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Overview on Switching-Mode Power Supply (SMPS)

1.1 Classification of Integrated Regulated Power Supply

There are tens of thousands of integrated voltage regulators in the market, which can be roughly classified into linear regulators and switching regulators. See Table 1.1 for the classification and characteristics of integrated regulated power supply.

1.1.1 Optimal Design of SMPS

The linear regulator, also known as series regulated integrated regulator, is named for its internal regulating tube, which works in the linear working area and is in series connection with load. It has advantages such as sound voltage regulation performance, low-output ripple voltage, simple circuit, and low cost, while its main disadvantages include relatively bigger voltage drop and high power consumption of the regulating tube with relatively low efficiency of the regulated power supply at about 45%. The linear regulator mainly consists of two types, namely, standard linear regulator using NPN regulating tube, which is also known as NPN linear regulator, and PNP low-dropout (LDO) regulator using PNP regulating tube. Besides, there are quasi low-dropout (QLDO) regulator and very low-dropout (VLDO) regulator. According to the characteristics of output voltage, linear regulators can be divided into different types such as fixed output, adjustable output, positive pressure output, negative pressure output, and multiplexed-output (including tracking output). The efficiency of traditional standard linear regulators is only around 45%, while that of LDO and VLDO can reach 80–90% under low voltage output.

The switching-mode power supply (SMPS) is known as a highly energy-efficient power supply. It leads the development direction of regulated power supply and now has become the leading product of regulated power supply. With the internal key components working under high-frequency switch status, the SMPS consumes quite low energy so that its power efficiency may reach up to 70–90%, twice as high as that of the standard linear regulated power supply. The SMPS integrated circuit mainly consists of the following four types: pulse width modulator (PWM), pulse frequency modulator (PFM), switching regulator, and single-chip SMPS.

According to the circuit principle, regulators can be divided into three types including series regulated linear regulator, shunt regulated linear regulator, and switching regulator.

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Table 1.1 Classification and Characteristics of Integrated Regulated Power Supply

Integrated regulated power supply	Linear power supply	Standard linear regulator	Fixed type	Three-terminal fixed type	Positive voltage output, negative voltage output
				Multiple-terminal fixed type	Positive voltage output, negative voltage output
			Adjustable type	Three-terminal adjustable type	Positive voltage output, negative voltage output, tracking mode
				Multiple-terminal adjustable type	Positive voltage output, negative voltage output, tracking mode
		Low dropout linear regulator	Low dropout regulator (LDO)	Three-terminal or multiple-terminal fixed/adjustable type	Positive voltage output, negative voltage output, tracking mode
			Quasi low dropout regulator (QLDO)		
			Very low dropout regulator (VLDO)		
	Switching mode power supply (SMPS)	Pulse width modulator (PWM)	With relatively low integration level and complicated peripheral circuit with constitutes high-power SMPS		
		Pulse frequency modulator (PFM)	With relatively low integration level, complicated peripheral circuit, switching frequency may reach over 1 MHz, and high efficiency		
		Switching regulator	With relatively high integration level and power switch tube inside, which needs to be equipped with industrial frequency transformer		
		Single-chip SMPS	With pretty high integration level and simple peripheral circuit, which constitutes SMPS of medium and small power		

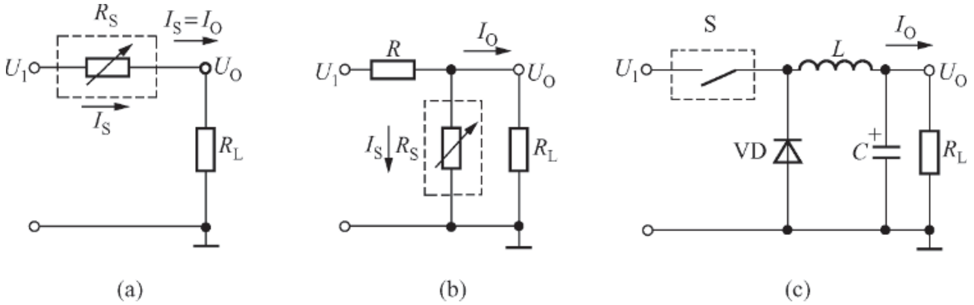


Figure 1.1 Equivalent circuits of the three kinds of regulators: (a) series regulated linear regulator; (b) shunt regulated linear regulator; and (c) switching regulator

Their equivalent circuits are respectively shown in Figure 1.1(a)–(c). In this figure, R_S refers to the equivalent resistance of regulating tube and S the power switch tube. As its output voltage is highly stable and output current is very small, shunt regulated linear regulator is generally used as reference voltage source. The main characteristics of various products are described in the following sections.

1.1.1.1 Three-Terminal Fixed Regulator

Fairchild Semiconductor Corporation firstly launched µ7800 and µA7900 series three-terminal fixed regulators in the beginning of the 1970s. It is a big revolution for integrated circuits of power supply, which greatly simplifies the design and application of power supply. The three-terminal fixed regulator can be placed in the circuits via the simplest way (such as a transistor) and has relatively complete overcurrent protection (OCP), overvoltage protection (OVP), and overheat protection (OTP) functions. At present, µA7800 and µA7900 series three-terminal fixed regulators have become universal ones in the world, with the widest application and largest sale volume. Such a three-terminal fixed regulator is easy to operate and needs no adjustment. It has a simple peripheral circuit and operates reliably and safely, and therefore is applicable to make general or nominal-output regulated power supply. However, it cannot regulate the output voltage or directly output non-nominal voltage, and its voltage is not stable enough.

1.1.1.2 Three-Terminal Adjustable Regulator

Three-terminal adjustable regulator was developed in the late 1970s and the early 1980s, which was the second-generation three-terminal regulator initiated by National Semiconductor (NSC). It not only reserves the advantage of simple structure the three-terminal fixed regulator has but also overcomes the disadvantage that the voltage could not be regulated. Moreover, its voltage stability is increased by one order of magnitude. Therefore, three-terminal adjustable regulator can be used to make laboratory power supply and DC regulated power supply. In addition, it can also be designed as fixed type to replace the three-terminal fixed regulator, to further improve the voltage regulation performance.

1.1.1.3 Low-Dropout (LDO) Regulator

LDO is a high-efficiency linear integrated regulator, whose input–output dropout voltage is about 500 mV, with power efficiency obviously higher than that of NPN linear regulator. VLDO is a new linear integrated regulator developed based on LDO in the beginning of the twenty-first century. VLDO uses the field-effect tube with very low specific on-resistance instead of the power tube that PNP uses, and its input–output dropout voltage can be as low as 45–150 mV.

1.1.1.4 Multiterminal Integrated Regulator

With plenty of pins, the multiterminal integrated regulator is flexible to use but with complicated connections. It can also be classified into fixed type and adjustable type.

1.1.1.5 Tracking Positive–Negative Balanced Output Integrated Regulator

Its characteristic is that when the positive voltage changes for some reasons, the negative voltage output may track automatically and make corresponding change to keep the absolute values of the two equal. The tracking function is particularly important for a precision operational amplifier powered by two supplies, which can prevent the operational amplifier from zero drift rising out of the unbalance between positive voltage and negative voltage.

1.1.1.6 Transformer SMPS without Power Frequency

The SMPS is also known as a low-loss power supply. As its internal parts operate under high-frequency switch status, the SMPS consumes low energy but with power efficiency twice that of ordinary linear regulated power supply.

1.1.1.7 Switching Regulator

A switching regulator is a switch integrated voltage regulator developed in the 1980s and 1990s. With PWM, power output, and protection circuit integrated on the same chip, the switching regulator has efficiency of over 90%. In addition, some switching regulators can even regulate output voltage continuously that can be used to SMPS with dozens to hundreds of wattage.

1.1.1.8 Single-Chip SMPS

With the main circuits (including MOSFET, required analog and digital circuits) of SMPS integrated on chip, the single-chip SMPS with the highest integration level can realize output isolation, PWM, and many other protection functions. A single-chip SMPS fits AC current of 85–265 V and 47–400 Hz via an input rectifier filter; it is thus an AC/DC power converter. The single-chip SMPS integrated circuit has displayed strong vitality since its appearance in the mid-1990s. It has such advantages as high integration level, high cost performance, simplest peripheral circuit, and best performance indicators. Now, single-chip SMPS integrated circuit has become an optimal integrated circuit for the development of medium- and small-power SMPS with wattage below 1000 W, precision SMPS, and SMPS modules. Besides, the development of single-chip SMPS has also created favorable conditions for the optimal design of SMPS.

1.1.1.9 Special SMPS

A special SMPS is characterized by "novelty, uniqueness, and wide application." It is novel in circuit, unique in function, and advanced in performance, with a great variety and wide application. Its varieties include constant voltage/current SMPS, LED driving power for lighting, constant power SMPS, high-voltage pulse power supply, high-power high voltage power supply, battery charger, and so on.

1.2 Characteristics of SMPS

1.2.1 Main Characteristics of SMPS

The SMPS is also called low-loss power supply. With its internal components working in a high-frequency switch status, it consumes low energy, and its power supply efficiency is twice that of the ordinary linear regulated power supply. The integrated circuits for SMPS are classified into two types: one is singled-ended or double-ended output PWM and the other is PFM, both of which can constitute the SMPS without power frequency transformer. Because they realize the voltage transformation and grid isolation with high-frequency transformer of very small volume, they can save power-frequency transformer of cumbersome volume. At present, the work frequency of SMPS has been increased from 20 kHz to hundreds of kilohertz and even above 1 MHz, so has the power efficiency. The output power range includes low power (dozens of wattage), medium power (hundreds of wattage), and high power (thousands of wattage). The disadvantage of SMPS is that the output voltage is not stable enough, and the output ripple is large and its noise is loud, making it inappropriate for making precise regulated power supply. However, it can be used as a pre-voltage regulator, with the standard linear regulator or low dropout linear regulator as the post-voltage regulator to constitute a high efficiency and precise regulated power supply of two stages. Such compound power supply possesses the advantages of SMPS and linear power supply.

