

Gain Scheduling Implementation in DC/DC Buck Converter using PID Controller

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Abstract-The objective of this paper is to design a Gain scheduling PID control scheme for the DC/DC buck converter to improve the transient performance in different load current conditions. Poor control of the DC/DC buck converter lead to high overshoot and steady state error. And its dynamic response varies with changes in load, especially at high load current conditions. So a Gain scheduling PID control scheme is introduced to overcome this. The proposed control scheme is designed with pole zero cancellation method to adaptively auto tune parameters of the discrete PID controller for efficiently improving the output transient response.

Index Terms- adaptive control, gain scheduling control, Proportional-Integral-Derivative (PID) control, pole zero cancellation, dc/dc converter

I.INTRODUCTION

For many years, analog controllers have dominated the control of power electronics systems such as converters, inverters, etc. But the digital controls have continued to improve in cost and usability in the past several years. This has made digital controls more appealing to replace analog control in power electronic systems. So, the digital controllers are widely used in dc/dc converter such as Voltage Regulator (VR), Point of Load (POL) because of their low power consumption and easily to implement in complex control architecture. The advantages of digital controllers are programmability, improved flexibility, and improved system reliability due to usage of lower part count, less sensitive to noise. And changing a controller does not require alteration in the hardware, they provide improved sensitivity to parameter variations and potentially faster design process [1].

Conventional PID controllers are commonly used in industry because of their simplicity, clear functionality and ease of implementation [2]-[4]. Recent research trends in the PID control area are summarized in [5]. The process for designing PID controllers for industrial automation is elaborated and can be difficult in practice, if multiple and conflicting objectives are to be achieved. The PID gains for non-linear plants are very difficult to select on the analytical basis of closed loop stability and performance [6] [7]. Owing to their complexity and the need of exact plant models, many studies on PID control tend to be difficult for practising engineers to fully understand and to competently apply practical systems. The difficulty is compounded applying the findings of research many practical devices, here tuning PID gains is the only thing users are allowed to do.

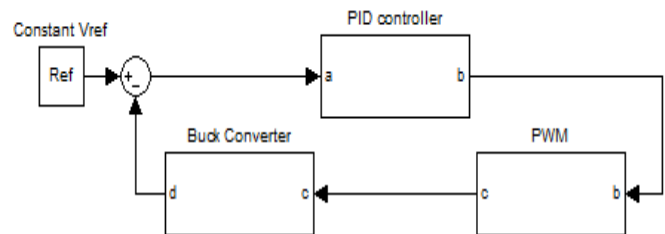


Fig.1 Block diagram of PID controlled buck converter

This paper addresses the issue of improving transient performance of DC/DC buck converters using digital controllers. A Gain scheduling control scheme is proposed to achieve an improved transient response.

The Gain scheduling control is a practical and useful adaptive control method [8]. It is a nonlinear feedback of special type; it has a linear controller whose parameters are changed as a function of operating condition in a pre-programmed way. Gain scheduling controller requires some knowledge about the plant and some auxiliary measured variables. When scheduling variables has been determined, the controller parameters are calculated at a number of operating conditions by using pole zero cancellation method. The controller is thus tuned or calibrated for each operating condition. The stability and performance of the system are evaluated by simulation; particular attention is given to the transition between different operating conditions. The great advantage of this method is that the controller adapts quickly to changing conditions. The design method can be easily extended to different technologies or modification to fulfil a new set of specifications such as fewer output capacitors or small board size requirement with very fast time to market.

The structure of this paper is as follows. The detail modeling of the synchronous buck converter is explained in the section II. In section III, we have presented the digital control of buck converter. The Gain scheduling control scheme is introduced in section IV. Simulation results of the Gain scheduling scheme have been presented in section V. Finally the concluding remarks are given in section VI.

