Comparative Analysis of Different Control Schemes for DC-DC Converter

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Abstract: ***DC-DC converters are some power electronic circuits that convert the DC voltage from one level to another. They have a very large area of applications ranging from computing to communication. They are widely used in appliance control transportations, and high-power transmission. Its increasing demand is based on its capability of electrical energy conversion. The basic topology of DC-DC converter are Buck converter and Boost converter, other topologies are derived from this two-basic topology. In this paper, mathematical modelling of both Buck and Boost converters has been done. Some of the control schemes are summarized in this paper. Current mode control (CMC), PID, control including their advantages and disadvantages are highlighted in this paper.***

Keywords: DC-DC converter, PID, IMC and Buck converter.

1. Introduction

The switch mode DC-DC converters are the simplest power electronic circuit that efficiently converts an unregulated DC voltage into a regulated DC voltage. Solid-state device such as transistors and diodes are used as switching power supplies. They operate as switch either in completely ON or completely OFF state. The energy storing elements such as inductor and capacitor are used for energy transfer and works as a low pass filter. The buck and boost converters are the two fundamental topologies of switch mode DC-DC converter. DC-DC converters have a wide area of applications. The drastic use of these converters in appliances control, telecommunication equipment's, DC-motor drives, automotive, aircrafts, etc. increases its interests in many fields.

The analysis along with the control of switching converters is the main factor to be considered. Various control schemes are used to control the switch mode DC-DC converter. There are many advantages and disadvantages related to every control methods. Preference is always given to the methods under which best performance is obtainable.

The most commonly used control technique is PWM voltage mode control, PWM current mode control, PID controller. The disadvantage of these controllers is that satisfied results are not achievable under large parameter or variation of load.

DC-DC converter usually operates in two modes of operation: continuous mode and discontinuous mode. In case of continuous mode, the current through the inductor never falls to zero whereas in case of discontinuous mode the current through the inductor falls to zero as the switch is turned off.

1.1 Advantages of Buck Converter

(i) Step down of voltage is possible with minimum component count.
(ii) Less costly compared to most of the other converters if compromised performance is desired for a low cost.

1.2 Disadvantages of Buck Converter

(i) Input current and charging current of the output capacitor is discontinuous resulting in larger filter size.
(ii) This converter is difficult to control. The transfer function of this converter contains a right half plane zero which introduces the control complexity.

1.3 Applications of Buck Converter

(i) **Battery Chargers:** In order to reduce the heat in the portable devices a buck converter is used.
(ii) **Solar chargers:** A solar charger is often a buck converter with a microcontroller control, converting a high voltage to low voltage efficiently

(iii) **Quadcopters:** Quadcopters often are powered from a multi cell lithium battery pack. These battery packs produce a voltage where buck converter drops the battery voltage down.

(iv) **POL converter for PC and Laptops:** a point-of-load converter is a non-isolated buck converter that is capable of efficiently driving power to high current load. This is especially helpful in PC and laptop motherboards.

The converter such as buck converters gives high power efficiency as DC-to-DC converter compare to linear regulators which are simpler circuits and lower voltages by dissipating power as heat, but do not step up output current. We have designed the mathematical model of both single input and dual input buck converter and have implemented with different control schemes for the converters and to compare the responses of different control schemes implemented in the converter.

2. Buck Converter

The buck converter is shown in figure 1. It is the step-down converter in which a fixed high voltage is step down to a desired low voltage level. It consists of non-dissipative switch, inductor, and capacitor. The switches will operate at the rate of PWM switching frequency. The ratio of ON time when the switch is closed to the entire switching period is known as the duty cycle and is represented as:

$$d = \frac{t_{ON}}{T}$$

and the output voltage is controlled by varying the duty cycle. During steady state, the ratio of output voltage over input voltage is d, which is given by:

$$d = \frac{V_{out}}{V_{in}}$$

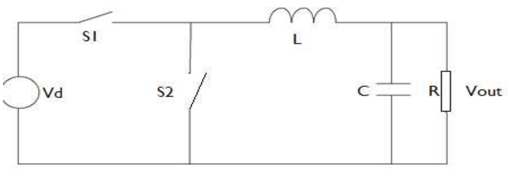

Figure 1: Basic Buck Converter

In the first sub circuit state when the switch S_1 is closed, the diode is reversed biased and the energy is transferred from the source to the inductor and the current through the inductor gradually increases during this time interval as shown in figure 2(a). In the next sub-circuit state when the switch S_2 is closed, the source is disconnected from the network. The diode will be forward biased and the current will flow through the freewheeling diode. During the second-time interval, the current through the circuit decreases linearly as the energy in the inductor discharges as shown in the figure 2(b).

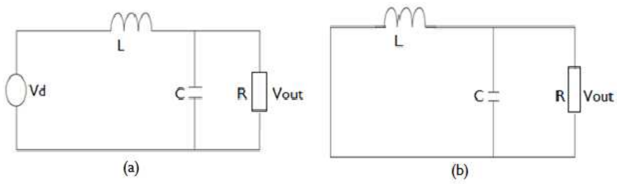

Figure 2: Buck Converter when (a)Switch is ON (b) Switch is OFF

3. PID Controller design for Buck Converters

To design a controller using the frequency response method, phase-lead, phase-lag or lead-lag compensation is usually used. A proportional-derivative (PD) controller is phase-lead compensation. The advantage of using PD controllers is that it leads to the increase of phase margin and improvement of cross-over frequency. The transfer function of a PD controller is:

$$G_C(s) = K_P + K_D(s)$$

A proportional-integral (PI) controller is a phase-lag controller. A PI controller is used to increase the low frequency loop gain, therefore reducing steady-state error. The transfer function of a PI controller is:

$$G_C(s) = K_p + \frac{K_I}{s} = \frac{K_p s + K_I}{s}$$

The PI controller has a pole at the origin. Both PD and PI controllers are first-order controllers.

By using a lead-lag compensator, the advantages of lead compensation and lag compensation can be combined to obtain sufficient phase margin, high loop gain and wide control bandwidth. A proportional-integral-derivative (PID) controller is a lead-lag compensator. It is the most widely used compensator in feedback control systems. The PID controller is defined as:

$$u(t) = K_P e(t) + K_I \int_0^{\tau} e(t)dt + K_D \frac{de(t)}{dt}$$

Where, e(t) is the compensator input and u(t) is the compensator output.

The Laplace transform of above equation yields the transfer function:

$$G_C(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s} + K_D(s)$$

The integral term is phase-lag and the derivative term is phase-lead. The low frequency gain is improved by the integral term, and the low-frequency components of the output voltage are accurately regulated. At high frequency, the phase margin and cross-over frequency are improved by the derivative term, which improves the system's stability and the speed of the transient response. An increase in the proportional term will increase the speed of system response; however, too much proportional gain will make the system unstable.

For operation during a startup transient and steady state, a PID and a PI controller were designed for the buck converter respectively. The derivative term in a PID controller is susceptible to noise and measurement error of the system, which could result in oscillation of the duty cycle during steady state. However, the derivative term is needed during a transient period to reduce the settling time by predicting the changes in error. Therefore, to obtain the desired response, the system switches between PID and PI controllers during transient and steady state period. The PID controller is applied during start up to obtain a fast-transient response. The PI controller is applied during steady state to reduce oscillation of the duty cycle and improve the system's stability.

4. Internal Model Control

In process control applications, model-based control systems are used to track set points and remove low disturbances. The internal model control (IMC) idea relies on the internal model principle which states that if any control system comprises within it, indirectly or openly, to easily achieve a perfect control, some representation of the process is to be controlled. In particular, if the control scheme has been developed based on the exact model of the process then perfect control is theoretically possible.