Compared with the linear power regulator, although the SMPS is of complex design and some performance indicators are inferior to those of the linear regulator and the noise is loud, the advantages of SMPS mainly lie in the power efficiency, volume, weight, and so on. Especially when it constitutes a high-power regulated power supply, its volume is greatly reduced compared with that of the linear regulated power supply under the condition of the same output power, and the costs also decline significantly.

The efficiency of SMPS generally ranges from 70% to 85% with the maximum of 90%. Equipped with the post-positioned linear regulator and constituting a compound regulated

Table 1.2 Performance comparison of 20 kHz SMPS and linear regulated power supply

Parameter	SMPS	Linear regulated power supply
Power efficiency (%)	70–85	30–40
Output power per unit volume (W/cm^3)	0.12	0.03
Output power per unit mass (W/kg)	88	22
Voltage regulation rate (%)	0.1–1	0.02–0.1
Load regulation rate (%)	1–5	0.5–2
Output ripple voltage (mV, peak–peak value)	50	5
Output noise voltage (mV, peak–peak value)	50–200	Extremely small
Transient response time (μs)	1000	20
Holding time of output voltage after power failure (ms)	20–30	1–2

power supply, it still can achieve a high efficiency ranging from 60% to 65%, while the efficiency of most of the linear regulated power supplies (excluding low dropout linear regulators) only ranges from 30% to 40%. Compared with the linear regulator, the overall size of the traditional 20 kHz SMPS is only 1/4 of that of the linear regulator, and the 100–200 kHz SMPS is 1/8, while the size of new 200 kHz–1 MHz SMPS can be much smaller. After the power outrage, the SMPS can maintain the output voltage for a longer time than the linear regulator, because the latter is generally equipped with a low-voltage input filter capacitor, while the former is equipped with a high-voltage input filter capacitor with the withstand voltage ranging from 200 to 400 V and it saves more charge Q because of the direct proportion between Q and $CU_1{}^2$ (U_1 is DC high voltage).

The disadvantage of the SMPS is that it has relatively low-voltage regulation rate and load regulation rate, which takes a long time to respond to the transient state of load change; the output ripple and noise voltage are relatively high so that it is likely to exert electromagnetic interference externally.

1.2.2 Performance Comparison of SMPS and Linear Regulated Power Supply

See Table 1.2 for the performance comparison of 20 kHz SMPS and linear regulated power supply. It can be seen from the table that many technical indicators of the SMPS are superior to those of the linear regulated power supply.

1.3 New Development Trend of SMPS

The SMPS has been developed for decades. The self-excitation push-pull type transistor single transformer DC converter invented in 1955 took the lead in realizing the high-frequency conversion control function; and the one invented in 1957 and the SMPS design without power frequency transformer plan proposed in 1964 forcefully promoted the technological progress of the SMPS. The emerging of the PWM in 1977 and the single-chip SMPS in 1994 paved the way for promotion and popularization of the SMPS. Meanwhile, the frequency of SMPS has also increased from 20 kHz at the beginning to hundreds of thousands of hertz, and even a couple of megahertz. The SMPS is developed to be highly efficient, energy-saving, safe, environment-friendly, short, small, light, and thin. A variety of new technologies, processes, and apparatuses spring up like mushrooms and emerge continuously and the application of SMPS has also been increasingly popular. Next, introduction will be made on the new trend and new technology for the development of SMPS.

1.3.1 New Development Trend of SMPS

1.3.1.1 Green and Energy-Saving SMPS

Many famous integrated circuit manufacturers are making great efforts to develop low-power consumption and energy-saving SMPS integrated circuit. For example, Power Integrations (PI) of the United States adopted the energy-saving technology EcoSmart® to develop single-chip SMPS such as TOPSwitch-HX series. PI announced recently that due to the single-chip SMPS IC EcoSmart®, as it would save electric charge of about USD 3.4 billion for consumers all over the globe. The Green Chip such as TEA1520 series launched by Philips of the Netherlands also attaches great importance to high efficiency and energy saving functions. Besides, the international standards for green and energy-saving power supply have also been widely applied. For instance, the United States has established Energy Star Program in 1992 to reduce the no-load power consumption of the SMPS. The compulsory energy-saving standards established by California Energy Commission (CEC) have been implemented from July 1, 2006, requiring that the standby power consumption and no-load power consumption of electronic products must be reduced substantially. These standards cover all electronic products using external power adapter or charger, including mobile phone, household appliance, portable music player (MP3), handheld game player, electronic toys, and so on.

According to the fourth edition of power saving standard (Code of Conduct) newly published by the European Commission, which came into effect since January 1, 2009, specified that the no-load power consumption of ordinary power supply with rated output power of 0.3–50 W shall not be more than 0.30 W and that of ordinary power supply with rated power of 50–250 W shall not be more than 0.50 W. The new standard raised stricter requirements on the no-load power consumption of mobile phone power supply of 0.3–8.0 W, requiring it not to exceed 0.25 W during January 1, 2009 and December 31, 2010 and 0.15 W from January 1, 2011.

1.3.1.2 Intelligent Digital Power Supply and Programmable SMPS

Digital Power Supply

At present, the SMPS is developed to be intelligent and digitalized. The intelligent digital power system, which emerged at the beginning of the twenty-first century, has drawn great attention of the public for its excellent performance and advanced monitoring functions. The digital power supply, being intelligently adaptive and flexible, is able to directly monitor, process, and adapt to the system condition and meet any complex power requirement. In addition, it also guarantees the reliability of the long-term system operation through remote diagnosis, including fault management, overcurrent protection, and preventing the system from stop.

The promotion of digital power supply created a favorable condition for the optimal design of intelligent power system.

The digital power system has the following features:

1. It is an intelligent SMPS system with a digital signal processor (DSP) or micro controller unit (MCU) as the core and the digital power driver and PWM controller as the control object. The traditional SMPS controlled by MCU (including MCU μP and single-chip machine μC) generally controls only the switch-on and switch-off of the power supply, which is not a digital power supply in real sense.
2. Developed with fusion digital power technology, it realizes the optimal combination of analog element and digital element in the SMPS. For example, the analog element used for the power stage – MOSFET driver can be conveniently connected to the digital power controller and help to manage the power protection and biasing circuit. PWM controller also falls into the category of digital control analog chip.
3. With high integration, it realizes power system on chip, integrating a big number of separated components into a chip or a set of chips.
4. It can make full use of the advantages of DSP and MCU, making the digital power designed reach high technical indicators. For example, the resolution of its PWM can reach 150 ps (or 10^{-12} s), far exceeding the traditional SMPS. The digital power supply can also realize many functions such as multiple phase control, nonlinear control, load share, and fault prediction providing convenience for the research and manufacturing of green and energy-saving SMPS.
5. It provides convenience for building a distributed digital power system.

In March 2005, Texas Instruments (TI) of the United States announced to launch innovative digital power products and displayed the solution of Fusion Digital Power^{TM} that includes the following three types of chips: UCD7K series digital power drivers, UCD8K series PWM controllers, and UCD9K series digital signal processors. Product series have been formed for the above- mentioned chips, supporting both the AC circuit and load power systems. They can be widely applied in telecommunication facilities, computer server, data center power system, and UPS.

Programmable SMPS

The adjustable SMPS changes the output voltage of regulator by manually regulating the resistance value, which is not only precise enough, but also inconvenient for application. Digital potentiometer, which is also called digitally controlled potentiometer (DCP), can replace the adjustable resistance to constitute a programmable SMPS under computer-based control.

The circuit design plan for the programmable SMPS constituted by digital potentiometer is shown in Figure 1.2. Figure 1.2(a) shows replacement of adjustable resistance with DCP, which works in the adjustable resistance model. The adjusted resistance value is R_{DCP}, which, together with R_1, constitutes a sampling circuit$_1$, which is sent to the feedback terminal FB of the switching regulator. The single-chip microcontroller can set the output voltage of adjustable switching regulator by changing the value of R_{DCP}. The second plan is to replace two sampling resistors with R_{DCP} simultaneously, which can save one resistance element, whose simplified circuit is shown in Figure 1.2(b) with other parts being the same with Figure 1.2(a). The third plan is to connect the DCP between R_1 and R_2 in series; the simplified circuit is

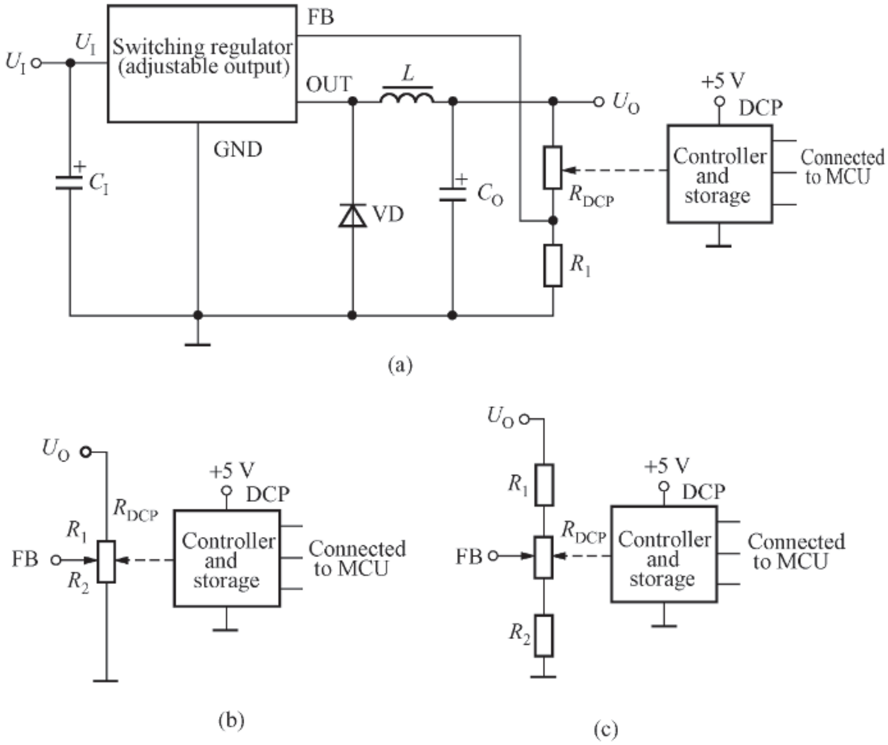


Figure 1.2 Circuit design plan for programmable SMPS constituted by DCP (a) Circuit 1; (b) Circuit 2 (simplified circuit); and (c) Circuit 3 (simplified circuit)

shown in Figure 1.2(c). This circuit is applicable to the fine regulation of output voltage in a small range.

