Implementation of Digital PID Controllers for DC-DC Converters using Digital Signal Processors

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Abstract— **Implementation of digital PID controllers for DC-DC converters is discussed in this paper. The primary advantages of digital control over analog control are higher immunity to environmental changes such as temperature and aging of components, increased flexibility by changing the software, more advanced control techniques and reduced number of components. Analog PID and PI controllers were first designed using frequency response techniques, then converted into digital controllers. Digital PID and PI controllers are then implemented using Digital Signal Processors (DSPs). Two possible choices of DSPs are introduced. The first one is the TMS320F2812 DSP from Texas Instrument, and the second one is the Si8250 Digital Power Controller from Silicon Laboratories. Main features and development tools for both DSPs are introduced. Digital PID and PI controllers were implemented on the TI TMS320F2812 DSP. Experimental results for a prototype buck converter are presented.**

I. INTRODUCTION

Switch mode DC-DC converters efficiently convert an unregulated DC input voltage into a regulated DC output voltage [1]. Compared to linear power supplies, switching power supplies provide much more efficiency and power density. Switching power supplies employ solid-state devices such as transistors and diodes to operate as a switch: either completely on or completely off. Energy storage elements, including capacitors and inductors, are used for energy transfer and work as a low-pass filter. Buck converters and the boost converters are the two fundamental topologies of switch mode DC-DC converters. Most of the other topologies are either buck-derived or boost-derived converters, because their topologies are equivalent to the buck or the boost converters.

Traditionally, the control methodology for DC-DC converters has been analog control. Analog-based control systems have two main advantages: low cost and a wide control bandwidth. But sophisticated control algorithms can require considerable amount of complex circuit hardware. In the recent years, technology advances in very-large-scale integration (VLSI) have made digital control of DC-DC converters with microcontrollers and digital signal processors (DSP) possible. Digital control of DC-DC converters offers several advantages over analog control [2]. First, more advanced control algorithms such as adaptive control and nonlinear control can be implemented using digital control. Second, implementation of digital control is more flexible by

changing the software. Third, digital control can be used to achieve power efficiency optimization. In a DC-DC converter, it is desirable to maintain high efficiency over a wide range of loads. Digital control algorithms can optimize efficiency by shifting between continuous and discontinuous conduction mode with changes of load and disabling synchronous rectification at small load. Fourth, digital control is able to integrate power management functions such as thermal management into one digital control chip, thus eliminating external components. Fifth, digital control of DC-DC converters has higher immunity to environmental changes such as temperature and aging of components.

Digital control for DC-DC converters can be implemented using digital signal processors (DSPs), microcontrollers and digital integrated circuits (IC). Generally, DSPs have more computational power than microcontrollers. Therefore, more advanced control algorithms can be implemented on a DSP. On the other hand, microcontrollers tend to be less expensive than DSPs, therefore providing digital control solutions at lower cost. This paper will be focused on implementation of digital controllers using DSPs.

II. DESIGN OF A LINEAR PID AND PI CONTROLLERS FOR A BUCK CONVERTER

In DC-DC converters, the output voltage is a function of the input line voltage, the duty cycle and the load current. It is desirable to have a constant output voltage in the event of disturbances such as a sudden change of input voltage or load current. Negative feedback control is applied to DC-DC converters to automatically adjust the duty cycle to obtain the desired output voltage with high accuracy in spite of disturbance [3]. In this section, frequency response techniques are used to design digital controller for a buck converter.

A. Design of Analog PID and PI controllers

The circuit diagram of a buck converter is shown in Fig. 1. The input voltage of the prototype buck converter is 20 V, and the output voltage Vo is 12 V. The load resistance R is 10 Ω, L is 150 μH and C is 1000 μF. The parasitic elements, R_C and R_L, are estimated to be 30 mΩ and 10 mΩ, respectively.
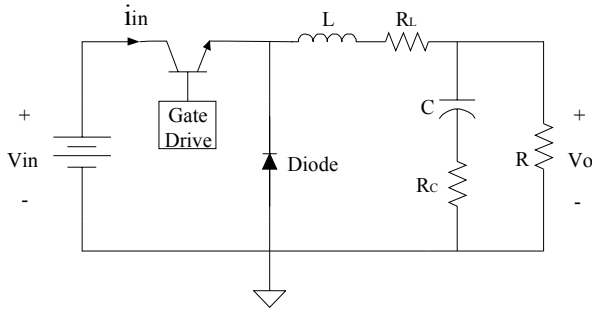
Fig. 1 Buck converter

