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Switching DC-DC Converters with Hybrid Control Schemes

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ABSTRACT : This paper presents a survey on DC-DC converters, especially on various kinds of techniques involved in the design of a buck converter (a step-down DC-DC converter). This includes the basic switch mode DC-DC converter and different types of control methodologies those can be used to improve circuit performance and transient response. Using hybrid schemes such as SIMO (Single Inductor Multiple Output) converters and Multiple output power converters, better power efficiency can be achieved.

***KEYWORDS*: DC-DC converter, switch mode DC-DC converter, control methodologies, hybrid schemes, Power reduction and efficiency.**

1. Introduction on DC-DC Converter

Microprocessors are often used in systems where the energy to operate the device is provided by a rechargeable battery. One example of such a system is a portable computer. The voltage regulation tolerance for the microprocessor is often smaller than the voltage variation of the battery, since the battery voltage can vary due to a number of reasons including temperature, state of charge, battery current, and aging. Therefore a voltage regulator is used to process the widely varying battery voltage and provide the well-regulated power supply voltage that the microprocessor requires.

It is desirable for the voltage regulator to be as efficient as possible to maximize the battery operation time and minimize the amount of heat generated by the portable device. It is also desirable to keep the weight and size of the voltage regulator as low and small as possible.

For these reasons, a DC-DC converter type of voltage regulator is often used. A switching converter uses switches and energy storage elements to efficiently convert power from one form to another. In this case, the power conversion needed is a voltage conversion from the battery voltage to the microprocessor power supply voltage. A switching converter that performs this type of function is called a DC-DC converter. The abbreviation “DC” stands for “Direct Current” and implies a voltage or current waveform that is constant with time, as opposed to an “Alternating Current” or “AC” waveform that changes polarity with time. A DC-DC converter can convert one DC voltage to another DC voltage.

2. Switch Mode DC-DC Converter

A switch mode power converter switches a power transistor between saturation (full on) and cutoff (completely off) with a variable duty cycle whose average is the desired output voltage, as shown in Figure 1. The resulting rectangular waveform is low-pass filtered with an inductor and capacitor. The main advantage of this method is greater efficiency because the switching transistor dissipates little power in the saturated state and the off state compared to the semiconducting state (active region).

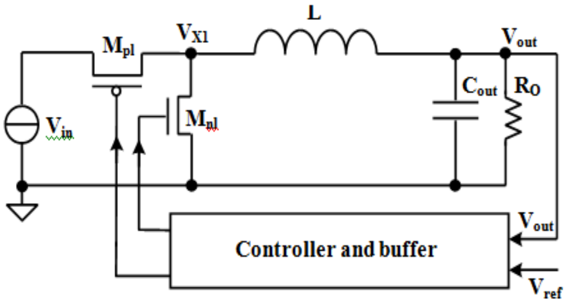

Fig. 1.Schematic of a switch mode buck converter.

Other advantages include smaller size and lighter weight (from the elimination of low frequency transformers which have a high weight) and lower heat generation due to higher efficiency. Disadvantages include greater complexity, the generation of high amplitude, high frequency energy that the low-pass filter must block to avoid electromagnetic interference (EMI), and a ripple voltage at the switching frequency and the harmonic frequencies thereof.

Switch Mode DC-DC Converter Topology

There are three major topologies in the switching DC-DC converters. Those are categorized as buck, boost, and buck-boost converters.

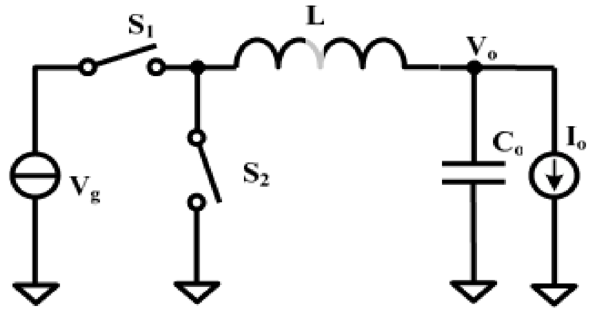

Fig.2. Switched mode DC-DC converter topologies: buck converter

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First, the buck converter realizes the step- down voltage conversion: the output voltage is lower than the input voltage. Second, the boost converter realizes the step-up voltage conversion: the desired output voltage is higher than the input voltage. Lastly, the buck-boost converter, which is also called as fly back converter, is realizes both step-up and step-down voltage conversions. Figure 2 shows a circuit diagram of the buck converter. The energy is transferred only when S_1 is ON and S_2 is OFF.