1.3.2 New Technology in the SMPS Field

1.3.2.1 Active Clamp Technology

The function of clamp circuit is to clamp down the peak voltage generated by the SMPS at work time within a certain range in order to protect the power switch tube. The clamp circuits can be divided into passive clamp circuits and active clamp ones. The general R, C, and VDz clamp circuits belong to passive clamp circuits. The advantage of such passive clamp is that it has a simple circuit and can absorb the peak voltage generated by leakage inductance of high-frequency transformers. However, the clamp circuit has larger energy consumption itself, thus reducing the power supply efficiency.

The active clamp circuit invented by VICOR of the United States can significantly reduce power loss of the SMPS. The typical active clamp circuit is shown in Figure 1.3. The active clamp circuit was named for an active power component, MOSFET (V_4), which is used as clamper tube in the circuit. In Figure 1.3, C_c is the clamp capacitor and V_3 is the power switch

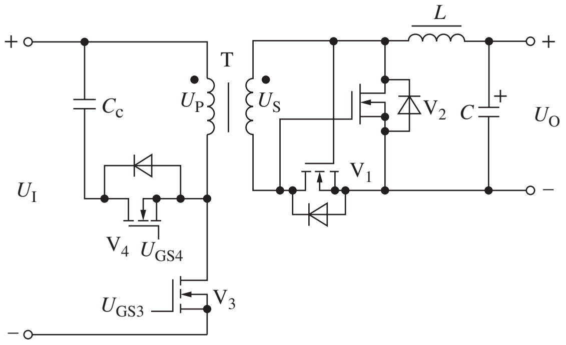


Figure 1.3 Active clamp circuit

tube of SMPS. It can be seen from this figure that U_{GS3} is 0 when V_4 is on, switching V_3 off and U_{GS3} will switch V_3 on when V_4 is off, thus clamping the peak voltage generated by leakage inductance of high-frequency transformers.

1.3.2.2 Synchronous Rectification (SR) Technology

Synchronous rectification (SR) was developed at the end of the twentieth century. It is a new technology of using the special power MOSFET with extremely low on-state resistance instead of rectifier diode to reduce the rectifier loss, which can significantly improve the efficiency of SMPS under low voltage and large current output. SR circuit adopts power MOSFET or Schottky Barrier Diode (SBD) as rectifier tube, requiring that the grid voltage should keep synchronous with the phase of rectified voltage to complete the rectification function. Therefore, it is called SR. For the synchronous rectifier comprising field effect transistor or SBD launched by Onsemi recently, the forward on-state voltage drop generally ranges from 0.2 to 0.4 V and the reverse recovery time is only 100 ns.

1.3.2.3 Soft Switching Technology

The general PWM-type SMPS adopts a "hard switching" technology, with which the voltage or current on VT is not zero when the power switch tube VT is either on or off. Nevertheless, the VT is forced to be on or off when the voltage or current is not zero, thereby increasing the switching loss. The switching loss includes the capacitor loss and the switch overlapping loss of the power switch tube. The capacitor loss, which is also called CU^2f loss, refers to a loss caused by discharging of the distributed capacitance of power switch tube when each switching cycle starts. The switch overlapping loss, caused by the switching time of the power switch tube, increases with the rising of switching frequency, which not only limits the development of high-frequency SMPS, but also easily generates electromagnetic interference.

Soft switching technology shall be introduced to make up the defects of "hard switching" technology. Soft switching refers to zero voltage switching (ZVS) or zero current switching (ZCS). With ZVS and ZCS, the power switch tube can be switched off when voltage and current crossing zero respectively, so as to minimize the switching loss for the purpose of improving the power supply efficiency and protecting the power switch tube.

1.3.2.4 Magnetic Amplifier Regulator Technology

A magnetic amplifier is composed of sampling circuit, reference voltage source, magnetic reset control circuit, controllable magnetic saturation inductor, and PWM. The controllable magnetic saturation inductor acts as a controllable magnetic switch in the voltage regulator circuit, which can accurately regulate the pulse width only by changing the delay time of magnetic reset to achieve accurate voltage regulation. Therefore, the magnetic amplifier is equivalent to an external PWM.

In the positive and negative voltage symmetrical output SMPS, using magnetic amplifier voltage regulator circuit can not only improve the precision of voltage regulation, but also increase the rate of cross loading regulation.

1.3.2.5 New Technologies for Single-Chip SMPS Application

With the increasing popularization of the single-chip SMPS, new technologies are also applied in the circuit design. The following examples are given for illustration.

1. StackFET$^{\mathrm{TM}}$ (stack field effect transistor) technology. The single-chip SMPS is integrated with a power field effect transistor MOSFET with a drain-source electrode breakdown voltage of 700 V. When the maximum AC input voltage $U_{\mathrm{I\,(max)}}$ is 580 V, the maximum primary voltage of high-frequency transformer reaches nearly 1050 V (including primary induced voltage U_{OR}, which is also called secondary reflected voltage), far above 700 V. To avoid any damage to the internal MOSFET, an MOSFET power field effect tube V can be stacked on its drain electrode as external MOSFET. These are the features of the StackFET circuit.
2. Design of industrial control power supply with ultrawide input range. To ensure that TinySwitch-III can work normally under ultralow AC input voltage, a floating high-voltage constant-current source shall be added exteriorly for the purpose of continuously supplying power to bypass end under low voltage. This technology is applicable for designing industrial control power supply with an ultrawide input range of 18–265 V.
3. PFC circuit. To improve the power factor of SMPS and reduce the total harmonic distortion (THD), AC/DC converter shall be provided with a power factor correction (PFC) circuit. Passive “valley fill circuit” (VFC) can be adopted when high-output ripple voltage (such as the driver composing white light LED lamp) is not required. VFC is used to greatly increase the conduction angle of rectifier diode, changing the input current from peak pulse into a wave form approaching sine wave via filling the valley points. The universal high-power SMPS is generally equipped with a new special chip with active PFC to simplify the circuit design.
4. Single-chip high-power SMPS. In recent years, the maximum output power of single-chip half-bridge LLC resonant converter with PFC, single-chip double-switch forward converter and other chips newly developed by chip manufacturers has reached 600–1000 W, creating favorable conditions for development of cheap high-power SMPS of high quality.
5. LED lighting driving power supply. LED lighting, also called semi-conductor lighting or solid state lighting, falls into the category of energy-saving and environment-friendly

“green lighting” characterized by low power consumption, high luminance, vibration resistance, long service life, small overall dimension, quick response, no pollution to environment, and other noticeable advantages. LED driving power supply is a power unit exclusive for power supply to LED lamps. At present, using new technologies and new processes, chip manufacturers have successively developed a batch of application-specific integrated circuit (ASIC) with advanced performance and unique characteristics. These chips have not only retained the advantages of SMPS chips, such as high efficiency and energy saving, but also are featured by constant current output, dimmable function, and PFC.

1.3.2.6 Highly Reliable Modular Design

It is well-known that integration technology cannot integrate the high-capacity capacitor, inductor, rectifier bridge, potentiometer, and high-power components of 10 A and above into a chip. Therefore, to develop an SMPS, a chip should be selected, the peripheral circuit should be designed, and the printed circuit should be designed as well, which brings inconvenience to users. However, the problems mentioned earlier can be readily solved if a power supply block is used.

The power supply block is a commodity component assembling power supply integrated circuit and miniature electronic components (such as pellet resistance and subminiature electrolytic capacitor) by microelectronic technique to complete a certain specific function. With the structural feature that all components are densely installed on a printed board, so the power supply block is also called secondary integration. The power supply blocks are generally divided into two categories by appearance: totally enclosed and non-removable ones and open ones.

Compared with the traditional whole machine, the whole machine composed of power supply block has the following prominent features: the circuit design can be greatly simplified so that the development cycle of new products can be shortened; with advanced technology and process, the qualified rate and reliability of the whole machine can be improved, and the one-time qualified rate is up to 100%; the volume and weight can be reduced; the machine is easy to install and maintain; and the use of totally enclosed power supply block can prevent forging, so as to protect the rights and interests of manufacturers.

At present, the power supply block is also developed to be intelligent. For example, the intelligent power supply block has achieved higher technical indexes (600 A, 600 V, with various protection functions and the failure self-detection and display function). The mean time between failures (MTBF) of single block has reached 10^7 h with the volume of the block gradually reduced. With the development of surface mount device (SMD) and surface mount technology (SMT), the volume of the power supply block will be further reduced while the performance indicators will be significantly improved.

1.3.2.7 Realization of SMPS Optimal Design Using Software

In recent years, with the development of power supply technology and the popularization of computer application, it has become a new technology in the international power supply field to design the SMPS using computer. At present, software has become the key technology for optimal design of the SMPS. The application of software can give full play to the advantages of high technology and greatly reduce the workload of designers, creating favorable conditions for optimal design of the SMPS.

Besides, computer simulation technology has also become a powerful weapon for developing new SMPS products. With the computer simulation technology, the prototype of SMPS can be created, so that the designers can solve potential technical problems when designing the SMPS before making a model machine, which greatly accelerates the research and development of new SMPS.

