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DC Power Supplies - Fundamental Concepts

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DC POWER SUPPLIES: FUNDAMENTAL CONCEPTS

By: Edwin Carrell, PE

Scope of Course

This course describes the functions, basic components, circuit configurations, and performance characteristics of typical DC power supplies (DCPS) found in all modern electronic devices which receive power from the common AC (alternating current) wall socket. The discussion relates to "power supplies", which process the power from a source into one or more DC (direct current) voltages, as distinguished from "power sources", which may be batteries, solar cells, or AC power systems. That distinction also defines the primary purpose of a DCPS.

Modern appliances typically have electronic components for sensing, control, timing, and, sometimes, power switching. Older kitchen appliances did not need a DCPS, since they used the AC directly for motors, relays, small timing devices, and all their other necessary functions. Today's ovens, refrigerators, and dishwashers usually have circuits requiring a DCPS, along with TV, radios, and computers.

Three configurations of DCPS are discussed in the sequence they were developed and entered the mainstream of electronic products. Each is identified for purposes of this course by an acronym, as follows:

LRPS: Linear Regulator Power Supply

SRPS: Switching Regulator Power Supply

SMPS: Switched Mode Power Supply

The term DCPS is used when the discussion applies to all three types.

Electrical Quantities

The names of common electrical quantities are capitalized because they usually are named in honor of scientists and inventors who contributed to fundamental advances in science. Units, their related name sources, and definitions are:

Volt (V): Alessandro Volta, 1745-1827, Italian physicist

The unit of "electromotive force" (emf, V) which causes electricity to "flow". One volt is equal to the emf produced across a resistance of one Ohm in which is flowing a current of one Ampere.

$$V = I \times R \quad V \text{ (Voltage = current } \times \text{ resistance, Volts)}$$

Ampere (A): Andre Marie Ampere, 1775-1836, French physicist

The unit of electrical current (I) equal to a flow of one Coulomb per second and equal to the current produced by one Volt applied across a resistance of one Ohm.

$$I = V/R \quad A \text{ (Current = voltage / resistance, Amperes)}$$

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Watt (W): James Watt, 1736-1819, Scottish inventor

The unit of power (P) equal to the work done at the rate of one Joule per second or the rate of work represented by a current of one Ampere under an emf pressure of one Volt.

$$P = I \times V \quad W \quad (\text{Power} = \text{current} \times \text{voltage}, \text{Watts})$$

Ohm (Ω): Georg Simon Ohm, 1787-1854, German physicist

The unit of electrical resistance (R) equal to the resistance of a circuit in which a potential difference of one Volt produces a current of one Ampere.

$$R = V / I \quad \Omega \quad (\text{Resistance} = \text{voltage} / \text{current}, \text{Ohms})$$

Hertz (Hz): Heinrich Rudolf Hertz, 1857-1894, German physicist

A unit of frequency equal to one cycle per second.

Coulomb (C): Charles Augustine de Coulomb, 1736-1806, French physicist

The unit of electrical charge (Q) equal to the quantity of electricity transferred by a current of one Ampere in one second.

$$Q = I \times T \quad C \quad (\text{Charge} = \text{current} \times \text{time (sec)}, \text{Coulombs})$$

Joule (J): James Prescott Joule, 1818-1889, English physicist

The unit of work or energy (E) equal to that resulting from a power of one Watt applied for one second.

$$E = P \times T \quad J \quad (\text{Energy} = \text{power} \times \text{time(sec)}, \text{Joules})$$

Some of the definitions given may seem esoteric. What is significant for this course are the names and symbols of the most common units of measurement and their relationships to the other units.

AC Power Source

Our wall socket standard is 120 Vrms, 60 Hz power, a fundamental factor in DCPS design. Other voltages and/or 50 Hz frequency are used in some other countries. The origin of this type of power source is so little known, and its impact on the world so pervasive, that a brief history is in order.

