

Digital Control of Switching Power Converters

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Abstract –The paper reviews the latest advance of the digital control technologies in DC-DC converters. The research on digital control is mainly focused on two areas. One is the methods to generate digital PWM (DPWM) signals to meet the output voltage accuracy requirement. Various dithering techniques have been developed to improve the output voltage resolution and at the same time to reduce the clock frequency requirement. The other is to develop new control methods that can utilize the advantages of the digital controller so as to improve the dynamic performance of the switching power converters. Several new digital control methods have been proposed and significant dynamic performance improvement has been achieved.

I. INTRODUCTION

DC-DC switching power supplies are used extensively in all areas of our work and daily life. For example, switching power supply is used in communication power systems, in our computers, and in our cell phones. The fundamental objective of the power supply is to maintain the output voltage stable when its input voltage and/or its load current changes.

Feedback control is used to achieve this objective. Analog circuit is used almost exclusively in today's DC-DC switching power supplies because of its simplicity.

In order to improve the performance and speed of the digital integrated circuit, such as CPU, FPGA (Field Programmable Gate Array), and other ASIC (Application Specific IC), the supply voltage to these circuits reduces continuously. Five to ten years ago, the voltage is 5V and 3.3V. Recently, the supply voltage is reduced to around 1V. It is expected in future, the supply voltage will become below 0.5V. What makes the situation even worse is that modern CPU requires more current. It requires more than 100A and very fast load current change.

The combination of lower output voltage and higher output current poses a significant challenge to power supply design. The lower the output voltage, the smaller the voltage margin becomes, and therefore it is more difficult to maintain the output voltage with the regulation range. High load current increases the voltage drop between the output pins of the switching power supply and the CPU. Fast load current change makes it even more difficult to meet the voltage regulation.

Analog circuits have been dominating in the control of switching power supplies because of its simplicity and low implementation cost. Unfortunately, it is can not meet the more and more stringent requirement of today's and future digital ICs. Alternatives have to be used.

Digital control method emerges as a better solution than the analog one as the cost of digital circuits has been reduced significantly in recent years. A lot of research has been performed in the areas of digital control of switching power supplies and significant progress has been achieved. The research work for digital control is mainly focused in two areas. One is how to generate Digital Pulse Width Modulation (DPWM) signal. The other is to develop new digital control strategies that can take advantages of digital circuit to improve the dynamic performance of switching power supplies.

This paper reviews the recent advances in the digital control of switching power converters in these two areas. Section II of the paper summarizes the advantages of digital control. Section III of the paper reviews technologies to generate DPWM signals. Section IV and V review the new digital control algorithms that can significantly improve the dynamic performance of switching power supplies. Some experimental results are provided to demonstrate the performance improvement. Section VI is the conclusion.

II. ADVANTAGES OF DIGITAL CONTROL

Although analog control is almost exclusively used in today's switching power supply, it can not meet requirement for the power requirement of today's digital circuit. It has several disadvantages, such as large part count, low flexibility, low reliability and sensitive to the environmental influence such as thermal, aging and tolerance.

In addition, power converters are very complicated due to the nonlinear and time varying nature of switches, variation of parameters, fluctuations of input voltage and load current. Sometimes, it is difficult to get the accurate model of power converter system. In analog implementation, power converters are usually designed using linear models. Therefore, it is difficult to design the control algorithms with high performance by using the analog control method.

Digital control of switching power supply becomes more and more attractive. Compared with analog circuit, digital control system offers a numbers of advantages,

(1) Programmability

In digital control, all the control algorithms are realized by software. Therefore, the digital control system has high programmability. Different control algorithms can be easily implemented into the same hardware control system. When the design requirement is changed, it is very easy and fast for digital controllers to change the corresponding software. The development time and cost will be greatly reduced.

(2) High Flexibility

Communication, protection, prevention and monitoring circuits could be easily built in the digital control system. Important operation data can be saved in the memory of digital control systems for diagnose. In addition, digital control system eases the ability to connect multiple controllers and power stages. The system integration becomes easier.