1.3.2.8 Anti-Electromagnetic Interference Capacity and Safety

With the increasing popularization of SMPS, higher requirements are put forward for its anti-electromagnetic interference capacity and safety, for which corresponding technical standards have been formulated. For example, the standards in relation to anti-electromagnetic interference include EN55022B, FCC Class B, CE Mark, and VCCI. The standards in relation to safety include IEC950, UL1950, CSA950, TUV-GS (EN60 950), and so on. China has implemented “3C” (China Compulsory Certification), the compulsory product certification, which is also called CCC certification concerning safety, since August 1, 2003.

1.4 Basic Principles of SMPS

1.4.1 Working Mode of SMPS

The SMPS has the following four working modes by control principles:

1. PWM: It is characterized by constant value of switching cycle and achieving voltage regulation by changing duty ratio through pulse width modulation with the core of the PWM.
2. PFM: It is characterized by constant value of pulse width and achieving voltage regulation by changing duty ratio through switching frequency modulation with the core of the PFM.
3. Pulse density modulation (PDM): It is characterized by constant value of pulse width and achieving voltage regulation by changing duty ratio through pulse count modulation. It adopts zero voltage technology and can significantly reduce the loss of power switch tube.
4. Hybrid modulation: It combines the modes referred to in points (1) and (2). Both the switching cycle and the pulse width are not fixed and adjustable. It includes PWM and PFM.

The four working modes discussed in the preceding text are collectively called as “time ratio control” (TRC), in which PWM is used most widely.

It should be noted that PWM can not only be used as an independent integrated circuit (such as UC3842 PWM), but also be integrated into a switching regulator (such as L4960 switching regulator integrated circuit) or an SMPS (such as TOP262E single-chip SMPS integrated circuit), in which the switching regulator belongs to the DC–DC converter and the SMPS is generally an AC–DC converter.

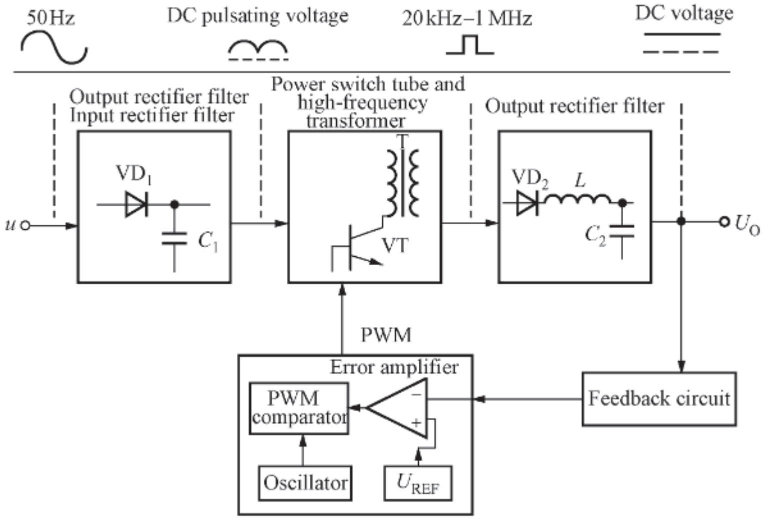


Figure 1.4 Basic composition of the SMPS

1.4.2 Basic Principles of PWM

The circuit of SMPS consisting of five components is relatively complex, which is shown in Figure 1.4. These five components refer to input rectifier filter, including the circuit from AC to input rectifier filter; power switch tube (VT) and high-frequency transformer (T); and control circuit (PWM), including oscillator, reference voltage source (U_{REF}), error amplifier, and PWM comparator. The control circuit can produce PWM signal and its duty ratio is controlled by feedback circuit, output rectifier filter, and feedback circuit. In addition, biasing circuit and protective circuit shall be added. PWM is the core of SMPS.

The operating principle of PWM SMPS is shown in Figure 1.5. u, AC of 220 V, changes into DC voltage U_1 after passing through rectifier filter circuit, then turn into high-frequency square-wave voltage after wave chopping by power switch tube and voltage reduction by high-frequency transformer T, and finally the required DC output voltage V_{o} through rectifier filter. PWM can produce driving signals with fixed frequency and adjustable pulse width to control the on-off state of power switch tube, so as to adjust the output voltage to achieve voltage regulation.

The sawtooth generator is to provide clock signal, and sampling resistance, error amplifier, and PWM comparator form a closed-ring regulating system. Having been taken as sample by R_1 and R_2, the output voltage U_{o} is sent to the inverting input terminal of error amplifier to be compared with the reference voltage U_{REF} on the non-inverting input terminal to get the error voltage U_{r}; then the PWO by PWM comparator is controlled by the amplitude of U_{r} and finally U_{o} can remain unchanged by power amplification and buck output circuit. U_{J} is the output signal of saw-tooth generator.

It should be noted that though the sampling voltage is generally connected to the inverting input terminal of error amplifier, it may also be connected to the non-inverting input terminal, which is related to the polarity of saw-tooth voltage input at the other end of the error amplifier. Generally, the sampling voltage is connected to the inverting input terminal when the input

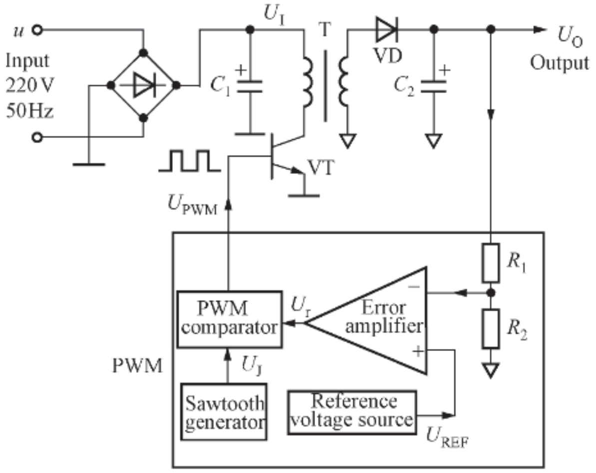


Figure 1.5 Operating principle of PWM SMPS

saw-tooth voltage is of positive polarity and to the non-inverting input terminal when the input saw-tooth voltage is of negative polarity (the same follows).

Given that DC input voltage is U_{I}, the efficiency of switching regulator is η and the duty ratio is D, then the impulse amplitude of power switch tube is $U_{\mathrm{P}} = \boxtimes U_{\mathrm{I}}$. The following formula can be worked out:

$$U_{\mathrm{o}} = \eta D U_{\mathrm{I}} \tag{1.1}$$

This indicates that when η and U_{I} are constant, U_{o} can be modulated automatically only by changing the duty ratio. When U_{o} increases because of some reason, $U_{\mathrm{r}} \downarrow\rightarrow D \downarrow\rightarrow U_{\mathrm{O}} \downarrow$ and when U_{o} decreases, $U_{\mathrm{r}} \uparrow\rightarrow D \uparrow\rightarrow U_{\mathrm{O}} \uparrow$

This is the principle of automatic voltage regulation. The wave form of automatic voltage regulation process is shown in Figure 1.6(a) and (b), in which U_{J} refers to the output voltage of sawtooth generator, U_{r} is the error voltage, and U_{PWM} is the output voltage of PWM comparator. It can be seen that when U_{o} decreases, $U_{\mathrm{r}} \uparrow\rightarrow D \uparrow\rightarrow U_{\mathrm{O}} \uparrow$ and when U_{o} increases for some reason, $U_{\mathrm{r}} \downarrow\rightarrow D \downarrow\rightarrow U_{\mathrm{O}} \downarrow$.

1.4.3 Classification of PWM Products

SMPS usually adopts PWM. There are hundreds of PWM integrated circuits. The classification of typical products is shown in Table 1.3. It should be noted that PWM can be divided into doubled-ended output and single-ended output. The former is of push-pull output type that can be used in high-power SMPS from hundreds to thousands of Watt, and the latter, with a simple peripheral circuit, that can be used to make SMPS with medium and low power ranging from dozens to hundreds of wattage. The higher the switching frequency is, the higher the frequency of SMPS is and the smaller its volume is. Generally, the SMPS with switching frequency up to 1MHz is called high-speed SMPS. The products whose models are listed with slashes in Table 1.3 are series products. Take UC1840/2840/3840 for example. The internal circuits and main performance indicators of these products are the same and they only vary in the range of

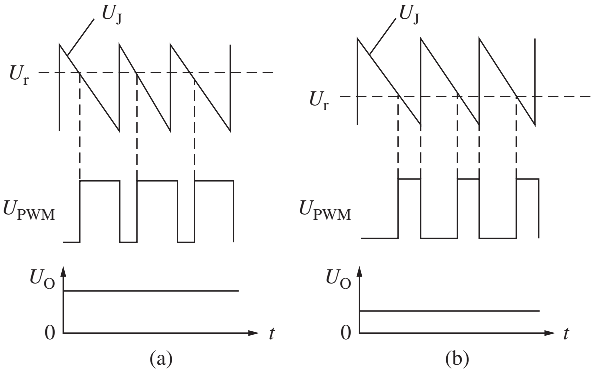


Figure 1.6 Oscillogram of automatic voltage regulation process. (a) The output voltage increases along with the rising of error voltage. (b) The output voltage decreases along with the dropping of error voltage

operating temperature. They respectively fall into Class I Military (−55 to +125 °C), Class II Industrial (−40 to +85 °C), and Class III Civil (0 to +70 °C).

1.5 Control Mode Type of SMPS

SMPS has two types of control modes namely voltage mode control (VMC) and current mode control (CMC) with respective pros and cons. It is hard to say which one is optimal to all applications and they shall be chosen according to actual conditions.

