Recent Developments in Switching Mode Power Supply Technologies

1.0 Introduction

With the rapid development of digital devices and semiconductor technology, switching power supplies are used in almost all applications with output power level above one watt including communications equipment, data centers, wireless base stations, computers, cell phones, and various types of battery chargers. Two types of commonly used switching power supplies are AC-DC and DC-DC. With AC-DC power supplies, the input voltage is from the AC utility and the output is a DC voltage, for loads such as a computer power supply, or battery chargers. With DC-DC power supplies, the input voltage is DC and the output voltage is another DC level for loads such as a USB charger, or Voltage Regulator (VR) in a computer motherboard.

The Distributed Power Architecture (DPA), shown in Fig. 1, is widely used in data center and communication power systems [1]. The Power Factor Correction (PFC) module converts the AC voltage to 400V DC, which is then converted by a front end converter to 48V DC. The 48V DC is distributed across the back plane of the system.

More recently, the electronic ballast power supply for Compact Fluorescent Lamps (CFLs) has been developed. This application requires a special AC-AC converter, where the 60Hz low frequency AC voltage is converted into high frequency AC at several tens of kHz.

Solar cell inverters are another class of power supplies which convert the DC voltage from photovoltaic cells to 60Hz low frequency AC to send the energy to the grid.

Power conversion efficiency is a very important performance feature for a switching power supply. Small size is another important specification. High efficiency not only means less energy loss, but also means lower temperature rise and therefore, more compact mechanical design. Presenting challenges to designers, a power supply is a supporting component, so cost is always under pressure.

Closed loop control is used to ensure stable operation of the switching power supply. It also determines the dynamic performance of switching power supplies. Recently, digital control has begun to find its way into switching power supplies due to reduced silicon costs and technology development.

In this paper, major advances in the topologies and digital control of switching power supplies are summarized.

2.0 HIGH EFFICIENCY CONVERTER TOPOLOGIES

2.1 Zero Voltage Switching

Switching loss occurs due to simultaneous overlap of voltage and current in power MOSFET switches during switching transitions as illustrated in Fig. 2(a).

Zero Voltage Switching (ZVS) is a technique that nearly eliminates turn on switching loss, \( P_{sw} \), in power MOSFETs by allowing the voltage across the switch, \( V_{ds} \), to go to zero before the switch turns on. This technique requires a negative current, \( I_{ds} \), at turn on as illustrated in Fig. 2(b). The negative current is used to discharge the capacitor across drain to source to zero before the MOSFET is turned on. The turn-off loss can be significantly reduced by adding a small snubber capacitor across drain and source terminals.

2.2 Bridgeless AC-DC Rectifier

In order to reduce the power loss in the utility lines and to reduce the Electro-Magnetic Interference (EMI), the harmonic current drawn from the AC line is limited. Power Factor Correction (PFC) circuits are required for most power supplies to minimize EMI and harmonic current. Fig. 3 shows a full bridge diode rectifier followed by a Boost converter. Using average current mode control, this circuit is widely employed to achieve PFC.

By forcing the current in inductor \( L_3 \) to follow the AC voltage, the input current is sinusoidal with the same shape and in phase with the input voltage. Therefore, high power factor is achieved.

A drawback of this circuit is that when the input voltage is positive, or negative, two diode voltage drops (i.e. \( D_1 \) and \( D_4 \) or \( D_2 \) and \( D_3 \)) plus the voltage drop across \( D_2 \) or \( S_2 \) in the current path, which increases the power loss. This is especially problematic at lower end of the input voltage range.
In this converter, pairs $S_2/S_3$ and $S_1/S_4$ operate at 50% duty cycle with a small amount of dead time between the pairs and out of phase with each other. The output voltage is regulated by adjusting the phase shift between $S_1$ and $S_3$. ZVS for $S_1$-$S_4$ can be achieved using the energy stored in the leakage inductance of the transformer. At 12V output, it is beneficial to replace the rectifier diodes, $D_1$ and $D_3$, with power MOSFET synchronous rectifiers to reduce conduction loss.