The output-to-control small signal transfer function of a buck converter is shown in (1). It is obtained using standard state-space averaging techniques [1].

$$\frac{\hat{v}_o(s)}{\hat{d}(s)} = \left(\frac{V_o}{D}\right) \left[\frac{1 + sR_cC}{1 + s\left(R_cC + [R//R_L]C + \frac{L}{R+R_L}\right) + s^2LC\left(\frac{R+R_c}{R+R_L}\right)} \right] \quad (1)$$

In the transfer functions, $\hat{v}_o(s)$ and $\hat{d}(s)$ are the small variations of the output voltage and duty cycle, respectively. D is the duty cycle of the PWM signal. It is a common two-pole low pass filter, with a left half plane zero introduced by the ESR of the filter capacitance. The cutoff frequency of the low pass filter is $\omega_c = \frac{1}{\sqrt{LC}}$. The magnitude falls with a slope of –40dB/decade at the cutoff frequency. The phase associated with it is a –180 degree phase delay. The zero is at $-\frac{1}{R_cC}$. There is a 20 dB/decade magnitude rise at that frequency and the phase shift is 90 degrees.

The control-to-output transfer function at the nominal operating point is given by (2). The model has complex conjugate poles at $-615.9 \pm j2481.5$, which causes a 180 degrees phase delay at the approximate frequency of 2500 radians/s. The model also has a zero at 33,333 radians/s.

$$\frac{\hat{v}_o(s)}{\hat{d}(s)} = \frac{6 \times 10^{-4} s + 20}{1.503 \times 10^{-7} s^2 + 5.4975 \times 10^{-5} s + 1} \quad (2)$$

A PID controller was designed for the buck converter to improve the loop gain, cross-over frequency and phase margin. One zero was placed an octave below the cutoff frequency (approximately 260 radians/s) and the other one at 4600 radians/s. The transfer function of the PID controller is given by (3):

$$G_c(s) = 0.5786 + \frac{142.4}{s} + 0.000119s \quad (3)$$

The Bode plot for the compensated system is shown in Figure 2. As can be seen in this plot, the gain at low frequency is high, the phase margin is 107 degrees and the bandwidth is 19100 radians/s.
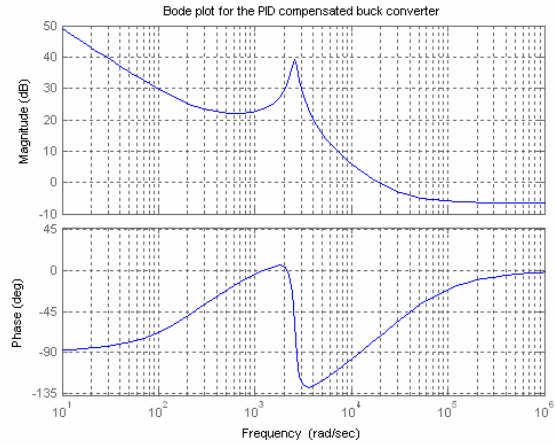

Fig. 2 Bode plot of PID controller compensated buck converter

A PI controller was also designed for the control of the buck converter at steady state to reduce steady-state oscillation. One pole was placed at the origin, and one zero was placed at 800 radians/s. The DC gain of the controller was adjusted to obtain sufficient phase margin and high cross-over frequency. The transfer function of the PI controller is given by (4):

$$G_c(s) = 0.75 + \frac{600}{s} \quad (4)$$

The Bode plot for the PI compensated system is shown in Figure 3. The Bode plot shows that the phase margin is 15.4 degrees and the bandwidth is 10600 radians/s.
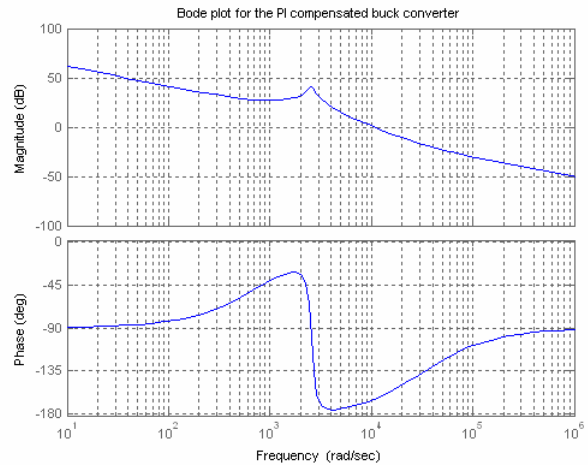