1.5.1 VMC-Type SMPS

VMC is the most common control mode of switching power supply. Take step-down switching regulator (or buck converter), for example. The basic principles and working waveforms of VMC-type buck converters are illustrated respectively in Figure 1.7(a) and (b). The characteristics of VMC-type SMPS are as follows: Firstly, the output voltage is sampled (a sampling resistance divider can be added if necessary), and the sampling voltage U_Q then acts as the input signal of control loop. After that, the sampling voltage U_Q will be compared with the reference voltage U_{REF}, and the comparison result is amplified into the error voltage U_r, which finally is sent to PWM comparator for comparison with sawtooth wave voltage U_J so as to obtain the modulating signal whose pulse width is directly proportional to the error voltage. The oscillator in Figure 1.7 has two channels for output signals: clock signal (in square wave or rectangular wave) and sawtooth signal. C_T refers to the timing capacitor of sawtooth oscillator, T refers to high-frequency transformer, and VT refers to power switch tube. The buck output circuit is composed of rectifier tube VD_1, freewheel diode VD_2, power inductor L, and filter capacitor C_o. R in PWM latch is the reset terminal, S is the set terminal, and Q is the output end of the latch. See Figure 1.7(b) for the output waveform.

The pros of VMC-type SMPS are as follows:

Table 1.3 Classification of typical PWM products

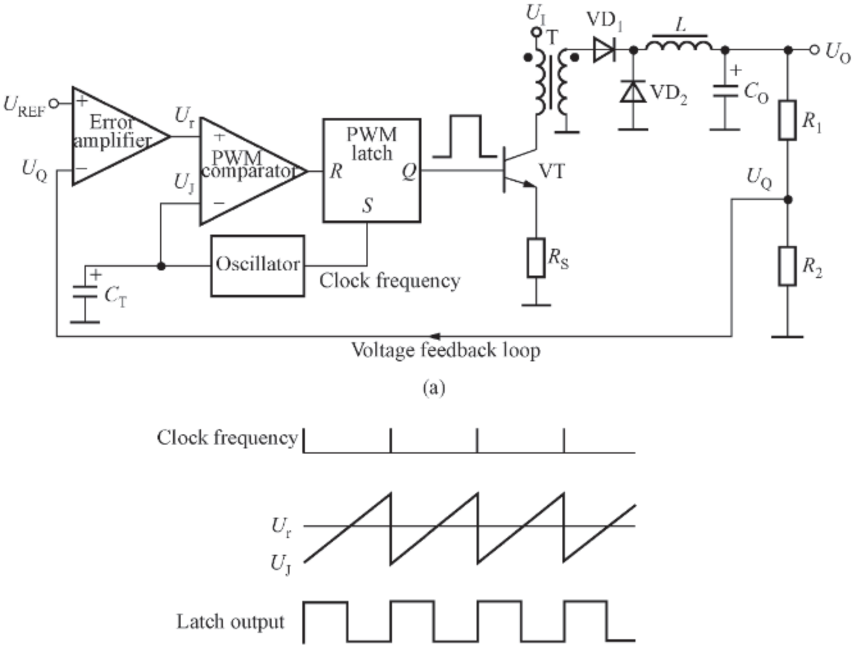
Features	Foreign model	Maximum switching frequency f_{max} (Hz)	Maximum output peak current I_{PM} (A)	Domestic model	Assembling form
Double-ended output, medium speed	MC3520 UC3520	100k	0.1×2	CW3520	DIP-16
	SG3525A	500k	0.4×2	CW3525A	DIP-16
	TL494 UC494A	300k	0.2×2	CW494	DIP-16
Single-ended output, medium speed	UC1840/2840/3840	500k	0.4	CW1840/ 2840/3840	DIP-18
	UC1842/2842/3842	500k	1	CW1842/2842/3842	DIP-8
	UC1841/2841/3841	500k	1		DIP-18
	TEA2018	500k	0.5	CW2018	DIP-8
	μPC1094	500k	1.2		DIP-14
Single-ended output, high speed	UC1823/2823/3823	1M	1.5		DIP-16
	UC1825/2825/3825	1M	1.5		DIP-16
	UC1848/2848/3848	1M	2		DIP-16

UC is developed by Unitrode, which has been incorporated into TI. SG and TL are products of TI, and TEA is a product of ST.

1. It is a closed-loop control system with only one voltage feedback loop (or voltage control loop) and simple circuit design.
2. It can work stably in the process of modulation.
3. With low output impedance, it allows power to be supplied through multiple channels to a load.

The cons of VMC-type SMPS are as follows:

1. Laggard response. Although the current sense resistor R_S is used in the VMC-type circuit, R_S is not connected to the control loop. As a result, when the input voltage changes, the pulse width can be modulated only after the output voltage changes as well. Owing to lag time in the filter circuit, the changes of output voltage can only be seen after multiple cycles. Therefore, the response time of VMC-type SMPS is laggard, which by some degree affects the stability of output voltage.
2. An overcurrent protection circuit shall be additionally designed.
3. Phase compensation of the control loop is quite complex, and closed loop gain will change with input voltage.



(a)

(b)

Figure 1.7 (a) Basic principles and (b) working waveforms of VMC-type SMPS

1.5.2 CMC-Type SMPS

CMC-type SMPS contains not only a voltage control loop but also a current control loop. Its basic principles and working waveforms are shown in Figure 1.8(a) and (b). The voltage drop of current sense resistor U_S, and PWM comparator also serves as a current sense comparator.

CMC-type SMPS detects the switching current in the power switch tube by sense resistor and limits the current cyclically, which helps to realize overcurrent protection. Fixed-frequency clock pulse will set PWM latch, driving signals output from Q are high-level signals that will make power switch tube VT-conductive and the primary side current of the high-frequency transformer increase linearly. When the voltage drop on current sense resistor R_s reaches and exceeds U_r, the current sense comparator will turn over, and the output high-level signals will set the latch, turning signals output from Q into low-level ones, which will cut off the power switch tube until the next clock pulse has the PWM latch set.

The pros of CMC-type SMPS are as follows:

1. It is a double closed-loop control system, of which the external loop is composed of voltage feedback circuits while the internal loop is composed of current feedback circuits, which are under the control of voltage feedback circuits. Compared with voltage feedback circuits, the gain bandwidth of current feedback circuits is larger.
2. It can respond to transient changes of input voltage quickly. This means when the input voltage changes, it can rapidly adjust the output voltage to the stable value, because changes of input voltage will lead to changes of the primary side inductive current, which in turn,

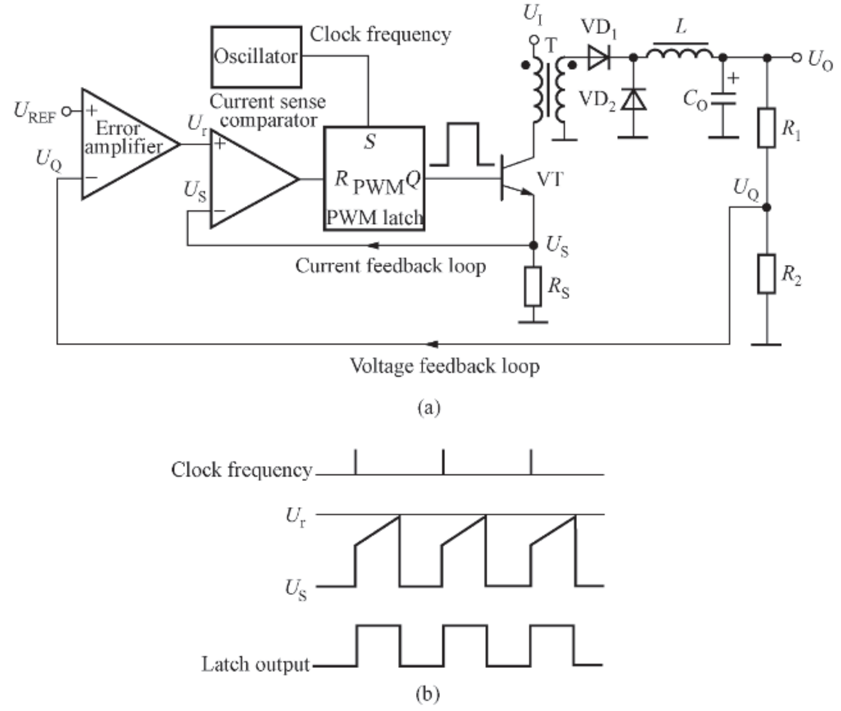


Figure 1.8 (a) Basic principles and (b) working waveforms of CMC-type SMPS

results in changes of U_s. This means that it can change the output pulse's duty ratio directly through the current sense comparator rather than the error amplifier.
3. The joint control of voltage control loop and current control loop may increase the voltage regulation factor.
4. It can simplify the design of error amplifier compensating network.
5. PWM comparator will cut off the power switch tube and maintain output voltage stable as long as the current pulse reaches the set threshold.
6. It is equipped with a limiting current protection circuit. Therefore, the limiting current threshold can be set precisely and simply by changing the value of R_s.

The cons of CMC-type SMPS are as follows:

1. Two control loops make it difficult to design and analyze circuits.
2. A duty ratio of over 50% may lead to instability of the control loops, in which case, a slope compensation circuit needs to be added.
3. It has a poor ability to restrain noises. As the primary side inductor works in the continuous energy storage mode, the rising slope of switching current signal is small. A relatively low noise overlaid to the current signal is likely to cause false operation of the PWM controller, for which a noise suppression circuit will be required.

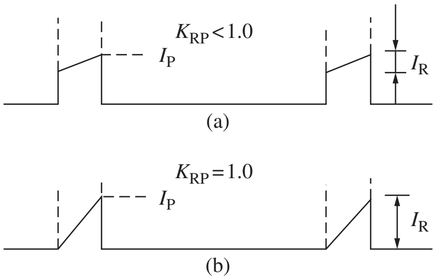


Figure 1.9 Waveforms of switching currents: (a) CUM and (b) DUM

1.6 Working Mode of SMPS

SMPS has two basic working modes: continuous mode (CUM) and discontinuous mode (DUM). Next, taking the single-chip SMPS of TOPSwitch series for example, we introduce the setting methods of the two working modes and then make comparison on power losses under these two working modes so as to derive the conclusion.