4.1 Internal Model Control Strategy

If we assume there exists model of the plant with transfer function modeled as $\tilde{g}_p(s)$ such that $\tilde{g}_p(s)$ is an exact representation of the process (plant), i.e. $\tilde{g}_p(s) = g_p(s)$ then set point tracking can be achieved by designing a controller such that:

$$g_c(s) = \tilde{g}_p(s)^{-1}$$

This control performance characteristic is achieved without feedback and highlights two important characteristic features of this control modeling. These features are:

- Feedback control can be theoretically achieved if complete characteristic features of the process are known or easily identifiable.
- Feedback control is only necessary of knowledge about the process is inaccurate or incomplete.

This control performance as already said has been achieved without feedback and assumed that the process model represents the process exactly i.e. process model has all features of parent model. In real life applications, however, process models have capabilities of mismatch with the parent process; hence feedback control schemes are designed to counteract the effects of this mismatching. A control scheme that has gained popularity in process control has been formulated and known as the Internal Model Control (IMC) scheme. This design is a simple build up from the ideas implemented in the open loop model strategy and has general structure as depicted by figure below.

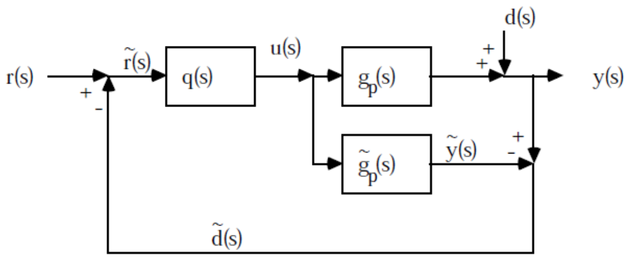

Figure 3: Block Diagram of IMC.

From the above figure, description of blocks is given as follows:

Controller = $g_c(s)$
Process = $g_p(s)$
Internal model = $g_p(s)$
Disturbance = d(s)

4.2 Equivalent Feedback To IMC

The feedback equivalence to IMC by using block diagram manipulation begins with the IMC structure shown in Figure 4.

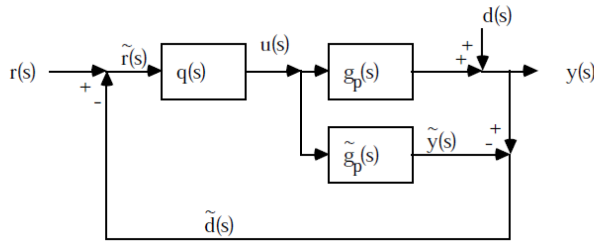

Figure 4: IMC Structure

Figure 4 can be rearranged to the form of Figure 5.

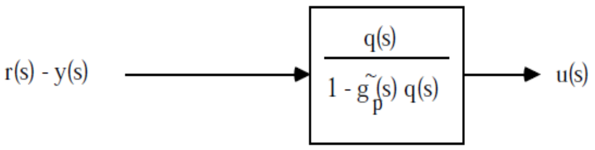

Figure 5: Equivalent Block

The r(s)-y(s) is simply the error term used by a standard feedback controller. Therefore, we have found that the IMC structure can be rearranged to the feedback control (FBC) structure. This reformulation is advantageous because we will find that a PID controller often results when the IMC design procedure is used. Also, the standard IMC block diagram cannot be used for unstable systems, so this feedback form must be used for those cases.

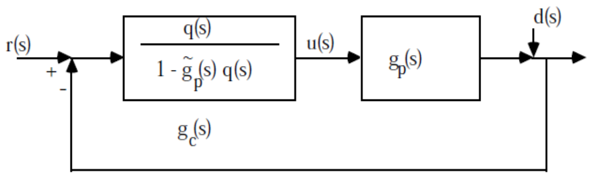

Figure 6: Standard Feedback Diagram Illustrating the Equivalence with IMC.

Where, the feedback controller, $g_c(s)$, contains both the internal model: $\tilde{g}_P(s)$ and $q(s)$.