This circuit is well suited for high input voltage applications since ZVS can be achieved. The main drawback of this circuit is that at light load, ZVS is lost. In addition, the leakage inductance resonates with the parasitic capacitance of the rectifier diodes which increases the voltage stress on the diode and therefore introduces additional loss when higher voltage rating diodes are used.

In order to improve the power conversion efficiency, the LLC resonant converter, shown in Fig. 6, was developed in [6] and [7].

For the LLC converter, two MOSFETs operate at 50% duty cycle with short dead time. The output voltage is regulated by adjusting the switching frequency. ZVS can be achieved if the current through the resonant tank lags the voltage at the input of the tank. Another advantage is that the voltage stress of the rectifier diode is limited to double the output voltage. Additionally, the converter size can be smaller than the PSFB since no output filter inductor is needed and due to ZVS operation, the switching frequency can be higher than the PSFB, which enables potential integration of the leakage inductance (Lr) and parallel inductance (Lm) into transformer.

Synchronous rectifiers (SRs) can also be used to replace the diodes in order to reduce the rectifier loss for low voltage outputs, such as 12V. In addition, the gate drive signal for the SRs must be carefully designed since the primary side current information is needed [6]. At 400V input, 48V/40A output, and a switching frequency of 1MHz, 96% peak efficiency has been reported [7].

### 2.4 Non-Isolated DC-DC Converters

On a data communications circuit card, or on a computer motherboard, the input voltage is 12V DC, but the integrated circuits require voltages ranging at logic levels typically of 2.5V, 1.2V and 0.8V. The DC-DC Buck converter is used almost exclusively to step down the voltage for these applications. However, with 12V input and 1.2V output, the Buck converter suffers from problems such as high switching loss, poor dynamic performance and large size.

Numerous topologies have been proposed (such as [8]) to solve the problems inherent to the Buck converter. Among them, the Non-Isolated Full Bridge (NFB) converter with direct input-to-output energy transfer (see Fig. 7), has potential to replace the Buck converter [9].

The unique aspect of the NFB is that the common end of the high side switches (i.e. sources of Q2 and Q4) are connected directly to the output voltage node. Therefore, some of the energy is transferred directly from input to output without passing through the transformer secondary side and synchronous rectifiers. Therefore, the conduction loss for the transformer secondary side winding and synchronous rectifiers is reduced enabling efficiency improvement [9].

In addition, the high side switches, Q1-Q4, operate in phase shift mode, so ZVS can be achieved. Another benefit is that the voltage stress for the synchronous rectifiers is only 3-4 times the output voltage (4 - 5V for...
With a CSD, a constant current is used to charge and discharge the MOSFET gate capacitance during turn on and turn off interval. The current source can be implemented using an inductor and two small switches, which direct the current flow. With this approach, some of the gate drive energy can be recovered. More importantly, the impact of the parasitic inductance can be reduced, enabling the switching time and switching loss to be reduced. It has been demonstrated that with CSDs, the efficiency at 1MHz is same as that of voltage source drive at 500 kHz.

3.0 DIGITAL CONTROL FOR SWITCHING POWER SUPPLIES

Traditionally, switching mode power supplies have been almost exclusively controlled by analog circuits, including operational amplifiers, analog comparators, resistors and capacitors. With ever increasing system complexity, including more voltage rails and complicated timing sequencing, monitoring among the rails is needed. However, analog controllers cannot meet these requirements effectively. Fortunately, due to the steady cost reductions of integrated circuits, the feasibility of digitally controlled switching power supplies has increased significantly. Fig. 10 shows the block diagram of a digitally controlled Buck converter.

Three issues should be resolved before digital control of switching power supplies is widely accepted. The first one is the Digital Pulse-Wide-Modulation (DPWM) technique. The second one is achieving a stability analysis method that appeals to power supply designers. The third one is establishing improved control methods that are optimized for digital implementation.