In the 1880s, renowned inventor Thomas Edison was busily capitalizing on one of his many inventions, the incandescent light bulb. That industry depended on power for the light bulbs, so Edison was designing and installing electric generator stations while routing electric wires to buildings and homes. In addition to light bulbs, DC motors were a major interest for mechanizing many tasks formerly done by hand labor. The power was DC because designs for DC generators and motors were well known while AC motor designs were believed to be technically unfeasible.

DC has some drawbacks. In the transmission of electricity, the transmission wires carrying the power have resistance which causes part of the power to be lost as heat. The lost power and resulting voltage "drop" are calculated by:

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$$P_L = I^2 R$$

$$V_L = I R$$

Where

P_L is power lost, W

I is current, A.

R is resistance, Ohms.

V_L is voltage loss, V

In order to deliver a certain voltage to the load, the generator had to supply a higher voltage, allowing for the voltage drop. Even then, the practical distance from a generating station to the point of use was limited to a mile or so. Larger conductors would reduce resistance (and voltage drop and loss) but were not economical or practical. Higher transmission voltage would reduce the current (and voltage drop and loss) for the same amount of power, since $P = I V$, i.e., the higher the voltage, the lower the current. Unfortunately, DC voltages above a few hundred volts were difficult to generate and converting DC from one voltage to another was not a simple process. As a result, a great number of relatively small generating stations had to be built, each serving only a limited surrounding area.

It was at that time that a brilliant young Serbian engineer named Nikola Tesla immigrated to the U.S. He had worked on electrical systems for years in Europe and, on his own, had conceived the design for AC motors and entire AC systems, having already built such a motor and successfully tested it. He had not been able to interest anyone in even looking at his concept and designs. He worked for a time for Edison, who was not receptive to a system which he believed could not work (and, if it did, would render his own power stations obsolete). After leaving Edison and enduring some difficult times, Tesla patented an array of AC devices - motors, generators, systems. Another successful inventor, George Westinghouse, hired Tesla, bought his patents and expertise, and established AC power as the preferred technique. (The entire story is much longer, much more technically complex, and very interesting.)

The advantages of AC over DC are fundamental. With electrical transformers, moderate voltages generated could be easily increased ("stepped up") to very high voltages, many thousands of volts, for long-distance power transmission. The correspondingly lower current caused less voltage drop and loss, and smaller conductors could be used. At the point of use, the voltage was converted ("stepped down") to a lower one suitable for home and office use or other voltages for industrial use.

Tesla was an inventor as imaginative and prolific as Edison and left a legacy of inventions. Unfortunately, he died without leaving details and proof of some very intriguing concepts still being studied. And we were provided with our standard AC power source.

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Basic DCPS

Most devices use relatively low DC voltages, such as 5 V, 10 V, 12 V, and 15 V, both positive and negative in some applications. The latest electronic circuits require only 3 V, designed to utilize certain types of batteries.