Hence, the average output voltage in this topology is,

$$\frac{V_o}{V_{g,buck}} = \frac{t_{on}}{T} = D,$$

where D is the duty-ratio, t_{on} is switching-ON period, and T is the one switching period.

3.Control Methodology in Switch Mode DC-DC Converter

In ideal case, the input-output voltage ratio is directly followed by the duty ratio. However, in a realistic case, the real input-output voltage conversion does not exactly depend only on the ideal duty ratio value due to following reasons. First, switch (MOS transistor) has a finite turn-on resistance value and produces a voltage drop across the switch. Second, this voltage drop is varied by the different load condition with saverage current level changes. Third, the inductor has the effective series resistance which builds another voltage drop. All of these increase the dependency of output voltage on load. Fortunately, the closed-loop regulation technique proposed recently can significantly reduce this dependency.

3.1. Voltage-Mode PWM Control

Based on the information used to control the converter, voltage mode or current mode control methods can be applied. Voltage mode control uses only output voltage information to control the converter. Current mode control uses both the output voltage and the inductor current information to control the converter. The details about voltage mode and current mode control will be discussed in the following sections.

A schematic of analog voltage mode PWM (pulse width modulation) controlled buck converter is shown in Figure 3. The output stage consists of a filtering capacitor C_O and a (resistive) load R_O. The output voltage V_O is attenuated by the resistor string R_3 and R_4, and is fed back to the error amplifier and compared with a reference voltage V_{ref} to determine the trip point of the PWM comparator and generate the error voltage V_e. Then, a comparator stage quantizes V_e with the reference of the fixed frequency ramp signal. PWM modulator generates the PWM signal that has a duty ratio proportional to the V_e.

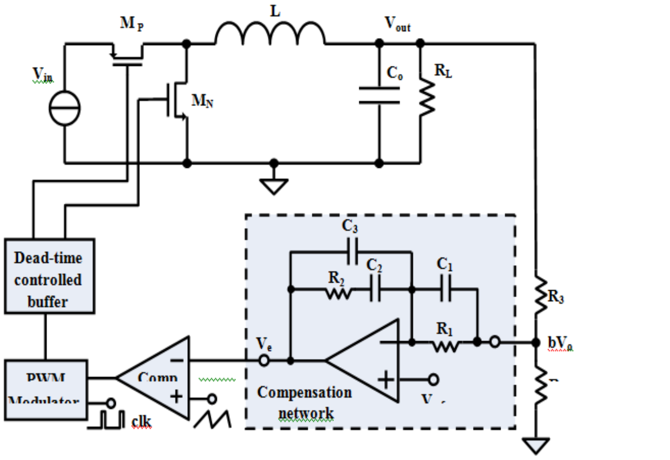

Fig. 3. Simplified structures of voltage-mode PWM control.

In a voltage mode PWM converter, due to the existence of the low-frequency complex poles in the loop gain transfer function, it is very difficult to design the compensation network for a wide loop-gain bandwidth.

3.2. Current-Mode PWM Control

Another popular control technique for switch mode DC-DC converter is the current mode control as shown in Figure 4. Instead of comparing the error voltage, V_e, to an externally generated ramp signal, the V_e is now compared to the inductor current signal. The basic operation of the current mode control can be shown in the waveforms of the V_{ref} and control signal (Figure 5): During the switching signal ON, the inductor current builds up linearly. When inductor current-sensed voltage V_{ref} reaches to the V_e, the comparator sends a reset signal to the PWM modulator and turns switching signal OFF. Now the inductor current decreases linearly so does the V_{ref}. Until the reset is performed from the system CLK, the switching signal stays OFF. Finally this switching ON/OFF action performs the output regulation. For example, when inductor suddenly carries higher currents, a V_{ref} will increase with stiffer slope during the period DT. This will turn the switch OFF earlier resulting narrower D.