II. BUCK CONVERTER MODELLING

As seen in Figure.1, Buck converter is a DC to DC converter which converts a variable DC input into a fixed DC output. To keep the output of the Buck converter at a fixed value, the gating pulse of the MOSFET S is controlled. The duty cycle of switch S is defined by

$$D = \frac{V_o}{V_{in}} \tag{1}$$

The value of D varies between 0 and 1. The governing state space equations for the buck conversion system are given by

$$\frac{dI_L}{dt} = \frac{1}{L}(V_{IN}d - I_L R_L - V_{out}) \tag{2}$$

$$\frac{dV_c}{dt} = \frac{1}{C_{out}}(I_L - I_o) \tag{3}$$

$$V_{out} = V_c + R_{esr} (I_L - I_o) \tag{4}$$

Here V_{out} is the output voltage, V_c is the voltage across the capacitor, I_L is the current through the inductor, I_o is the output current and V_{IN} is the input voltage of the converter. From the figure, duty to output voltage transfer function and duty to inductor current transfer function are given by

$$G_{vd}(s) = \frac{V_{out}(s)}{d(s)} = \frac{V_{IN}(1+sR_{esr}C_{out})}{1+s[R_{esr}C_{out} + (\frac{R_L R_{out}}{R_{out}+R_L})C_{out} + \frac{L}{R_{out}+R_L}] + s^2[LC_{out}(\frac{R_{out}+R_{esr}}{R_{out}+R_L})]} \tag{5}$$

$$G_{id}(s) = \frac{I_L(s)}{d(s)} = \frac{V_{IN}(1+sC_{out}(R_{out}+R_{esr}))}{1+s[R_{esr}C_{out} + (\frac{R_L R_{out}}{R_{out}+R_L})C_{out} + \frac{L}{R_{out}+R_L}] + s^2[LC_{out}(\frac{R_{out}+R_{esr}}{R_{out}+R_L})]} \tag{6}$$

Where $G_{vd}(s)$ is the duty to output voltage transfer function in the s domain, $G_{id}(s)$ is the duty to inductor current transfer function in the s domain, R_L is the inductor series resistance of an output inductor and R_{esr} is the equivalent series resistance of an output capacitor.

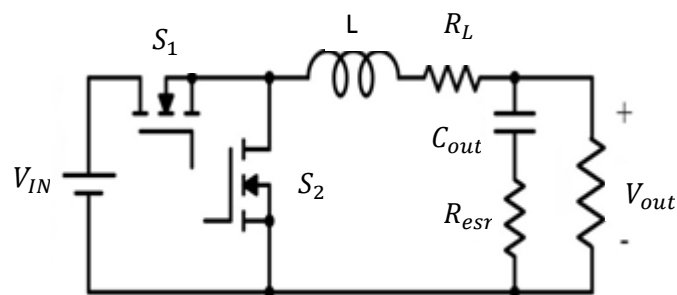


Fig.2 Schematic of a Synchronous buck converter

III. DIGITAL CONTROL OF BUCK CONVERTER

For digital control of DC/DC buck converters, there are three main functional blocks: Analogue to Digital converter (ADC), Digital Pulse Width Modulation (DPWM) and digital controller. The characteristics of ADC, DPWM and digital controller are given below

DPWM: Digital PWM is used for generating driver signals from control signals. It consist of a sufficient resolution digital counter with digital comparator and the trailing edge modulation technique for generating saw tooth ramps. The gain function is given by

$$G_{DPWM}(s) = K_{DPWM} e^{-s(DT_s + T_{DPWM})} \tag{7}$$

Where D is the duty cycle under steady state, T_s is the sampling time, T_{DPWM} is the Digital PWM delay time and K_{DPWM} is the gain of Digital PWM.

ADC: Analogue to Digital converter (ADC) is used for sampling and converting analogue variables to digital variables. In a digital controller, the delay in the control loop will degrade the performance of the system. The ADC conversion time and computation time are considered as the total delay. The modulator delay is the relationship between the switching and the sampling periods. The transfer function of the ADC is expressed as

$$G_{ADC}(s) = K_{ADC} e^{sT_{ADC}} \tag{8}$$

Where K_{ADC} and T_{ADC} are the gain and conversion time of ADC respectively.