Fig. 3 Bode plot of PI controller compensated buck converter

B. Transformation from Analog Controllers into Digital Controllers

An analog PID controller's transfer function is shown in (5), and is implemented using (6), where K_P, K_I and K_D are determined when the controller is designed.

$$G_C(s) = K_P + \frac{K_I}{s} + K_D s \quad (5)$$

$$G_C(t) = K_P e(t) + K_I \int e(t)dt + \frac{K_D de(t)}{dt} \quad (6)$$

.

A digital PID controller also satisfies (6), except the multiplication, integration and differentiation are performed numerically in a digital computer [4]. If the numerical calculations are performed accurately, the system response using digital control will be very similar to the system response using analog control.

Several methods can be used to obtain the discrete-time equivalent of an analog PID controller. These methods are backward difference method, forward difference methods, bilinear transformation method, impulse-invariance method, step-invariance method and matched pole-zero method [5]. The backward difference method is one of the simplest methods to obtain numerical integration of a signal. It will produce a stable discrete-time filter for a stable continuous-time filter. Using the backward difference method, the transfer function of a numerical integrator is shown in (7).

$$M(z) = \frac{Tz}{z-1} E(z) \qquad (7)$$

The transfer function of a numerical differentiator is the reciprocal of the transfer function of the numerical integrator shown in (7). Therefore, by substituting (7) and its reciprocal into the PID controller's s-domain transfer function in (5), the digital PID controller's transfer function is shown in (8).

$$G_C(z) = K_P + \frac{K_I Tz}{z-1} + \frac{K_D(z-1)}{Tz} \qquad (8)$$

A digital PI controller's transfer function is shown in (9) by eliminating the derivative term in (8).

$$G_C(z) = K_P + \frac{K_I Tz}{z-1} \qquad (9)$$

The difference equation to calculate a new duty cycle for the digital PID controller is written in (10).

$$u[k] = K_P e[k] + K_I T \sum_{i=0}^{k} e[i] + \frac{K_D}{T} \{e[k] - e[k-1]\} \qquad (10)$$

In the difference equation, $u[k]$ is the controller output for the k_{th} sample, and $e[k]$ is the error of the k_{th} sample. The error $e[k]$ is calculated as $e[k] = \text{Ref-ADC}[k]$, where $ADC[k]$ is the converted digital value of the k_{th} sample of the output voltage, and Ref is the digital value corresponding to the desired output voltage. $\sum_{i=0}^{k} e[i]$ is the sum of the errors and $\{e[k]-e[k-1]\}$ is the difference between the error of the k_{th} sample and the error of the $(k-1)_{th}$ sample. It is noted that when K_D is equal to zero, the PID algorithm changes into a PI algorithm.

III. IMPLEMENTATION OF DIGITAL PID AND PI CONTROLLERS

This paper will mainly concentrate on implementation of digital PID and PI controllers using Digital Signal Processors (DSP). The first DSP discussed is a TMS320F2812 DSP from Texas Instrument. The second DSP discussed is a Si825x Digital Power Controller from Silicon Laboratories.

A. TMS320F2812 Digital Signal Processor

The TMS320 family of digital signal processors (DSP), produced by Texas Instruments, is composed of fixed point, floating point and multiprocessor DSPs. The TMS320 family

has three DSP platforms: the TMS320C6000™ DSP, the TMS320C5000™ DSP, and the TMS320C2000™ DSP. The TMS320C2000™ DSP platform is optimized for control applications. The TMS320F2812 DSP belongs to the TMS320C28x generation, which is the newest member of the TMS320C2000™ DSP platform. By integrating the DSP core and on-chip peripherals, the TMS320C28x DSP generation offers a high-performance solution to digital control. It targets a wide variety of digital control applications including industrial control, motor control and automobile control applications.