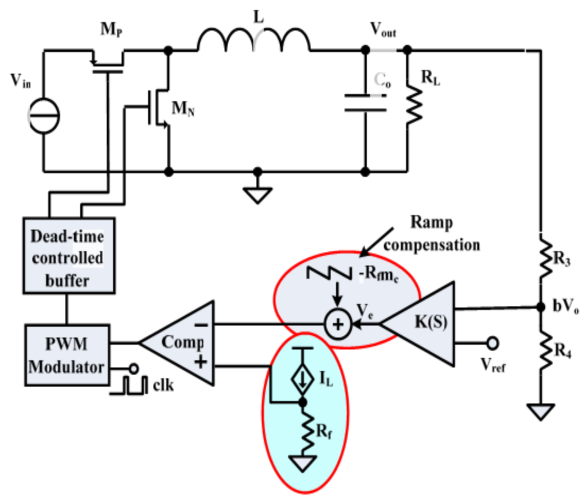

Figure 4. Schematic of conventional current mode PWM controlled buck converter.

Comparing the current mode control with voltage mode control, we can see that, in current mode control, the inductor current follows the current command almost instantaneously. In a simple and approximate model, it removes the inductor pole from the loop. This makes the power stage transfer function to the first order shape. Therefore, faster transient response can be obtained with current mode control with a simpler compensation network. Furthermore, a current limit protection can be easily implemented by limiting the maximum level of error voltage, V_e, hence the inductor current i_L.

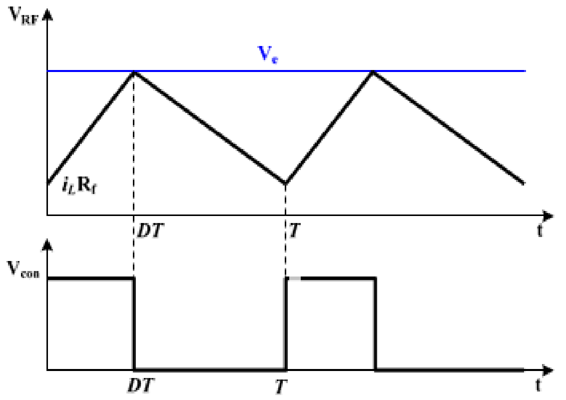

Fig 5. Waveforms of Control signals in current mode control

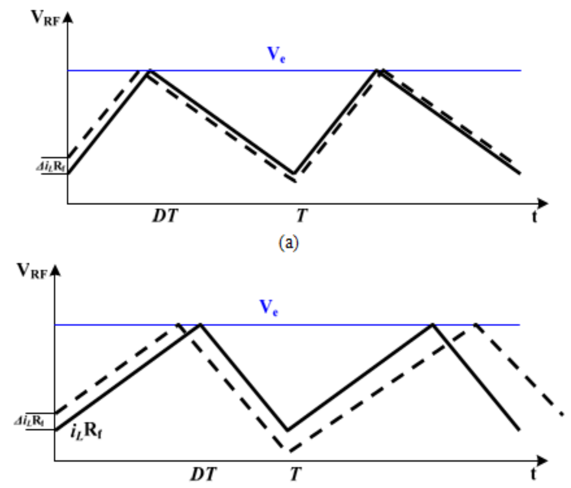

Fig. 6. Effect of small disturbances with current mode control:
(a) D<0.5 (b) D>0.5.

But sub-harmonic oscillation occurred in the fixed frequency current mode control working in CCM mode when the duty ratio D is larger than 0.5. This sub-harmonic oscillation is shown in Figure 6. When D > 0.5, the small disturbance ΔI_L rapidly increases in subsequent cycles and this indicates the instability. In Figure 6(a), where D < 0.5, the small disturbance, $\Delta I_L R_f$, dies away along with time, *t*, resulting stable condition. On the other hand, In Figure 6(b), where D > 0.5, $\Delta I_L R_f$ is continued to amplify along with time, *t*. This problem can be solved with extra compensation ramp signal added to the control signals, as shown in Figure 7.