Digital Controller: A digital controller is for generating control signals which are computed by the control law. Here a proportional integral Derivative (PID) controller is used as the digital controller for the DC/DC buck converter. The PID controller consists of proportional, integral and derivative components and it is widely used in feedback control of power converters. The s domain transfer function of the PID controller has the form

$$G(s) = K_p + \frac{K_i}{s} + K_d s \tag{9}$$

Where K_p , K_i and K_d are the proportional, integral and derivative gains of the PID controller. The equivalent form of the PID controller is

$$G(s) = K_p (1 + \frac{1}{T_i s} + T_d s) \tag{10}$$

Where $T_i = \frac{K_p}{K_i}$ and $T_d = \frac{K_d}{K_p}$ and T_i and T_d are known as the integral and derivative time constants. The discrete PID controller can be expressed as

$$u(k) = K_p e(k) + K_i T_s \sum_{i=1}^n e(i) + \frac{K_d}{T_s} \Delta e(k) \tag{11}$$

where $u(k)$ is the control signal or input to the plant, $e(k)$ is the error between the reference and output of the plant, T_s is the sampling period for the controller and $\Delta e(k) = e(k) - e(k - 1)$. An optimal PID controller with fixed gains provides satisfactory control under a specific operating condition. But it does not perform well under a wide range of operating conditions. So a controller with an auto tuning gain that can adapt to the prevailing condition is more in demand. The proposed Gain scheduling PID control scheme realises the auto tuning gain function to improve the transient response of DC/DC converters under different operating condition.

IV. PROPOSED CONTROL SCHEME FOR BUCK CONVERTER

A. Principle of Gain Scheduling

Gain scheduling scheme is an approach to the control of non-linear systems that uses a family of linear controllers, each of the linear controller provides satisfactory control for a different operating point of the system. One or more observable variables (scheduling variables) are used to determine what operating region the system is currently in and to enable the appropriate linear controller. Gain scheduling scheme based on measurements such as load current information for buck converters is often a good way to compensate for variations in process parameters.

A general block diagram of again scheduling control scheme is shown in fig.3. When the scheduling variables have been determined, parameters of controllers are optimally designed and stored in a schedule under different operating conditions by using pole zero cancellation method. The digital PID controller is thus online tuned or calibrated for each operating condition. Gain scheduling scheme has the advantage that the controller parameters can be changed quickly in response to process changes such as load current variations in DC/DC buck converters.

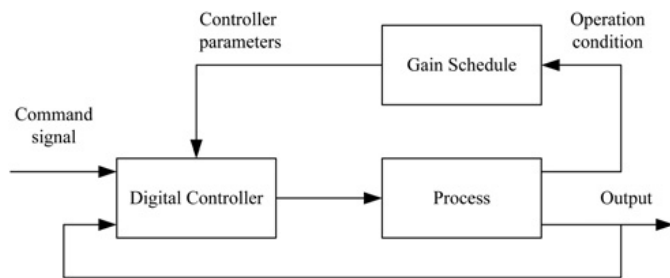


Fig.3 Block diagram of general gain scheduling control scheme

B. Pole zero cancellation method

Here, the change in load current condition is taken as the operating conditions for the controller design. Then these load currents are divided into several intervals. For each interval, gain schedule of the controller is designed according to the pole zero cancellation method. From the duty to output voltage transfer function, it is clear that there is a complex conjugate pair of poles. So, a pair of complex zeros is introduced to completely cancel out the poles. The inductance, L and inductor series resistance, R_L are considered as the scheduling variables of the controller. That is, the

component's tolerance such as L, R_L are considered in the gain schedule for flexible operation under load current condition. The pole-zero cancellation will be based on the tolerance of the component with load current changed to obtain the series gain scheduling parameters. Therefore an optimal PID controller with changed gains provides satisfactory control under load current changed with component's tolerance. The transfer function of the compensator is given by

$$G_c(s) = \frac{1}{sG_{vd}(s)} \tag{12}$$

$$G_c(s) = \frac{1 + s \left[R_{esr}C_{out} + \left(\frac{R_L R_{out}}{R_{out} + R_L} \right) C_{out} + \frac{L}{R_{out} + R_L} \right] + s^2 [LC_{out} \left(\frac{R_{out} + R_{esr}}{R_{out} + R_L} \right)]}{sV_{in}(1 + sR_{esr}C_{out})} \tag{13}$$

Consider the s-domain control blocks for digital buck DC/DC converters in Fig.4.