(3) Fewer components

In digital control system, fewer components are used compared with the analog circuit. Therefore, the digital control system is less susceptible to the environmental variations. Hence, digital control system has better reliability than analog circuits.

(4) Advanced control algorithms

Most importantly, it is much easier to implement the advanced control techniques into digital control system. Advanced control algorithms can greatly improve the dynamic performance of power converter system. These advanced control methods can be implemented easily using digital circuit, but not analog circuit. As a result, the system dynamic performance could be significantly improved.

The above mentioned advantages make the digital control a viable option to meet the requirement for latest CPU and other digital circuit application.

III. DIGITAL PWM SIGNAL GENERATION

As compared with analog circuit, one major drawback of digital control is resolution of the PWM signal. A lot of work has been done to solve this problem.

(1) Requirement of PWM signal resolution

Due to the nature of digital signal, the duty cycle generated by the Digital Pulse Width Modulator (DPWM) can only provide discrete number. Therefore, the output voltage is also a discrete value. For example, for Buck converter and for a given required resolution in the output voltage, ΔV_o , the number of bits required for the analog to digital converter (ADC), N_{ADC} , is given

$$N_{ADC} = \log_2 \left(\frac{1}{\Delta D} \right) = \log_2 \left(\frac{V_{IN}}{\Delta V_o} \right) \quad (1)$$

In order to avoid a phenomenon known as limit cycle oscillation [1], the number of bits required for the Digital PWM generator, DPWM, is at least one greater than the ADC, so N_{DPWM} is given by

$$N_{DPWM} = N_{ADC} + 1 \quad (2)$$

When the power converter is in limit cycle oscillation, output voltage oscillates at frequencies lower than the switching frequency [1]. The amplitude and frequency of limit cycle ring is hard to predict and compensate. This would affect the operation of its load. Therefore, it is very important to achieve high resolution of PWM generation in digital control of DC-to-DC converters.

Theoretically, as long as the clock frequency of digital circuit is high enough as compared with the switching frequency, the limit cycle oscillation can be avoided. Unfortunately, the required clock frequency will be too high to be implemented efficiently. For example, for a Buck

converter with 12V input and 1V output, and with switching frequency of 1MHz, in order to achieve 0.25% accuracy, 11-bit ADC is needed and 12-bit DPWM is needed. Therefore, a clock frequency of 4GHz will be needed. This is too high.

Extensive research has been done to achieve high enough resolution of output voltage with reasonable clock frequency. Some of these methods are (1) fast clock counter comparator, (2) dither method, (3) tapped delay line and (4) ring oscillator.

(2) Fast clock counter comparator

One simple method to achieve high resolution of DPWM generation is using a fast-clocked counter-comparator scheme [3]. Fig. 1 shows the structure of counter-comparator scheme.

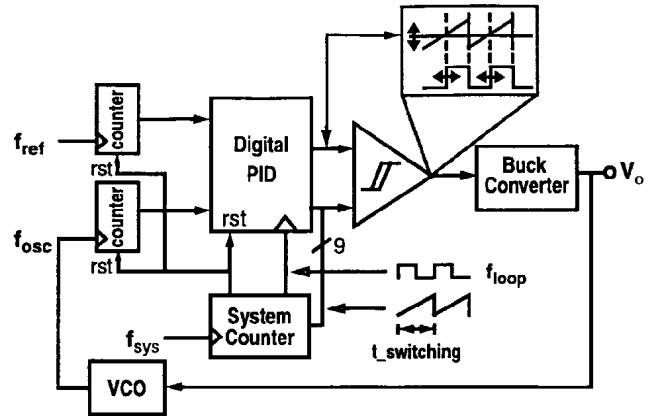


Fig. 1 Digital fixed frequency counter-comparator scheme

In this scheme, the reference voltage and feedback output voltage are converted to equivalent pulse signals separately. In every sampling period, digital PID controller samples these two pulse signals and given out the calculated duty cycle value. A system counter is used to generate the fixed sampling period and saw-tooth switching waveform. By comparing the saw-tooth waveform and the numerical duty cycle value, the switch of the converter is turned on/off. This scheme is very simple and easy to implement.