1.6.1 Setting Methods of CUM and DUM

1.6.1.1 Characteristics of CUM and DUM

In CUM, the high-frequency transformer starts to work from a non-zero energy storage state in every switching cycle, while in DUM, all energy stored in the high-frequency transformer should be released. Their difference can be seen in Figure 1.9. The switching current in CUM starts from a certain level, goes up to the peak along the slope, and then back to zero rapidly. At this time, the scale factor K_{RP} between primary winding pulse current I_R and peak current I_P is less than 1.0, or

$$I_R = K_{RP} I_P < I_P \tag{1.2}$$

The switching current in DUM starts from zero, goes up to the peak, and then back to zero rapidly. At this time,

$$K_{RP} = 1.0,$$

or

$$I_R = I_P \tag{1.3}$$

1.6.1.2 Working Mode Setting

Using the proportional relationship between I_R and I_P (or the value of K_{RP}), the working modes of SMPS can be quantitatively described. The value range of K_{RP} is 0–0.1. When $I_R = I_P$ and $K_{RP} = 1.0$, the SMPS is set in DUM. When $I_R < I_P$ or $K_{RP} < 1.0$, the SMPS is set in DUM. To be specific, there are two situations: (i) when $0 < I_R < I_P$, or $0 < K_{RP} < 1.0$, it is in CUM; and (ii) ideally, when $I_R = 0$ and $K_{RP} = 0$, it is in absolute CUM, which also can be called extreme CUM. Then the primary winding inductance $L_{p \to}\infty$, and the switching current on primary side appears as a rectangular wave.

As a matter of fact, there is a transition instead of a strict boundary between absolute CUM and DUM. For a given AC input range, a smaller K_{RP} value means a more continuous working mode, larger primary winding inductance, and smaller primary side I_P value and I_{RMS} value. At this time, a lower power TOPSwitch and a larger high-frequency transformer can be used to optimize the design. Otherwise, a larger K_{RP} value means poor continuity and smaller primary winding inductance but relatively larger I_P and primary side RMS current I_{RMS}. At this time, a large power TOPSwitch and a small high-frequency transformer shall be used.

In conclusion, the working mode of SMPS can be set by selection of K_{RP} value. The setting process is $L_p \uparrow \to \quad (I_R < I_P) \to (K_{RP} < 1.0) \to$ CUM.

$K_{RP} = 0.4$–1.0 is the best for 100 V/115 V AC power supplies. $K_{RP} = 0.6-1.0$ is preferred for 85–265 V wide-range input or 230 V fixed-input AC power supplies.

1.6.2 Power Consumption Comparison between These Two Working Modes

The following two design cases can illustrate the changes in values of I_P and I_{RMS} corresponding to $K_{RP} = 1.0$ (DUM) and $K_{RP} = 0.4$(CUM) in the wide range input of 85–265 V so that comparison can be made on TOPSwitch power consumptions under these two modes.

1.6.2.1 DUM Design Case

The given working parameters are $K_{RP} = 1.0$, $U_{Imin} = 90\,V$, $D_{max} = 60\%$, $P_O = 30$ W, power efficiency $\eta = 80\%$ and that the primary winding peak current I_P can be expressed either as the function of I_R and K_{RP} or the function of the basic parameters (output power P_O, minimum DC input voltage U_{Imin}, maximum duty ratio D_{max}, and power efficiency η) and I_R; the equations are as follows:

$$I_P = I_R / K_{RP} \tag{1.4}$$

$$I_P = \frac{P_O}{U_{Imin} D_{max}} + \frac{I_R}{2} \tag{1.5}$$

Convert Equation (1.4) to $I_R = K_{RP} I_P$, and put it into Equation (1.5), to calculate the value of I_P:

$$I_P = \frac{2P_O}{U_{Imin} D_{max} \eta (2 - k_{RP})} \tag{1.6}$$

The final RMS current I_{RMS} of primary winding is

$$I_{RMS} = I_P \sqrt{D_{max}\left(\frac{K_{RP}^2}{3} - K_{RP} + 1\right)} \tag{1.7}$$

Put $U_{Imin} = 90V$, $D_{max} = 60\%$, $\eta = 80\%$, $P_O = 30W$, and $K_{RP} = 1.0$ into Equation (1.6) and we will obtain $I_p = 1.39$ A. Put the result into Equation (1.7) to obtain $I_{RMS} = 1.39 \sqrt{0.6 \times \left(\frac{1}{3} - 1 + 1\right)} = 0.62$ (A)

1.6.2.2 CUM Design Case

The given working parameters are $K_{\mathrm{RP}} = 0.4$, $U_{\mathrm{Imin}} = 90\mathrm{V}$, $D_{\max} = 60\%$, $P_{\mathrm{O}} = 30\mathrm{W}$, $\eta = 80\%$. Different from the first case, K_{RP} here is 0.4, which indicates that the working mode is more continuous. Similarly, it can be worked out that $I'_{\mathrm{P}} = 0.87$ A and $I'_{\mathrm{RMS}} = 0.54\,\mathrm{A}$.

It is easy to work out that the peak current in CUM is only 63% of that in DUM, whereas the RMS current in CUM is 87% of that in DUM. Therefore, for the given TOPSwitch chip, the power consumption ratio of the two working modes is

$$\frac{P'_{\mathrm{O}}}{P_{\mathrm{O}}} = \frac{(I'_{\mathrm{RMS}})^2 R_{\mathrm{L}}}{(I_{\mathrm{RMS}})^2 R_{\mathrm{L}}} = (87\%)^2 = 75.7\%$$

This indicates that, 24.3% of power consumption can be reduced in CUM than in DUM. In other words, under the same output power, CUM allows the use of low-power TOPSwitch, or allows TOPSwitch to work with low power consumption. Besides, when an SMPS is designed in CUM, the AC component on primary side circuit is lower than that of DUM. In addition, it can reduce the skin effect and the power consumption of high-frequency transformers.

1.7 Feedback Type of SMPS

1.7.1 Basic Types of SMPS Feedback Circuit

Consider the Single-Chip SMPS of TOPSwitch series, for example. The SMPS feedback circuits can be grouped into four basic types: (i) basic feedback circuit; (ii) improved basic feedback circuit; (iii) optical coupling feedback circuit with a voltage-regulator tube; and (iv) optical coupling feedback circuit with TL431, whose simplified circuit diagrams are illustrated in Figure 1.10(a)–(d).

Figure 1.10(a) shows a basic feedback circuit. Its advantages include simple circuit, low cost, and applicability to small-scale and economic SMPS and disadvantages include poor voltage regulation performance, voltage regulation $S_{\mathrm{V}} = \pm 1.5\%$ to $\pm 2.5\%$, and load regulation $S_{\mathrm{I}\approx} \pm 5\%$.

Figure 1.10(b) shows an improved feedback circuit. Equipped with a voltage-regulator tube $\mathrm{VD}_{\mathrm{Z2}}$ and a resistance R_1 additionally, the load regulation can reach ±2.5%. The stable voltage of $\mathrm{VD}_{\mathrm{Z2}}$ is 22 V generally. The number of turns of the bias winding shall be increased correspondingly for a comparatively higher bias voltage U_{B} to satisfy the requirement of circuit.

Figure 1.10(c) shows an optical coupling feedback circuit with a voltage-regulator tube. The reference voltage U_{Z} is provided by $\mathrm{VD}_{\mathrm{Z2}}$. LED inside the optical coupler may get an error voltage when the output voltage U_{O} fluctuates. Therefore, this circuit is equivalent to adding an external error amplifier to TOPSwitch. U_{O}, which can be regulated using both external and internal error amplifiers. This kind of feedback circuit can make the voltage regulation factor lower below ±1%.

Figure 1.10(d) shows an optical coupling feedback circuit with TL431 with a relatively complicated circuit but the best voltage regulation performance. Here an adjustable precision shunt regulator of TL431 type instead of a common regulator is used to form the external error amplifier so that the precision adjustment to U_{O} can be realized, and the voltage regulation factor and load regulation factor of single-output SMPS can reach ±0.2% and ±0.5% respectively, which can be compared with the linear regulated power supply. This kind of feedback circuit is suitable to constitute a precision SMPS.

In the design of single-chip SMPS, a proper feedback circuit shall be chosen according to actual conditions so that the specified technical indicators can be reached.

1.7.2 Feedback Principle of the Single-Chip SMPS

Taking the basic feedback circuit of TOPSwitch for example, an in-depth analysis is carried out on the feedback principles of CUM and DUM. It should noted that such feedback principle analysis only discusses the interaction between the primary winding and the output circuit, which is different from that of the control circuit constituted by the bias winding and the external circuit. The control circuit is especially used to adjust the duty ratio. Therefore, the discussion in the following text does not relate to the bias winding.

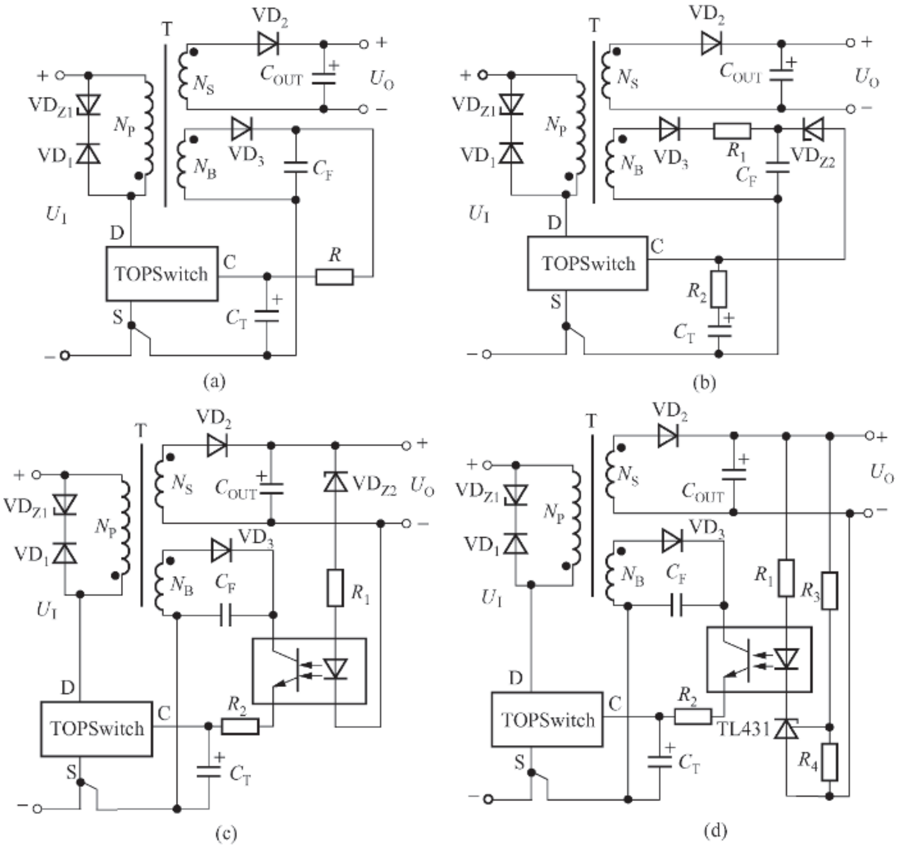


Figure 1.10 Four basic types of feedback circuit: (a) basic feedback circuit; (b) improved basic feedback circuit; (c) optical coupling feedback circuit with a voltage-regulator tube; and (d) optical coupling feedback circuit with TL431