The TMS320F2812 is a 32-bit fixed point DSP controller with on-board flash memory [6]. The CPU operates at 150 MHz. The C28x DSP generation is efficient in executing C and C++ programs, hence enabling control algorithms to be developed in high level languages. The CPU features 16×16 and 32×32 MAC operations, 16×16 dual MAC, Harvard bus architecture, atomic operations, fast interrupt response processing, unified memory programming model and up to 4M linear program/data address reach. The on-chip memory includes up to 128K flash memory, up to 128K ROM devices, and a combined 18K SARAM devices. Development tools include ANSI C/C++ compiler/assembler/linker and Code Composer Studio (CCS) IDE. The TMS320C2000 Code Composer Studio is a Windows-based integrated development environment (IDE). The CCS IDE includes software tools for project managing and editing, code generation, debugging, code optimization, real time kernel and analysis.

The F2812 supports peripherals used for embedded control and communication, such as an event manager module for pulse-width-modulation (PWM) and a dual 12-bit, 16-channel analog-to-digital converter (ADC). Serial port peripherals include serial peripheral interface (SPI), two serial communication interfaces (SCIs), enhanced controller area network (Ecan) and multichannel buffered serial port (McBSP). The peripheral interrupt expansion (PIE) block supports 45 peripheral interrupts [7].

. The TMS320F2812 DSP controller comes in a 176 pin package. The pins can be categorized according to functions: address and data bus, interface control signals, ADC inputs, bit I/O and shared functions bits, serial communication interface, compare signals, interrupts signals, clock signals and test signals.

The overall program structure is shown in Figure 4. Once the program starts to run, the first task is to initialize the DSP. Macros such as clearing bit, setting bit and setting a certain amount of delay time are defined. The interrupt vector addresses map the subroutines corresponding to each level of interrupts. The global variables are declared and given initial values. The event manager module is initialized to define the sampling and switching frequency, which is determined by the period of the general purpose timers. Then certain bits are set to start the PWM. The analog to digital conversion is set to be in the continuous conversion mode.

After the configuration of the DSP is complete, the main algorithm starts to run. Each time when the value of the general purpose timer is equal to the timer's period value, an interrupt is requested and directed to the corresponding interrupt subroutine. The sampling period is equal to the period of the general purpose timer.

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The interrupt subroutine is executed every sampling period. The subroutine acquires a sample once every sampling period, utilizes a digital controller algorithm to calculate a new duty cycle, and updates the new duty cycle at the start of the next switching period. Different digital control algorithms, including PID and PI controllers and fuzzy logic controllers can be implemented as interrupt subroutines.

The flowchart for the digital PID and PI controller is shown in Figure 5. At the start of each sampling period, there was a 2μs delay before taking the analog to digital conversion. Because the sampling and PWM switching frequency were the same and their periods were synchronous, the start of the sampling and switching periods happened at the same time. The switching action of the MOSFET in the DC-DC converter produces a glitch in the converter output voltage which can be measured by the A/D converter. Measurement of this glitch will produce oscillation in the duty cycle calculated by the digital PID controller. The sample was taken after the start of the switching period instead to avoid sampling the switching glitches.

When both the absolute value of the error of the k_{th} sample $e[k]$ was less than ε, and the absolute value of the difference between the error of the k_{th} sample and the error of the $(k-1)_{th}$ sample $de[k]$ was less than φ, the converter was considered to be operating in steady state. The values ε and φ can be determined based on experimental results of the converters. The PI controller was applied in steady state to reduce oscillation of the duty cycle. The gain of the integrator K_D was assigned to be zero, and the proportional and integral gains K_P and K_I were assigned according to the design of the PI controller. The result of the PID controller was a sum of the proportional, derivative and integral controllers.

The duty cycle of the PWM signal in the digital control system for the buck converter was limited between 10% and 90%. This prevents the MOSFET from being turned on or off for a full switching period. After updating the new duty cycle, and the error of the $(k-1)_{th}$ sample, the interrupt subroutine returned to the main program and waited for a request for the next interrupt.