However, in this circuit, a very high frequency clock frequency and other related fast logic circuits are needed to achieve sufficient DPWM resolution at high switching frequency. Therefore, the power consumption is very high. In addition, in multiphase application, this circuit can not be easily shared among phases, so independent counter-comparator pair is needed for each phase. This increases the die area and power consumption even further [4].

(3) Dithering method

In order to increase the resolution of DPWM, several dither methods are proposed to increase the effective resolution of DPWM generation without increasing the clock frequency [1] - [5]. By using dither methods, the LSB bit of the duty cycle is alternating between 0 and 1 in a specific pattern during the steady state operation. As a result, the effective resolution of DPWM is increased, shown in Fig. 2.

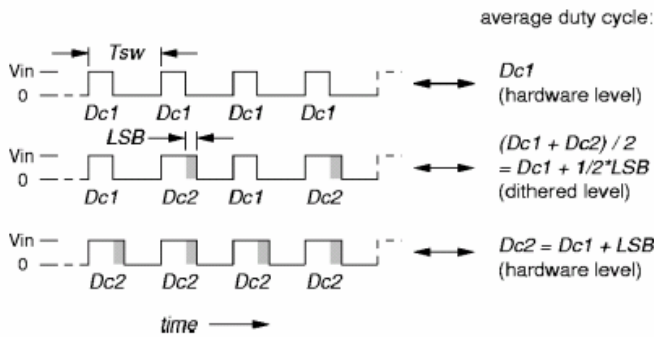


Fig. 2 Illustration of 1 bit dither method

Fig. 3 shows a dither generation scheme based on a look-up table [1]. In the proposed look-up table, 2^M dither sequences are stored for the M LSBs of the duty cycle value. Each sequence is M bit long. By selecting the dither sequence corresponding to the appropriate M LSB's value, M bit counter sweeps through this dither sequence. By using this dither pattern, the effective DPWM resolution is increased by M bits.

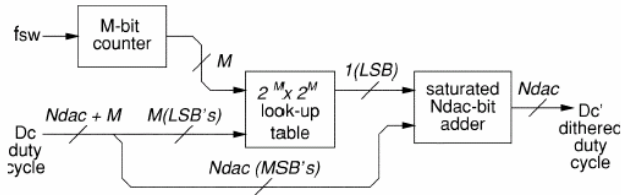


Fig. 3 Arbitrary dither patterns to the duty cycle

In reference [5], another simple dither method is presented to increase the resolution of DPWM generation, as shown in Fig. 4.

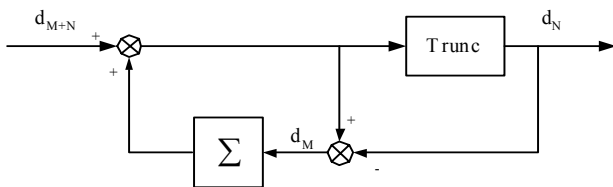


Fig. 4 The block diagram of accumulating dither method

The input of the dither module is an M+N bit duty cycle signal d_{M+N} . The M LSBs of d_{M+N} are truncated by the dither method to get the N bit output duty cycle signal d_N for DPWM. The residual error d_M is accumulated and then added back to the input of dither circuit. By using this dither method, the resolution of DPWM generation is increased by M bits, too.

These two dither methods have advantages such as simple and easy to implement, and high DPWM resolution can be achieved in high switching frequency without increasing the clock frequency and power consumption. However, by using dither methods, sub-harmonic may occurs, with frequency lower than the switching frequency. This may cause EMI problem during the operation.