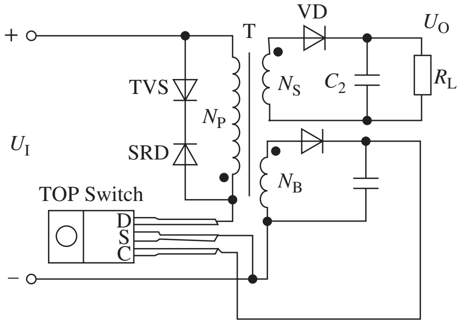


Figure 1.11 Basic feedback circuit of TOPSwitch

1.7.2.1 Basic Feedback Process

Single-chip SMPS of TopSwitch series can be regarded as a single-chip combinational device, which combines the MOSFET and all the needed analog and digital circuits, to perform output insulation, PWM, and various protection functions. The basic feedback circuit of TOPSwitch is shown in Figure 1.11. Being moderately adjusted, the circuit will realize single or multiple output, boost or buck output, and positive or negative voltage output.

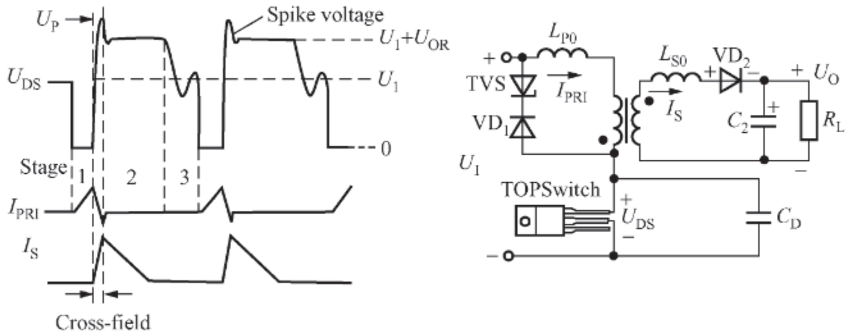
In the basic feedback circuit of TOPSwitch, the high-frequency transformer has three major functions of energy storage, output insulation, and voltage regulation. In Figure 1.11 N_P, N_S, and N_B represent primary winding, secondary winding, and bias winding, and respective number of windings. A transient voltage suppressor (TVS) and a super fast recovery diode (SRD) form a drain electrode clamp protection circuit that can absorb the peak voltage generated by the leakage inductance of the primary winding, keeping the drain voltage of MOSFET in a safe range. VD is the output rectifier tube; C_2, the output filter capacitor; RL, the load resistance; and U_O, the output voltage. AC input circuit and the rectifier filter circuit are omitted in Figure 1.11. AC passes through the rectifier bridge and the filter capacitor to produce DC input high voltage U_I when TOPSwitch is on; VD is in off-state, and the primary side current rises along a ramp. The formula is

$$I_{PRI} = I_I + \frac{(U_I - U_{DS(ON)})t_{ON}}{L_P} \tag{1.8}$$

In this formula, I_{PRI} is the primary current containing the peak current I_P and the ripple current I_R; I_I, the initial value of the primary current; $U_{DS\,(ON)}$, the drain-source on-state voltage of MOSFET; t_{ON}, the conducting time; and L_P, the inductance value of the primary winding.

Owing to the off-state of VD, the primary side is insulated from the output load. Therefore, the electric energy originally stored on C_2 is supplied to the load, with the output voltage unchanged. At this moment, the electric energy is stored in the high-frequency transformer in the form of magnetic energy.

During the off-state of TOPSwitch, the magnetic flux in the high-frequency transformer starts to decrease and the polarity of the induced voltage of the secondary winding changes, making the VD connected because of forward bias. As a result, the energy stored in the high-frequency transformer is transferred to the output circuit to power up R_L, and to recharge C_2. The secondary current starts to attenuate from the initial value according to the following



(a) (b)

Figure 1.12 Feedback principle of the discontinuous conduction mode in actual situations. (a) Working waveform; and (b) circuit principle

formula:

$$I_{\mathrm{S}} = \frac{I_{\mathrm{P}N\mathrm{P}}}{N_{\mathrm{S}}} - \frac{(U_{\mathrm{O}} + U_{\mathrm{F1}})t_{\mathrm{OFF}}}{L_{\mathrm{P}}} \cdot \frac{N_{\mathrm{P}}}{N_{\mathrm{S}}} \geq 0 \tag{1.9}$$

In this formula, I_S is the secondary current; $I_P N_P/N_S$, the initial value of the secondary current; I_P, the peak value before the conduction of TOPSwitch ends; U_{F1}, the forward voltage drop of the output rectifier tube VD; and t_{OFF}, the time period when TOPSwitch is off. During the off-state of TOPSwitch, the output current is provided by C_2 if the secondary current I_S wanes to zero.

TOPSwitch has two working modes, which is decided by the final value of I_S. If I_S wanes to zero during the off-state, the TOPSwitch is working in the DM. Otherwise, it is working in the CM.

1.7.2.2 Feedback Principles of the Two Working Modes in Actual Situations

Ideally, the influence of parasitic elements (including distributed capacitance and leakage inductance) in the feedback circuit can be ignored. However, in actual situations, the impact of distributed capacitance and leakage inductance should be considered; therefore, there exist spike voltage and spike current in the working waveform.

Feedback Principle of the Discontinuous Conduction Mode in Actual Situations

Working waveform and simplified circuit principle of the discontinuous conduction mode in actual situations are illustrated in Figure 1.12(a) and (b) respectively. Figure 1.12(b) indicates that in the discontinuous conduction mode, the period of each switch consists of three stages. In addition, there are three parasitic elements in this actual circuit, namely leakage inductance of the primary winding L_{PO}; leakage inductance of the secondary winding L_{SO}; and distributed capacitance C_D, which is the sum of output capacitance C_{OSS} of TOPSwitch; and distributed capacitance C_{XT} of the primary winding of the high-frequency transformer, or $C_D = C_{OSS} + C_{XT}$. Here we discuss exclusively about the impact of those parasitic elements in the circuit.

In stage 1, C_D would discharge as long as TOPSwitch is conducted. Energy E_D stored on C_D at the end of the previous cycle would be unleashed at the initial stage. As E_D is in direct proportion to $U^2{}_{CD}$, the power efficiency would be significantly declined when C_D has a big volume, and it is even more true when U_I is rather high. It should be noted that because the high-frequency transformer at stage 1 is gathering energy and the current of the secondary winding is zero, the impact of leakage inductance can be ignored.

In stage 2, TOPSwitch is turned off. At the previous stage, energy stored in the high-frequency transformer is transmitted to the secondary winding. At this moment, both leakage inductance L_{PO} and L_{SO} are preventing the current from changing. To be specific, L_{PO} is preventing the primary current I_{PRI} from decreasing, while L_{SO} is preventing the secondary current I_S from increasing. Therefore, a cross-field is formed when I_{PRI} decreases and I_S increases. Finally, I_{PRI} reduces to zero along the diagonal, determined by the leakage inductance L_{PO} and the primary voltage; and I_S climbs to the peak value I_{SP} along the diagonal, determined by the leakage L_{SO} and the secondary voltage. The most important issue is that the primary current in the cross-field must be continued without interruption. The attenuated primary current would charge C_D to U_P when it flows through C_D. The peak voltage U_P generated by leakage inductance L_{PO} would overlay on the waveform of U_{DS}, forming a peak voltage of leakage inductance, which is also called drain-source peak value pulses. The relation is shown herewith:

$$U_{DS} \approx U_I + U_{OR} + U_P \tag{1.10}$$

The actual circuit, drain clamp is usually adopted to protect the circuit, so it is feasible to clamp U_{DS} down below the rated leakage-source breakdown voltage (700 V in general) of TOPSwitch to prevent the chip from damage resulting from increase of U_{DS} caused by U_P.

In stage 3, induced voltage U_{OR} (also called secondary reflected voltage) wanes to zero. Then the high-frequency transformer unleashes all the energy stored at stage 1, reducing the leakage-source voltage from $U_{DS} = U_I + U_{OR}$ at the end of stage 2 to $U_{DS} \approx U_I$. However, this voltage change generates damped oscillation wave that was overlaid on waveform U_{DS} by stimulating the resonance circuit constituted by stray capacitance and the primary inductance, and does not stop oscillating until the TOPSwitch is on power again. Therefore, there are valleys and peaks in waveform U_{DS} at stage 3. Obviously, this damped oscillation wave “modulate” the voltage and energy on C_D and determines the power consumption of transformation in the next cycle of switch.