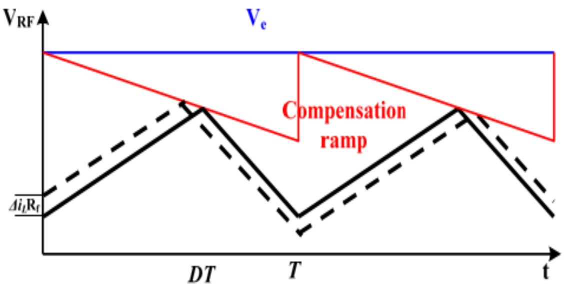

Fig. 7. Extra compensation ramp is added for sub-harmonic oscillation

3.3. Hysteresis Control (Band-Band Control)

Hysteretic voltage-mode control, also known as band-band control or ripple voltage control is well known for its fast response for line and load transients. Moreover, hysteretic switching converters have been shown to have unconditional stability under all operation conditions. Figure 8. shows the block diagram of a conventional hysteresis voltage mode control. If the output voltage V_{out} is lower than the low-voltage band V_{low}, the hysteretic comparator turns on the pMOS power switch M_p, and turns off the nMOS M_n, charging up the output capacitor C_o through the inductor L, and the output voltage V_{out} increases. When the V_{out} is higher than the higher band V_{high}, M_p will be turned off, and M_n will be turned on to make V_{out} drop into the band. If the change of the input voltage V_{in} or the load current I_{load} causes V_{out} to be outside of the band limited by V_{high} and V_{low}, the hysteretic comparator will make the gate drive signals to charge or discharge continuously (that is, full or zero duty cycle) to steer back to within the band as quickly as possible. Thus, the output voltage V_{out} is corrected as fast as the output filter (C and L) allows and, incidentally, the converter is unconditionally stable.

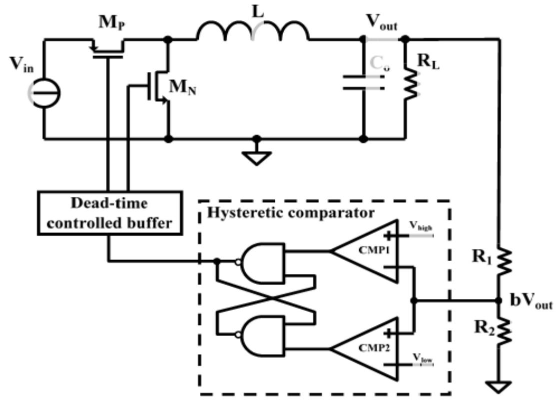

Fig. 8. Block diagram of the voltage mode hysteresis controlled buck converter

There are also some disadvantages of the voltage mode hysteresis control. As discussed above, the control signal can go 100% duty cycle and zero duty cycles, the inductor current could rise beyond the current limit of the power switches during large signal transient responses, for example, during the start-up period. Second, the switching frequency varies with all of the design parameters of the converter, such as C_O, L, R_O……

3.4. Digital Control

Digital controlled DC-DC converters enjoy growing popularity due to their low power, immunity to analog component variations, compatibility with digital systems, and faster design process. They have the potential to implement sophisticated control schemes and to accurately match duty cycles in interleaved converters. Figure 9. gives a block diagram of a digital voltage mode control.

Some salient features of the digital controlled power system are listed below:

1. Advanced Control Strategies
2. Communication with Host System
3. Synthesizability and programmability
4. Insensitivity to Component Variation and Noise
5. Reduced Power and Area

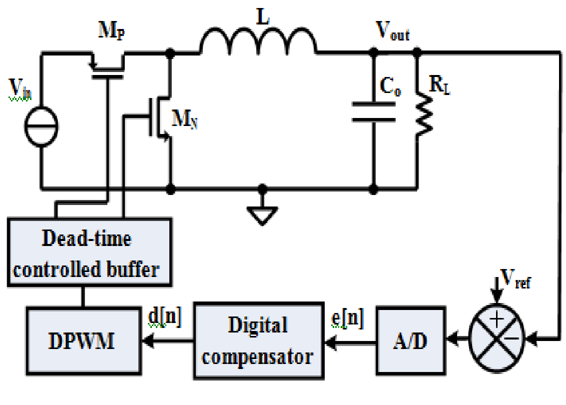

Fig. 9. Block diagram of digital voltage mode control

There is also one important disadvantage of the digital voltage mode control: quantization and limit cycling. Limit cycling refers to steady-state oscillations of the output voltage V_O. It may result from the presence of signal amplitude quantizers like the ADC and DPWM modules in the feedback loop. It is an undesired effect which will increase the output ripple voltage and also increase the power consumption of the controller. Obviously, steady-state limit cycling becomes very undesirable when it leads to large, unpredicted output voltage variations. Furthermore, since the limit cycle amplitude and frequency are hard to predict, it is difficult to analyze and compensate for the resulting V_{out} noise and the electro-magnetic interference (EMI) produced by the converter.