(4) Tapped delay line

Recently, tapped delay line techniques are used to achieve high resolution DPWM [6]. The essential components of the tapped delay line DPWM circuit are the delay line and multiplexer, shown in Fig. 5.

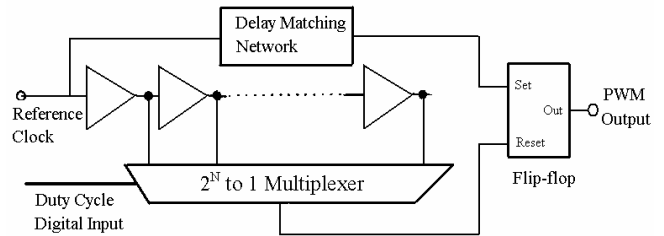


Fig. 5 Structure of DPWM circuit using tapped delay line

A pulse from a reference clock starts a cycle and sets the DPWM output to go high. The reference pulse propagates through the delay line, and when it reaches the output selected by the multiplexer, the DPWM output goes low. The total delay of the delay line is adjusted to match the reference clock period.

The power loss is significant reduced compared with the fast counter-comparator scheme as the fast clock is replaced by a delay line, which operates at the switching frequency of the converter. One disadvantage of this method is that the size of multiplexer increases exponentially with the number of resolution bits [4]. Another drawback of the tapped delay line is that when it is applied to the multiphase control, precise delay matching among the phases places a stringent symmetry requirement on the delay line. In [7] - [8], combined delay line-counter structures are used to make a compromise between die area and power. However, the asymmetry of the delay line remains a problem for multiphase application.

(4) Ring-Oscillator

A new DPWM scheme using ring-oscillator for 4-phase application is proposed in [4]. Main component of the DPWM module is a ring-MUX scheme, shown in Fig. 6.

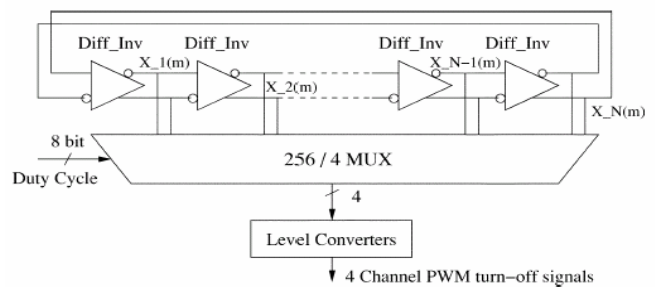


Fig. 6 Structure of DPWM circuit using ring oscillator

The above scheme is composed of 128 stage differential ring oscillators, which yield 256 symmetrically oriented taps, and a 256-4 MUX that can select the appropriate signals from the ring. During the operation, a square wave propagates along the ring. When the rising edge reaches tap zero in the ring, the rising edge of the PWM signal for phase one is generated. The falling edge of this PWM signal is generated when the rising edge of the propagating square wave reaches a specified tap in the ring.

This scheme has area and power consumption similar to those of the delay line techniques. However, this scheme has the advantage of symmetric structure. Since the different phases can be tapped out from symmetric positions on the ring, this technique is especially suitable for multiphase PWM generation [4].

It is shown from the above review that with the techniques developed so far, the resolution of the duty cycle, and consequently, the resolution of the output voltage, is high enough to avoid the limit cycle oscillation and to maintain reasonably low clock frequency. A digital controller prototype built in [14] achieves switching frequency of 4 MHz with clock frequency of only 128 MHz.

IV. IMPROVED FUZZY LOGIC CONTROL ALGORITHMS

It should be noted that achieving high enough output voltage resolution is only one small part of the digital control equation. It demonstrates that the digital control is a viable solution. A more important part is to develop new control algorithms that can take advantages of digital circuits and improve the dynamic performance of the switching power supplies.