Feedback Principle of the Continuous Conduction Mode in Actual Situations

There exist the same parasitic elements as those in discontinuous conduction mode in the feedback circuit of continuous current mode in actual situations. Besides, the actual characteristics of the output circuit shall be taken into consideration as well. An ideal rectifier tube needs no time for forward voltage drop and reverse recovery. Time is needed for reverse recovery of junction rectifier tube because there are a few charge carriers passing through the nodes of diode, while that of Schottky diode is brought about by junction capacitance. For single-chip SMPS, Schottky diode that requires a very short time for reserve recovery or super fast recovery diode is recommended to be the output rectifier. Nevertheless, no ordinary low-speed rectifier should be used, for it would not only increase the high-frequency energy consumption or decrease the energy efficiency, but also cause the thermal breakdown of the rectifier.

Working waveform of the continuous conduction mode in actual situations is shown in Figure 1.13. At stage 1, there is still current running at the secondary side when TOPSwitch starts conducting, which means at the moment of power supply the equation $U_{DS} = U_I + U_{OR}$

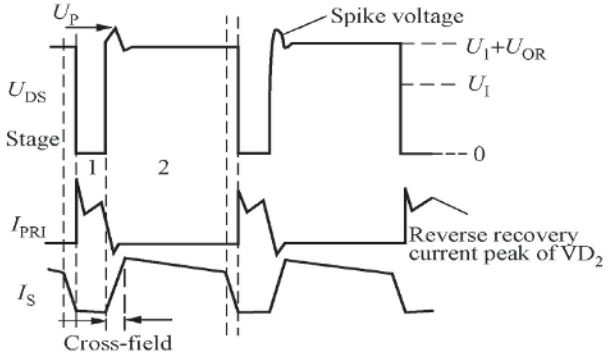


Figure 1.13 Working waveform of the continuous conduction mode in actual situations

rather than $U_{DS} = 0$ makes sense. It turns out that power consumption of TOPSwitch in continuous conduction is higher than that of discontinuous conduction. That's because there is extra energy on distributed capacitance C_D. In addition, it is necessary to charge secondary leakage inductance L_{SO} before turning off the secondary winding output, which generates cross-over current when I_S increases and I_{PRI} wanes. Once L_{SO} is fully charged, the output rectifier would be cut off by a reverse bias and the secondary current I_S would change into zero. Meanwhile, change of I_S would be inducted to the primary winding and form a reverse recovery current peak (spike current) at the leading edge of the primary side current waveform. This spike current leads to a sudden increase of the primary current, which is very likely to cause malfunction of the internal overcurrent protection for the circuit. Therefore, a leading-edge blanking circuit is especially designed in the TOPSwitch, with the purpose of preventing false triggering caused by spike current through blocking the leading edge output by the overcurrent comparator for 180 ns when TOPSwitch is initially conducted.

There is no stage 3 but only stage 2 when TOPSwitch is off. At the moment of turning off TOPSwitch, under the impact of leakage inductance L_{PO} and L_{SO}, the primary current and the secondary current would also form a cross-field, driving U_{DS} up to $(U_I + U_{OR})$. What differs from the discontinuous conduction mode is that induced voltage U_{OR} would exist till the next conduction of TOPSwitch. Therefore, there is no time interval (or stage 3) after U_{OR} decreases to zero.

1.8 Load Characteristics of SMPS

The SMPS supplies power to various loads and each load has its own characteristics. The load characteristics of SMPS can reflect the relation between the output voltage and the load. From a design perspective, there exists a "provide-demand" relationship between the SMPS and the load. On one hand, the SMPS provides stable voltage (or current or power) to the load. On the other hand, the load raises special requirements on the SMPS. Therefore, in order to design a matching SMPS for a load, the designer must know the characteristics of different loads.

Loads of the SMPS generally can be divided into two categories: constant load (also called static load or permanent load) and dynamic load (also named variable load). There are a variety of dynamic loads, such as transient load, constant current load, constant power load, peak power load, inertia load, and low noise load. For dynamic loads, the SMPS shall have the current-limiting protection or current cut-off protection function.

1.8.1 Constant Load

Constant load, usually pure resistor load, is featured by little load current change and can be matched with common SMPSs. This kind of load is ideal but not commonplace in reality.

1.8.2 Transient Load

Transient load is also called high di/dt dynamic load. It is characterized by frequent and transient load current changes and high load current change *t* rate (d*i*/d*t*). For instance, the current change rate of high speed logic circuit and radio frequency/microwave transmitter may exceed 100 A/ps. The low-voltage microprocessor lately developed will have an impact on the power supply when switching among different operating modes rapidly, making the supply current vary by several orders of magnitude within nanoseconds. For another example, the power supply voltage of many computers is $+3.3\,\mathrm{V}$. When loading data from the database, the power supply shall be able to respond to load current jump of $30\,\mathrm{A}/\mu\mathrm{s}$. Suppose that it takes $1\,\mu\mathrm{s}$ for the load current to change from zero to 5 A, it takes $1/25\,\mathrm{kHz} = 40\,\mu\mathrm{s}$ to complete the change if the bandwidth of SMPS is 25 kHz. Suppose the current rises linearly, the missing quantity of electric charge is $(5\mathrm{A}/2) \times 40\,\mu\mathrm{s} = 100\,\mu\mathrm{C}$. If a fluctuation of $50\,\mathrm{mV}$ of $+3.3\,\mathrm{V}$ voltage is allowed, and the instant energy is provided by the output filter capacitor, then a capacitance of $100\,\mu\mathrm{C}/50\,\mathrm{mV} = 2000\,\mu\mathrm{F}$ is needed to prevent the voltage from dropping below the setting value. It should be noted that rather than using a nominal capacitor, several low capacitance capacitors shall be paralleled with a total capacitance of $2200\,\mu\mathrm{F}$. As the total equivalent series resistance of each output filter capacitor is $\mathrm{RESR} = 50\,\mathrm{mA}/5\,\mathrm{A} = 10\,\mathrm{m}\Omega$, the equivalent series resistance of each filter capacitor of low capacitance is $\mathrm{R}'ESR = 10\,\mathrm{m}\Omega \times n$, where n represents the number of paralleled capacitors. When $n = 4$, $\mathrm{R}'ESR = 40\,\mathrm{m}\Omega$, which may greatly lower the requirement on the output filter capacitor.

Some DC/DC converters adopt broadband and high speed amplifiers so that the switching frequency can reach 2 MHz and the bandwidth 100 kHz, which provides favorable conditions for further improving the transient response of the SMPS and making the power supply smaller.

In order to improve the transient response, AVX tantalum capacitors are recommended as the output capacitor for many new switching regulators. In these capacitors, Tantalum acts as the positive electrode while dilute sulfuric acid as the negative electrode and the oxidation film on the surface of tantalum as the dielectric. It boasts of high insulation resistance, wide-range frequency response, extremely low leakage current, low temperature drift (with the operating temperature ranging from -55 to $+125\,^{\circ}\mathrm{C}$), small volume, high capacity, stable performance, and long service life. It can be widely used in such high-end technology realms as military, computer, mobile phone, and power controller.

1.8.3 Constant Current Load

Constant current load needs to be provided with constant current. Battery chargers, resistance strain gauge bridges, and constant current transistors are all constant current loads. Common constant voltage/current SMPSs consist of two control loops namely current control loop and voltage control loop. Under normal conditions, the voltage loop works and the SMPS operates in the constant voltage area, and when the output current reaches the limit value, the SMPS enters the constant current area, then the current loop works and the output current remains constant.

1.8.4 Constant Power Load

When the output voltage U_o wanes, the constant power load will increase the output current I_O with the constant power control circuit and vice versa, so as to keep the product I_oU_o of the Uo and Io unchanged and the load power P_L constant. This kind of SMPS can be used to charge battery of laptops as a high-performance, quick, and safe battery charger. The specific property of constant output power is almost a hyperbolic line. When designing the constant-power SMPS, a suitable SMPS integrated circuit shall be chosen based on the maximum load current under the minimum operating voltage so as to ensure enough current for the load even when the voltage is low.

1.8.5 Peak Power Load

For some electronic products, the load needs to be provided with the peak power within a short time, while the output power is required to decrease significantly in non-operating time. It is hard for a common SMPS to meet the requirements mentioned earlier. Such products as ink-jet printers, audio power amplifiers, digital video recorders (DVR), the power supply of data storage device, and direct current motor drives all fall into these electronic products. This kind of SMPS shall be featured by "the maximum peak output/continuous output power ratio" ($P_{OM(pk)}/P_{OM}$). The Peak Switch series and the Tiny Switch-PK series SMPS-integrated circuits lately developed by PI in the US boast excellent peak-power output property.

1.8.6 Inertia Load

Some devices (such as disc drives, fan motors, and motion control systems) need large current in the instant of powering on. If the starting current exceeds the set current value of the SMPS, the output power of the power supply will decrease. As a result, the load takes more time to accelerate or even fails to start. This kind of load is called inertia load, which has similarities with peak power load. The difference between these two loads is that the power of inertia loads only peaks at the starting point, while that of the peak power loads peaks during operation. To meet the requirement of inertia loads, an SMPS with relatively high output power may be chosen to ensure enough extra power.

1.8.7 Low Noise Load

Communication devices such as mobile phones, global positioning systems (GPS), and satellite navigation systems have strict restrictions on power supply noise and radio-frequency interference (RFI) for the noise of the SMPS directly influences the output of the radio frequency power amplifier. A variety of measures can be considered to reduce the noise. On one hand, the device itself shall adopt the circuit of low-noise amplifier; on the other hand, measures such as “frequency jitter” and lowering the switching frequency can be adopted for the SMPS. For example, we can adjust the switching frequency jitter at 250 times per second and the offset $\Delta f = 4\,\text{kHz}$. As the switching frequency changes within a narrow range and is independent of the higher harmonic interference of the central frequency, the noise can be lowered by frequency jittering signals. Some SMPS chips with half-frequency operating modes can reduce the video frequency interference of the SMPS when used as the standby power supply in televisions, DVDs, and video recorder cameras. Besides, hybrid regulated power supplies can be made with switching voltage regulators and low dropout linear regulators to reduce output ripple and noise.