The difference equation in (10) is a linear combination of feedback and control signals. A series of scalar multiplications and addition instructions can be used to implement the linear PID and PI controllers on the TMS320F2812 DSP. The TI TMS320F2812 DSP is optimized for implementation of digital filters. It has several instructions to multiply a number by a constant and add the previous product in a single instruction. Therefore, the implementation of linear PID and PI controllers in real time is quite straightforward.
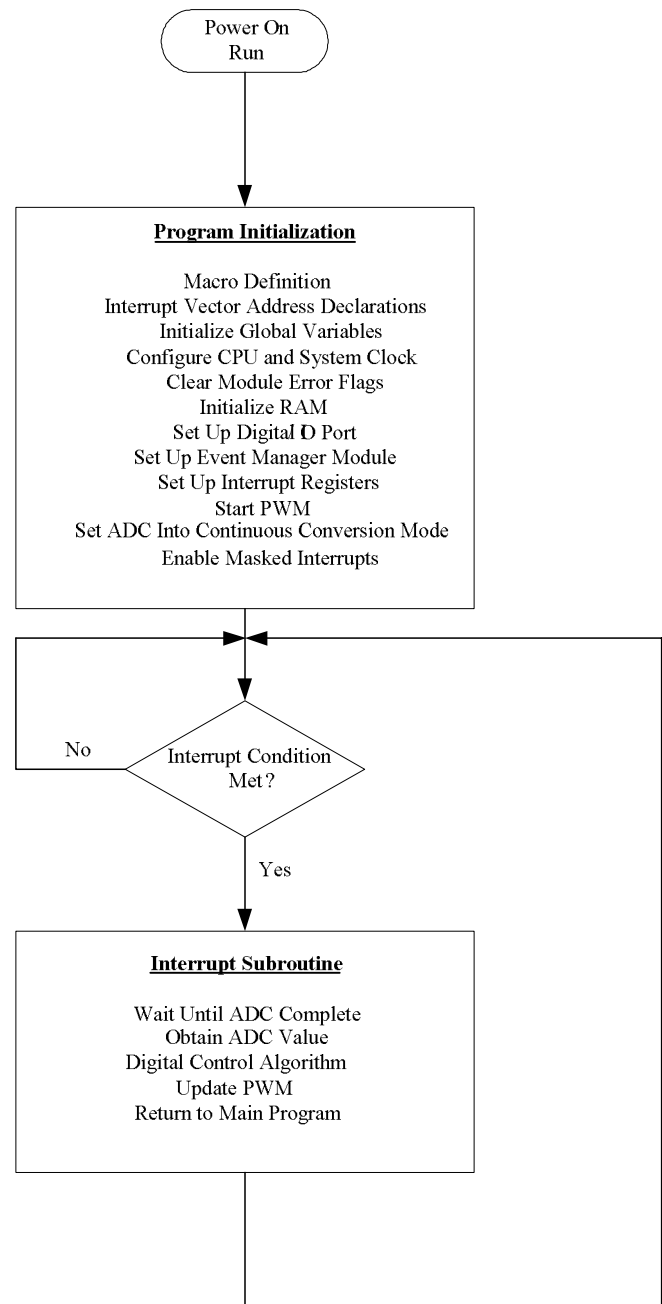

Fig. 4 Overview of the program structure for digital controllers on a TMS320F2812 DSP

Because of the strong computation power of the TMS320F2812 DSP, more advanced control algorithms such as fuzzy logic control and adaptive control can be implemented on the DSP [8].