Among many available digital control methods, fuzzy logic controller (FLC) has emerged as one of the most active and promising control methods in the power electronics due to its capability of fast computation with high precision. The fuzzy control systems are based on expert knowledge that converts the human linguistic concepts into an automatic control strategy without any complicated mathematical modelling [9]. Therefore, it naturally provides the ability to deal with the highly nonlinear, time-variant and ill-defined systems where the mathematical models are difficult to be obtained or the control variables are too hard to measure. This makes it well suited in resolving the time-varying nonlinear nature of switches in DC-to-DC converters [10].

In addition, design of fuzzy logic controller is easier than other advanced control methods in that its control function is described by using fuzzy sets and if-then rules rather than cumbersome mathematical equations or large look-up tables. This will greatly reduce the development costs and time.

More importantly, fuzzy logic control can provide desirable both small signal and large signal dynamic performance at the same time, which is not possible with linear control technique. Therefore, fuzzy logic controller has been potential ability to improve the robustness of DC-to-DC converters.

In this section, two new digital control algorithms based on fuzzy logic control is reviewed.

(1) Current mode fuzzy logic control

It is well known that the inductor current plays a very important role in the dynamic response of DC-to-DC converter. It can provide additional information on the energy stored in the converter. It is known that using the current feedback, better dynamic performance can be achieved. The stability of the converter system can also be improved. Therefore, by combining the fuzzy logic controller

and current mode control together, the advantages of both methods will be exploited. A new fuzzy logic control system using inductor current feedback is proposed in [11]. Fig. 7 shows its block diagram.

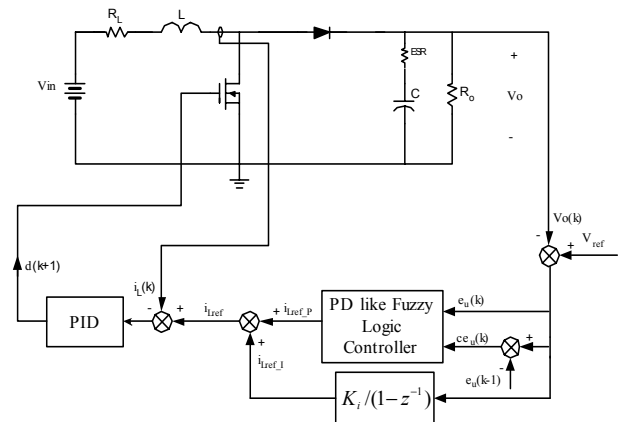


Fig. 7 Block diagram of current mode fuzzy logic controller using i_L in the inner control loop

As shown in the above figure, the current mode fuzzy logic control is implemented with two control loops. The outer voltage loop is controlled by a PD like fuzzy logic controller with integrator, and the inner current loop is controlled by a PID controller. The output of the voltage loop serves as the reference of the inductor current.

The current mode FLC method has significant advantages as the inductor current is utilized. The system stability and response time can be improved as compared with conventional fuzzy logic control.

(2) Fuzzy logic control with ESO

In order to further improve the dynamic performance of current mode fuzzy logic controller, a new nonlinear configuration called Extended State Observer (ESO) is introduced into the control of DC-to-DC converter [12]. Fig. 8 shows its block diagram.

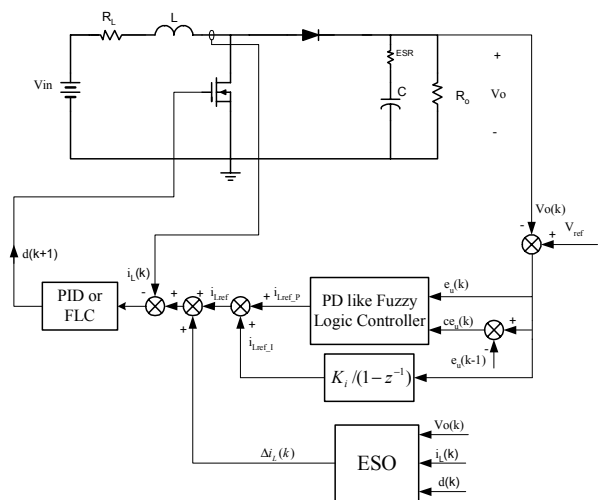


Fig. 8 Block diagram of current mode fuzzy logic controller with ESO

Based on the concept of generalized derivative and nonlinear feedback, extended state observer is inherently

suitable for dealing with the system uncertainties, even in the presence of large and fast variation of load disturbances and parameters changes.