4. Power Reduction and Efficiency Enhancement with Hybrid schemes

4.1. Multiple Output Power Converters

Meanwhile, in a portable device, such as cell phone, MP3 player, PDA, or Laptop, some different DC supply voltage levels suitable for different components are included. In modern electrical and electronic technology, voltage scheduling with multiple supply voltage V_{DD} optimization draw great interests, because multiple V_{DD} optimization is the single most effective way to reduce power consumption of circuits, especially digital circuit. And in the most recent technology of Organic Light-Emitting Diode (OLED) display, Active-Matrix (AM) OLED panels need a different sophisticated voltage supply for each color (Red, Green, or Blue) to optimize display efficiency and display quality with brightness, contrast, and vividness. All of the above-mentioned typical needs from real applications pose a challenge to DC-DC switching converter designers: from a single input power supply, usually a battery, several outputs with different voltage levels are regulated.

Before the 1900s, a very first implementation was to use a separate DC-DC converter for each output. This is a straightforward and timesaving method with many available commercial chips. On the other hand, it causes too many bulky power devices as inductors, capacitors, and control ICs. Hence, the cost for implementation of one and mass-production is apparently expensive.

To overcome the problems, from the 1900s until now, many designers have developed their researches on Multiple-Output ICs, where there is only one control IC to control several outputs. This approach can reduce remarkably the Printed Circuit Board (PCB) areas, and from that, reduce the implementation cost. However, DC-DC converters of this type still require one energy-storage component, usually an inductor, for each output. That results in costs of PCB place for inductors and of inductors themselves.

It is, therefore, desirable to develop compact DC-DC converters that are possible for Multiple-Output, small in size, with fewer IC pins, fewer off-chip inductors, and fewer on-chip power switches, while keeping EMI and cross couplings due to the reduction of magnetic components at an acceptable level. Single Inductor Multiple Output (SIMO) DC-DC converter shows up as a most suitable and cost-effective solution.

4.2. Single-Inductor Multiple-Output (SIMO) DC-DC Converter

Conventional implementation of a DC-DC converter that has N output voltages may consist of N independent converters, or employ a transformer that has N secondary windings to distribute energy into the various outputs (isolated multiple-output converter). The first method requires too many components, including controllers and power devices, and this will increase the system cost. The second method does not allow individual outputs to be precisely controlled and has a big limitation for the applications of multiple voltage supply scaling. In addition, leakage inductance and cross coupling among windings cause a serious cross-regulation problem. Moreover, both methods require at least N inductors or windings, which may be too bulky and costly. A multiple-output architecture was proposed which combines the control loops of N converters into a single one. Multiple inductors are still needed and the reduction in external components is very small.

Among existing multiple-output power supply implementations, Single-inductor multiple- output (SIMO) switching converter is a very cost-effective solution. Inductors are expensive and bulky elements in switching converters. For a considerable saving in cost, weight and size, it is natural to investigate the possibility of using fewer inductors and power switches to fulfill the task without compromising the performances. The invention of SIMO switching converters nicely fit this need. With only one single inductor, it provides multiple, independently regulated outputs successfully.

To overcome the problems mentioned above, a single-inductor dual-output (SIDO) boost/boost converter by Dr. Ma. Only one inductor is required for providing two different output voltages. Using a novel time-multiplexing (TM) control scheme, the converter only need one controller loop to regulate all outputs. Compared with other designs, both on-chip and off-chip components are reduced significantly, while low cross-regulation is maintained at the same time.

Conclusion

The basic models involved in the design of DC-DC converters, especially buck converter (a step-down DC-DC converter) are studied in this survey. This includes the basic switch mode DC-DC converter and different types of control methodologies those can be used to improve circuit performance and transient response. By introducing multiple control schemes, high-efficient converters such as SIMO (Single Inductor Multiple Output) converters and Multiple output power converters are designed to obtain better power efficiency.

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