3.1 DPWM Technologies

The output voltage of a Buck converter and other PWM converters are controlled by the duty cycle, which is the on time of the control MOSFET, $T_{on}$. With analog control, $T_{on}$ is determined by comparing a saw-tooth waveform signal and an error signal using a comparator. Therefore, $T_{on}$ can have any value between 0 and one switching period $T_s$.

With digital control, $T_{on}$ is discrete. If its resolution is not fine enough, Limit Cycle Oscillation (LCO) can occur. LCO is not caused by instability of the feedback loop. In [13] a detailed analysis of how to avoid LCO is provided. Generally speaking, a resolution of 5-10ns for $T_{on}$ is sufficient to avoid LCO in most applications.

Dithering is another method to effectively increase the DPWM resolution [18]. It involves applying a pattern to successive DPWM signals in order to generate an effectively higher DPWM resolution. In the example illus-
The effective resolution is increased by 2 bits (the acronym “LSB” in the figure represents Least Significant Bit). It is noted that a low frequency tone will be present in the spectrum of the output voltage. Therefore, high bit dithering (i.e. larger than 3 bits) is not advisable.

A second order multi-bit Σ–Δ generator has been proposed to increase the effective resolution of the DPWM with the benefit of reduced magnitude of the low-frequency spectral content compared to dithering, as in Fig. 14 [19].

In the past decade, a significant amount of quality research work has been done in this area. At the present time, it is the authors’ opinion that sufficient DPWM resolution has been achieved to meet the output voltage accuracy requirements and to avoid LCO. Recently, the research focus has shifted toward implementing unique features that can only be accomplished using digital circuits.

### 3.2 Digital Feedback Loop Design Method

Feedback control is critical to maintain stable operation of power supplies and to achieve satisfactory dynamic response. Power supply engineers are accustomed to analog design where zeroes and poles introduced in the feedback loop and open loop transfer functions are used to determine the stability using Bode plots.

In [20], a new digital controller design method based on the analog parameters is proposed. The paper relates the pole and zero frequencies to digital implementation. In this way, digital zeros and poles can be placed at the desired frequencies using the transfer function of the converter power train. In addition, multiple zeroes can be introduced to further boost the phase.

### 3.3 Dynamic Performance Enhancement

The dynamic performance of switching power supplies can be significantly improved using digital control strategies that can perform complicated arithmetic and logic manipulation. One example is Charge Balance Control (CBC) proposed in [21], which can also be implemented using analog circuits [22]. The key waveforms of the control strategy are illustrated in Fig. 15.

Using CBC, the controller will respond to load current transients immediately at $t_0$. It has been demonstrated that with CBC, near-optimal dynamic performance can be achieved including smallest overshoot/undershoot and shortest response time. The key point is how to determine time $t_2$ to turn off the control MOSFET so that the inductor current will reach the new steady state value at the same time, $t_3$, when the output voltage also recovers from the undershoot. With CBC, this problem has been solved.

### 3.4 Other Performance Enhancement with Digital Control

Digital control can also be used to improve the converter efficiency under different load conditions. The dead time between the control switch and synchronous rectifier can be dynamically controlled to minimize the body diode loss [23]. In addition, the number of phases in a multi-phase buck voltage regulator can be dynamically changed during operation so that each Buck converter phase operates at its highest efficiency point [24].

Digital auto tuning has tremendous potential for switching power supply design. The idea of a “plug-and-play” controller that can automatically
identify and control a converter has attracted interest from both industry and academia. Paper [25] proposes a digital control strategy that can automatically estimate the power train parameters and then design the digital compensating network automatically to achieve stable operation. The significance is that the complicated procedure of digital feedback controller design can be done automatically. The power supply designers can focus on the power circuit design. Therefore, the design cycle can be reduced.

4.0 CONCLUSION

This paper summarizes recent developments in the switching power supply area. The research is focused on two areas, improving conversion efficiency and digital control technologies. In Canada, researchers at the University of Toronto and Queen’s University have made significant contributions in these areas.

5.0 REFERENCES


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