Using the ESO, accurate estimation and compensation of system disturbances, such as load current change, could be achieved. In addition, in the design procedure of ESO, the accurate knowledge of power converter model is not required. As a result, the design of ESO is inherently independent of the mathematical model of the controlled system and its parameters. Therefore, this observer has the advantage of good robustness.

Experimental result shows that significant dynamic performance improvement can be achieved with ESO, as shown in Fig. 9.

V. BEST POSSIBLE CONTROL STRATEGY

The above discussed control method can improve the dynamic performance of the switching converters. However, it cannot guarantee that the best possible transient response can be achieved. In other word, there may still be a huge room for improvement in terms of dynamic performance.

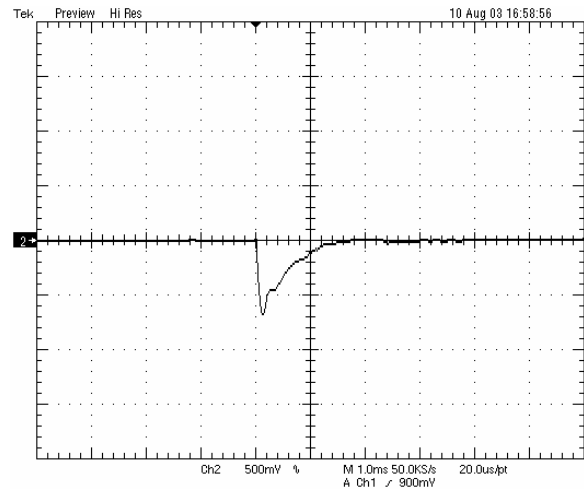
In theory, for any specific power converter, there must be a best possible dynamic performance (minimum overshoot and/or minimum transient time) under load current change and input voltage change.

In [13], new digital optimal control algorithms are developed to achieve the best possible dynamic performance of DC-to-DC converters under load current change and input voltage change. The basic idea of the control strategy is illustrated in Fig. 10.

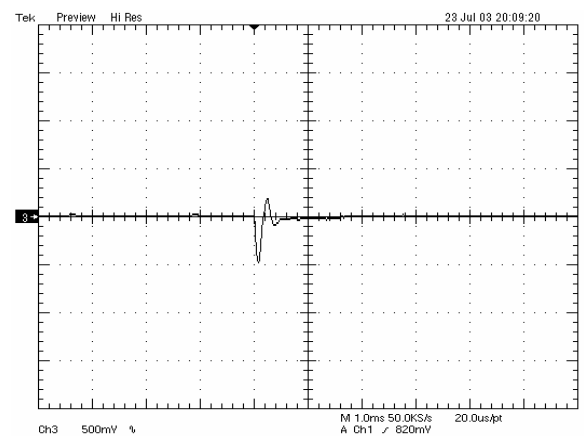
When the load current has a step change, the output capacitor is discharged to supply the extra load current and at the same time, the inductor current should be increased by increasing the duty cycle.

It can be observed from Fig. 10 that at the end of time period t_1 , the inductor current reaches the same level of the output current. Before the end of t_1 , the extra load current is supplied by the output capacitor. After the end of t_1 period, the inductor current should keep rising to charge the output capacitor. If the inductor current stops rising at the end of t_2 period, such that the discharged area $A_0 + A_1 + A_3$ equals to the charged area A_2 , then the output voltage will recover to its original value and at the same time, the inductor current reaches to the new steady state value. In this case, the dynamic response will be fastest and the output voltage undershoot will be the minimum. The key point is to decide the time period t_2 . In [13], the detailed equations are provided to determine the time period t_2 , as well as other time periods in order to achieve the best possible dynamic performance.