B. Si8250 Digital Power Controller

The Si825x family of programmable digital power controllers from Silicon Laboratories provides closed-loop feedback control, system protection and power management functions for switch mode power supplies. The Si825x architecture combines a dedicated DSP-based control loop processor with a microcontroller-based programmable system management processor. This architecture guarantees the
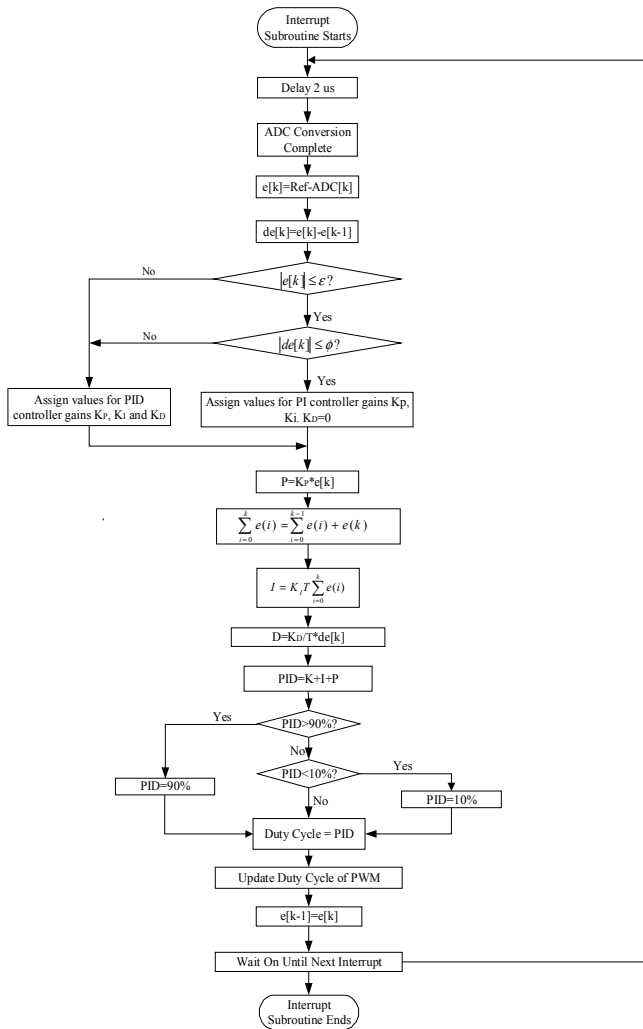
Fig. 5 Flowchart for the digital PID and PI controller

Fig. 6 Compensator Editor

control loop is updated at 10 MHz, regardless of firmware size and complexity. Firmware can change control parameters on the fly including loop gain, compensation and timing. This enables the system to quickly and intelligently adapt to changing operating conditions, such as loading and unloading transients. The Si825x family is supported by a development kit, which includes a complete real-time firmware kernel with design tools. The Si825x family of digital power controllers is packaged in a 5 x 5 mm 28-pin QFN package or 32-pin LQFP. The Si8250 digital power controller is mainly targeted in digital control of DC-DC converter, AC-DC converters, power factor correction circuits (PFC) and motor control [9].

The DSP-based control loop processor includes a first stage PID filter and a second stage low-pass filter. The PID controller coefficients can be designed using the Compensator Editor shown in Figure 6. In the Compensator Editor, both the power stage and the compensators can be designed, and frequency response can be viewed. The compensator editor will automatically convert the analog controller into digital controller and provide the compensator's coefficients. The second stage can be chosen as either a two-pole low pass filter or a SINC decimation filter. The second stage filter is used to reduce noise at higher frequencies [10].
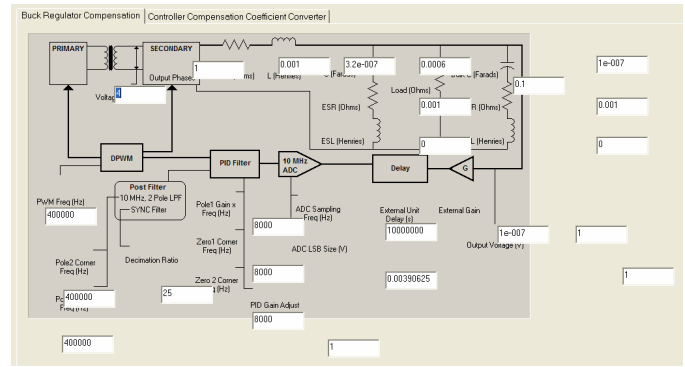
The Si8250 digital power controllers include a six-channel DPWM. Fixed or dynamically-adjustable dead times are supported. Cycle-by-cycle current limiting and overcurrent protection are provided by the peak current limit comparator. When the inductor current exceeds the comparator threshold setting, current limit comparator is asserted. An overcurrent protection accumulator asserts an OCP interrupt when the number of consecutive current limit cycle interrupts reaches a programmed maximum number.