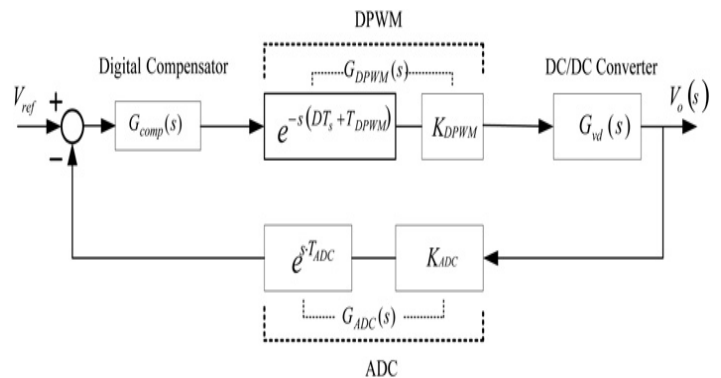


Fig.4 S-domain control blocks of the digital buck DC/DC converters

The transfer function $G_c(s)$ of the digital compensator can be expressed in the z-domain by bilinear approximation in the following form

$$G_c(z) = \frac{1 + \left(\frac{2}{T_s} \right) \left(\frac{z-1}{z+1} \right) \left[R_{esr}C_{out} + \left(\frac{R_L R_{out}}{R_{out} + R_L} \right) C_{out} + \frac{L}{R_{out} + R_L} \right] + \left(\frac{2}{T_s} \right) \left(\frac{z-1}{z+1} \right)^2 [LC_{out} \left(\frac{R_{out} + R_{esr}}{R_{out} + R_L} \right)]}{V_{in} \left(\frac{2}{T_s} \right) \left(\frac{z-1}{z+1} \right) + \left(\frac{2}{T_s} \right) \left(\frac{z-1}{z+1} \right)^2 V_{in} R_{esr} C_{out}} \tag{14}$$

The term $R_{out} + R_{esr}/R_{out} + R_L$ can be approximated to '1' as shown in

$$\frac{R_{out} + R_{esr}}{R_{out} + R_L} \cong 1 \tag{15}$$

Let

$$R_{esr}C_{out} + \left(\frac{R_L R_{out}}{R_{out} + R_L} \right) C_{out} + \frac{L}{R_{out} + R_L} = R_{sum} \tag{16}$$

By substituting (15) and (16) into (14), then the digital controller can be derived as follows

$$G_c(z) = \frac{\left(\left(\frac{T_s^2}{LC_{out}} \right) + \left(\frac{2R_{sum}T_s}{LC_{out}} \right) + 4 \right) z^2 + \left(\left(\frac{2}{LC_{out}} \right) - 8 \right) z + \left(\left(\frac{T_s^2}{LC_{out}} \right) - \left(\frac{2R_{sum}T_s}{LC_{out}} \right) + 4 \right)}{K \frac{V_{in} \left(\frac{2}{T_s} \right) \left(\frac{z-1}{z+1} \right) \left(\frac{T_s}{LC_{out}} \right) [z^2(T_s + 2R_{esr}C_{out}) + 2T_s z + T_s - 2C_{out}R_{esr}]}{}} \tag{17}$$

Equation (17) can be expressed in the form of the difference equation as follows

$$d(n) = \frac{8C_{out}R_{esr}}{2T_s+4C_{out}R_{esr}} d(n-1) - \frac{4C_{out}R_{esr}-2T_s}{4C_{out}R_{esr}+2T_s} d(n-2) + \frac{K(T_s^2+2R_{sum}T_s+4C_{out}L)}{2T_sV_{in}+4C_{out}R_{esr}V_{in}} e(n) + \frac{K(2T_s^2-8C_{out}L)}{2T_sV_{in}+4C_{out}R_{esr}V_{in}} e(n-1) + \frac{K(T_s^2-2R_{sum}T_s+4C_{out}L)}{2T_sV_{in}+4C_{out}R_{esr}V_{in}} e(n-2) \quad (18)$$