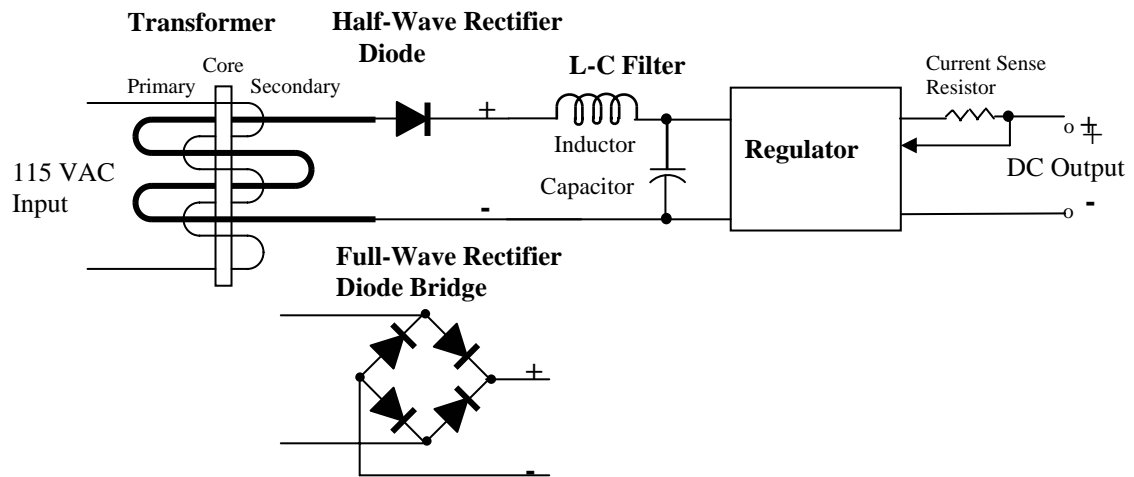


Figure 1: Basic DC Power Supply Schematic Diagram

A basic DCPS is shown schematically in Figure 1. Its component functions are:

Transformer: Steps the voltage down or up to an AC voltage level suitable for producing the desired DC output voltage,

Rectifier: Converts the AC wave to DC.

Filter: Smooths the AC ripple in the rectified waveform.

Regulator: Keeps the DC output voltage nearly constant in spite of variations in the AC input voltage and load current.

Transformer

A transformer consists of a metal core - usually iron or ferrite, a ceramic ferromagnetic material - around which are wound at least two coils of wire, a primary winding and one or more secondary windings. A varying magnetic field is created in the core material by the AC input on the primary winding, in turn causing an AC voltage to be induced in the secondary winding. The secondary voltage is related to the primary voltage by the ratio of winding turns, as:

$$V_{\text{sec}} = V_{\text{pri}} \times N_{\text{sec}}/N_{\text{pri}}$$

Where:

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V_{sec} is the voltage available from the secondary.

V_{pri} is the voltage applied to the primary.

N_{sec} is the number of turns in the secondary winding.

N_{pri} is the number of turns in the primary winding.

Example: A secondary voltage of 10 V_{rms} is desired with primary voltage of 120 V_{rms} and 120 turns in the primary.

$N_{sec} = N_{pri} \times V_{sec} / V_{pri} = 120 \times 10 / 120 = 10$ turns, secondary winding

Wires are sized according to the design currents to be accommodated, with suitable insulation for the voltages. Transformer size and weight are driven by the low frequency of 60 Hz and the amount of power to be transformed. DCPS for high power applications can be quite large and heavy.

For very low power, the transformer and possibly a simple rectifier with filter may be built into a small unit with an integral AC plug to hang on the wall socket. This unit, called a "wall wart", is common in home telephones, electronic games, and toys.

NOTE: A "plug" is the connector with contact pins, as on a power cord, designed to be inserted into a "socket" like the wall receptacle. Alternative connector terminology specifies "male" and "female" versions.

Rectifier

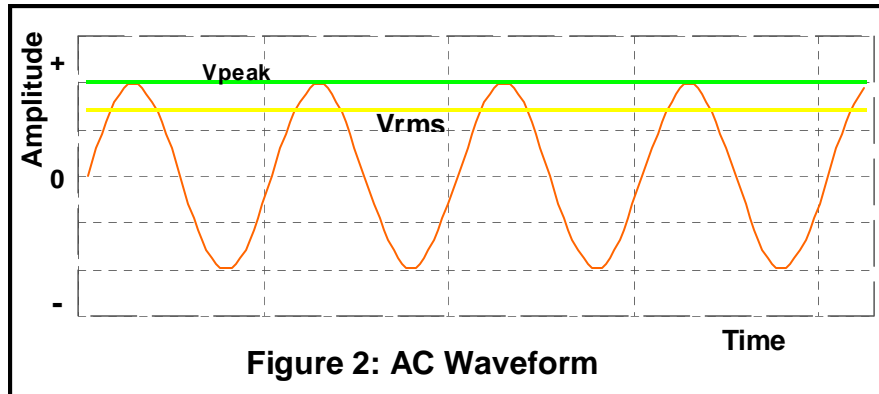
Figure 2 illustrates for reference the sinusoidal AC power waveform. A sinusoidal wave has a "root-mean-square" (rms) value, equal to a DC value which would deliver the same amount of power into a resistive load. A resistive heating element will be heated the same with 120 V_{rms} as with 120 VDC.