The system management processor is based on the CIP-51 microcontroller core. The CIP-51 uses a pipelined architecture that increases its instruction throughput over the standard 8051 architecture. The system management processor operates at 50 MIPS and features 16 or 32 kB of Flash memory, a self-sequencing, 8-channel 12-bit ADC and a programmable general-purpose comparator. The ADC digitizes key analog parameters to provide protection, management and control of the system. On-board digital peripherals include four 16-bit timers, a PMBus hardware interface, and a universal asynchronous receiver/transmitter (UART) for serial communicating across an isolation boundary.

The system management processor mainly performs the following functions: continuously optimize DSP control processor operation such as efficiency optimization, executes user-specific algorithms, provides regulation for low-bandwidth system variables including input voltage feed forward control, performs system fault detection and recovery, provide system housekeeping functions such as PMBus communication support and manages external device functions such as external supply sequencing and fan control [10].

IV. EXPERIMENTAL RESULTS

The PID and PI controllers were both implemented on the TI TMS320F2812 DSP. The sampling and switching frequencies of the digital PID and PI controllers are both 150 kHz. The start up transient response is shown in Figure 7. The settling time is about 1ms. The load transient response is shown in Figure 8 when the load current changes from 1.364A to 0.16A. The settling time is about 2ms, and the maximum transient error is 120mV.
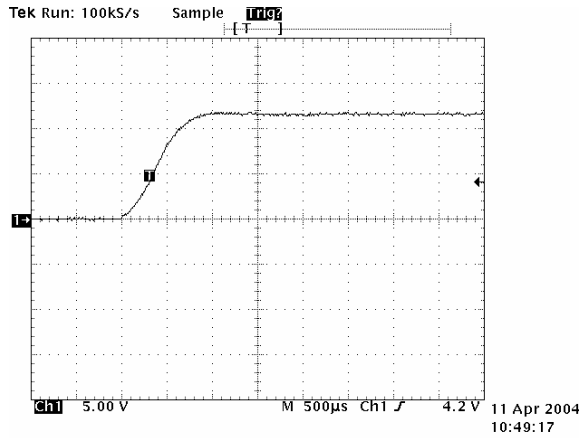
Fig. 7 Start up transient response of the buck converter using the digital PID and PI controller (5V/div, 500μs/div)
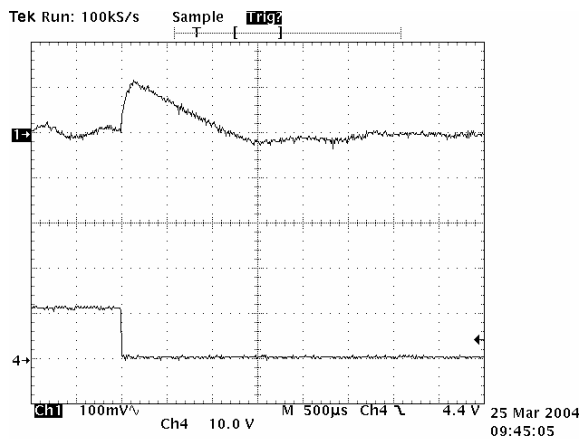

Fig. 8 Transient response for the buck converter using the digital PID and PI controller when the load changes from 1.364A to 0.16A (100mV/div, 500μs/div)

V. CONCLUSION

DC-DC converters convert unregulated DC input voltage into regulated DC output voltage. Digital control of DC-DC converters has several advantages over analog control. The advantages include higher immunity to environmental changes, increased flexibility by changing the software, more advanced control techniques, integration of power management functions and reduced number of components.

Analog PID and PI controllers were designed using frequency response techniques for a buck converter, and then converted into digital controllers. Digital controllers were then implemented using Digital Signal Processors (DSPs). Two possible choices of DSPs were discussed. The first one is a TMS320F2812 DSP from Texas Instrument, and the second one is a Si8250 Digital Power Controller from Silicon Laboratories. Digital PID and PI controllers were implemented on the TMS320F2812 DSP for a prototype buck converter and experimental results were presented. Experimental results indicate that the digital PID and PI controllers were able to achieve fast transient response without

overshoot and good rejection to load disturbances in steady state.

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