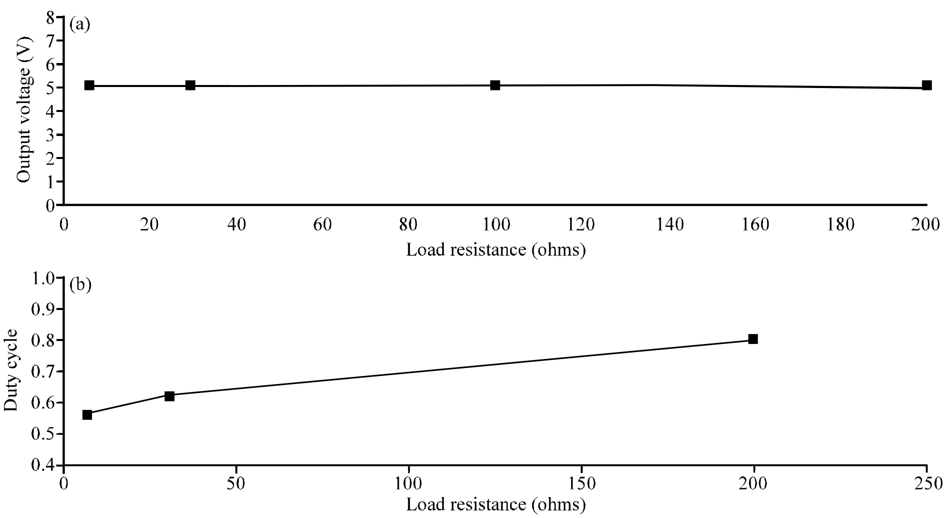

Fig. 8(a-b): Disturbance rejection-load variations, (a) Load resistance vs output voltage and (b) Duty cycle

Table 4: Set point tracking

Set point (V)	Load voltage (V)	Duty cycle
4.000	4.000	0.450
5.084	5.084	0.586
5.000	5.010	0.566
6.100	6.110	0.680
8.100	8.108	0.890

For constant load, the output voltage is taken for various reference values and the output voltage is observed for load variations by keeping reference value same. The results are tabulated in Table 4 and 5 and also expressed as tracking characteristic curves.

Table 5: Load resistance variation

Load resistance (ohms)	Load voltage (V)	Duty cycle
6.8	5.084	0.56
30	5.084	0.62
100	5.084	0.70
200	5.084	0.80

The Set point tracking characteristic curves were plotted for the set point disturbance method against set point, load voltage and duty cycle in Fig. 7. The Disturbance rejection-Load variation characteristic curves were plotted for the Load resistance, load voltage and duty cycle in the Fig. 8.

CONCLUSION

The controller design for a buck converter is found to be very complex and challenging. However there are various tools to design a PID controller for a buck converter. Here QAD, IMC and pole placement methods with suitable methodology have been tried and successfully completed. The controller designed by IMC method is fabricated using operational amplifiers. The set point tracking and disturbance rejection characteristic of the controller are evaluated and the results are tabulated and plotted. At steady state, for a constant resistive load connected to the output, it is observed experimentally that the desired output can be obtained by adjusting the set point input. Similarly for the given set point, if there is any change in the load, the steady state output is maintained constant by the controller designed. However, the transient response of the output voltage under this condition is to be verified which will be taken up for future work.

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