The proposed digital controller can be represented by rewriting (18) in the following difference equation form

$$d(n) = K_1d(n-1) + K_2d(n-2) + K_p e(n) + K_i e(n-1) + K_d e(n-2) \quad (19)$$

where

$$K_1 = \frac{8C_{out}R_{esr}}{2T_s+4C_{out}R_{esr}} \quad (20)$$

$$K_2 = -\frac{4C_{out}R_{esr}-2T_s}{4C_{out}R_{esr}+2T_s} \quad (21)$$

$$K_p = \frac{K(T_s^2+2R_{sum}T_s+4C_{out}L)}{2T_sV_{in}+4C_{out}R_{esr}V_{in}} \quad (22)$$

$$K_i = \frac{K(2T_s^2-8C_{out}L)}{2T_sV_{in}+4C_{out}R_{esr}V_{in}} \quad (23)$$

$$K_d = \frac{K(T_s^2-2R_{sum}T_s+4C_{out}L)}{2T_sV_{in}+4C_{out}R_{esr}V_{in}} \quad (24)$$

where $d(n)$ and $e(n)$ are duty ratio and the error signal at the present time and $d(n-1)$, $d(n-2)$, $e(n-1)$ and $e(n-2)$ are the previous two consecutive values of duty ratio and the error signal. Parameters K_1, K_2, K_p, K_i and K_d for each operating conditions are computed using (20)–(24). These parameters are stored in gain schedule to tune the controller under different load current operating conditions. Additionally, the output inductor corresponds to its inductance and series resistance under different load conditions are also implemented in this control scheme for optimisation in the controller. When a transient occurs, the gain scheduling control scheme will determine the interval which the load current belongs to and retrieve the corresponding parameters of the controller from the schedule to optimise the transient performance.

Table 1. Specification of buck converter

Symbol	Parameter
Switching frequency, f_s	300KHz
Input voltage, V_{IN}	12V
Output voltage, V_{out}	2V
Output current, I_o	30A
Output inductor, L	1.5 μH
Output capacitor, C_{out}	400 μF
Inductor series resistance, R_L	4.5m Ω
Equivalent series resistor, R_{esr}	2.5m Ω

Table 2. Gain scheduling table with load condition

I_{out} (A)	K_p	K_i	K_d
5	153.915	-305.080	151.465
10	152.025	-300.807	149.083
15	150.202	-296.686	146.785
20	148.443	-292.709	144.567
25	146.744	-288.868	142.425
30	145.102	-285.157	140.355

V. SIMULATION RESULTS

Simulation verification is performed in a 12 to 1.2 V single phase synchronous buck converter with 300 KHz switching frequency and 30 A load current. The simulated parameters values are expressed in Table 1. The simulation model was built in SIMULINK. Table 2 is the constructed gain schedule using the procedure described in Section IV. The operating condition (load current) is divided into 6. 5 A, 10 A, 15 A, 20 A, 25A and 30A

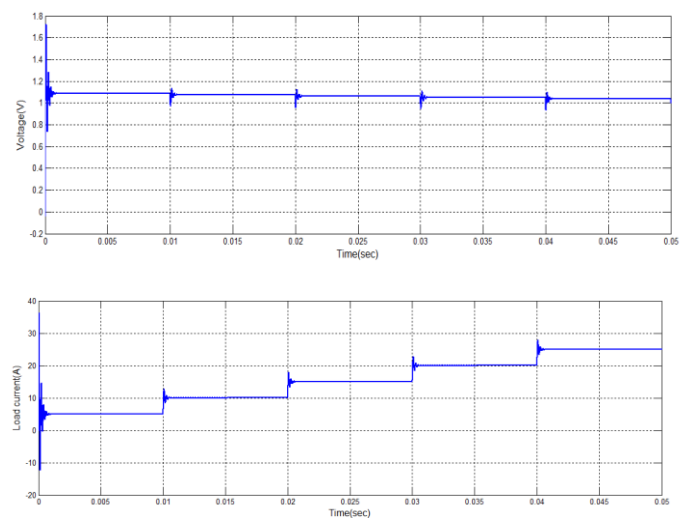


Fig.5 Transient performance of buck converter with different load current

In order to verify the proposed Gain scheduling scheme, simulation test are conducted for different loads. Compared to the paper [9] the proposed Gain scheduling control can improve the over shoot as 80 mV from 112 mV even if the load current is 30A. But the steady state error increases as compared to [9]. If the Fuzzy Gain Scheduling PID controller is introduced the steady state error, over shoot, etc may be improved.

VI. CONCLUSIONS

In this paper, a Gain scheduling control scheme was presented that based on PID controller with pole-zero cancellation method to optimize the transient response under different load conditions. The proposed control scheme is tested under several load current conditions. The transient performance improves as compared to the method in [9].

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