The standard feedback controller which is equivalent to IMC is:

$$g_c(s) = \frac{q(s)}{1 - g_p(s).q(s)}$$

4.3 Internal Model Control Based PID Controller

The IMC configuration is designed for setting up a comparison between the process and model output to form a standard feedback structure. Figure 5 shows the basic IMC implementation in the process transfer function.

The transfer function for our Buck converter is:

$$\tilde{g}_p(s) = \frac{k_p(\beta s + 1)}{\tau^2 s^2 + 2\varepsilon\tau s + 1}$$

$$\tilde{g}_p(s) = \tilde{g}_{p+}(s)\,\tilde{g}_{p-}(s)$$

$$\tilde{g}_{p+}(s) = \frac{k_p(\beta s + 1)}{\tau^2 s^2 + 2\varepsilon\tau s + 1}$$

$$q(s) = \tilde{g}_{p+}(s)^{-1} f(s) = \frac{\tau^2 s^2 + 2\varepsilon\tau s + 1}{k_p(\beta s + 1)}$$

$$g_c(s) = \frac{q(s)}{1 - q(s)\,\tilde{g}_p(s)}$$

$$g_c(s) = \frac{\tau^2 s^2 + 2\varepsilon\tau s + 1}{\lambda s(\beta s + 1)}$$

The transfer function for the PID controller is:

$$g_c(s) = k_c\left[\frac{\tau_i\tau_d s^2 + \tau_i s + 1}{\tau_i s}\right]$$

Then the PID parameters based on IMC will be derived as shown in Table 1.

Table 1: IMC based PID parameters for Buck Converter

$\tilde{g}_p(s)$	$f(s)$	k_c	τ_i	τ_d
$\frac{k_p(\beta s+1)}{\tau^2 s^2 + 2\varepsilon\tau s + 1}$	$\frac{1}{(\lambda s+1)}$	$\frac{2\varepsilon\tau}{k_p(\beta s+1)}$	$2\varepsilon\tau$	$\frac{\tau}{2\varepsilon}$

5. Results

In this work, more emphasis is given for improving the dynamic response of the DC-DC buck converter by identifying proper controller parameter. The following dynamic parameters are considered in this work: i) Rise Time ii) Settling Time iii) Peak Overshoot.

In order to examine the effectiveness of the proposed algorithm, extensive simulation and experimental studies have been carried out on the closed loop system of Buck converter.

5.1 Response Based on IMC based PID controller

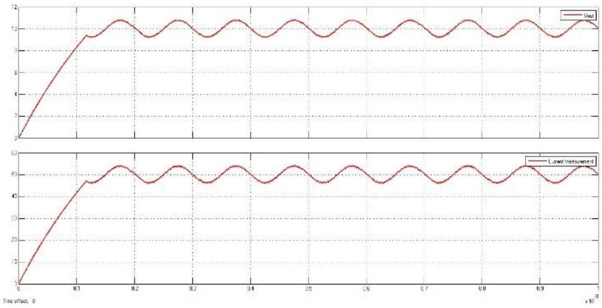

Figure 7: Response of Buck Converter based on IMC-PID Control

Table 2: Transient Response of the Buck Converter based on two control schemes

Sl. No.	Transient Parameters	IMC-PID Control
1	Settling Time	1.63 X 10^{-3} sec
2	Peak Time	665 sec
3	Rise Time	101.19 sec
4	Overshoot	7.56 volt

6. Conclusion

The design of controller for the buck converter is perceived as an optimization task and the controller constants are estimated through different control algorithms. Initially the designs of PID controller parameters for the buck converter were designed based on Internal Model Control (IMC)) and later the results are compared with Genetic Algorithm (GA). By observing the rise time, settling time, peak overshoot from the response curves which are obtained by using the controller parameters of two different control schemes it can be concluded that GA based parameter gives good and robust response compared to IMC.

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