Experimental result shown in Fig. 11 demonstrates that the best possible control strategy produces much better dynamic performance such as very small overshoot and transient time compared with the conventional current mode PID controller.



(a) Current Fuzzy Logic Control



(b) Current Fuzzy Logic Control with ESO

Fig. 9 Experimental result of output voltage response to load current change from 1A to 3A for Boost converter (X axis: 1ms/div; Y axis: 500mV/div)

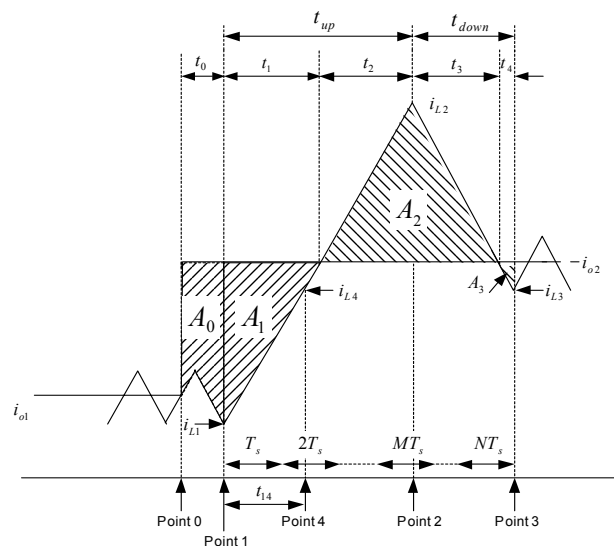
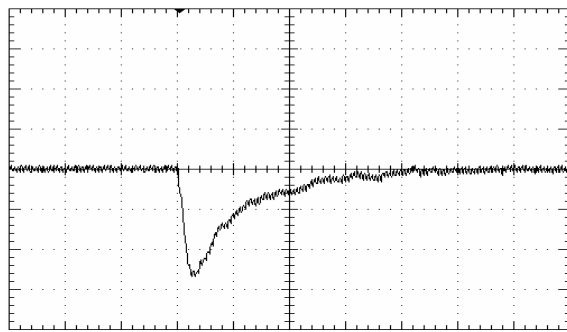
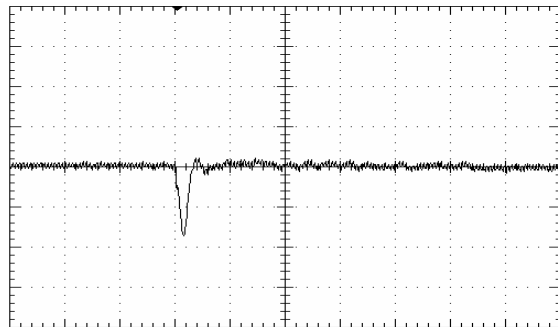


Fig. 10 Optimal inductor current transient for load current positive change



(a) Current mode PID controller



(b) Best possible control algorithm

Fig. 11 Experimental result of output voltage response to load current change from 5A to 10A for Buck converter (X axis: 40us/div; Y axis: 50mv/div)

VI. CONCLUSION

This paper reviews the digital control technologies for switching power supplies. After reviewing the advantages of digital control, the paper described various DPWM technologies to achieve high enough output voltage resolution at reasonable clock frequency, and therefore, to demonstrate that DPWM can achieve same performance as analog PWM and to meet the accuracy requirement.

The paper described the control strategies that can take advantages of digital circuits in order to improve the dynamic performance of switching power supplies. Current mode fuzzy logic control algorithms with and without ESO are described and dynamic performance can be improved.

The basic idea of the best possible control strategy is described. Based on the charge balance concept, this control method can achieve the best possible dynamic response for a given set of converter parameters, such as inductor value, capacitor value, switching frequency. The experimental result shows significant transient performance improvement.

Digital control is the trend in switching mode power supply control and better performance can be achieved using digital control.

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