NOTE: The rms voltage is calculated from the AC wave by squaring the voltage wave, calculating the average of the squared waveform, and taking the square root of that average. Hence the name, "root-mean-square", the mathematical operations in reverse order. For a sinusoidal waveform with a peak value, V_{peak} :

$$V_{rms} = 0.707 \times V_{peak}$$

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Semiconductor diodes are used to rectify the AC. Figure 3 shows the effect on waveform of a single diode, which passes current in one direction only and blocks current in the reverse direction, effectively clipping off the negative part of the AC wave (half-wave). The rectified output is DC, in that it will cause current to flow in one direction only. It has an average or DC value of:

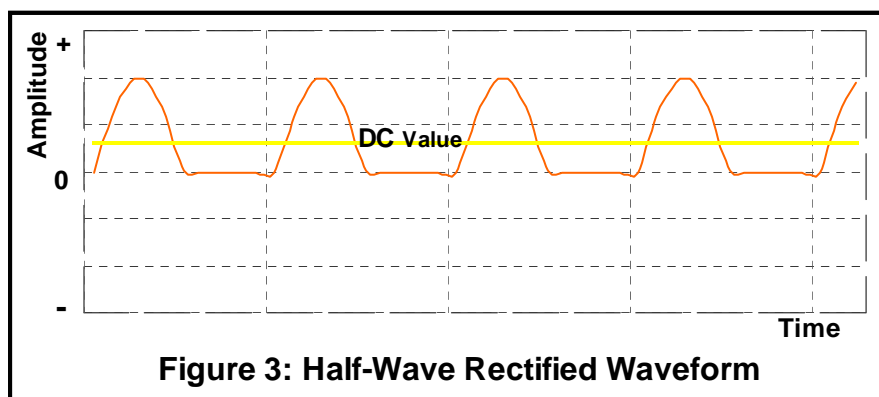
$$V_{HW} = 0.318 \times V_p$$

Where:

V_{HW} is the DC value, half-wave rectification, Volts

V_p is the peak voltage of the rectified sine wave, Volts

The waveform may be viewed as having several components, a DC value and a number of AC components which together create the composite waveform. The single diode rectifier is simple and suitable for some basic, low-power applications.



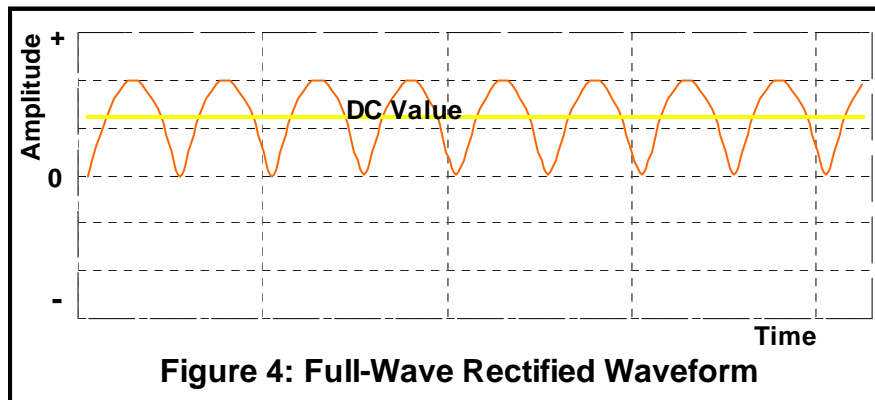
More often, a diode "bridge" is chosen to utilize both halves of the AC wave, for "full-wave" rectification as illustrated in Figure 4. Its DC value is twice that of the half-wave rectifier:

$$V_{FW} = 0.636 \times V_p$$

In Figure 1, the single diode rectifier would be replaced by the diode bridge shown also.

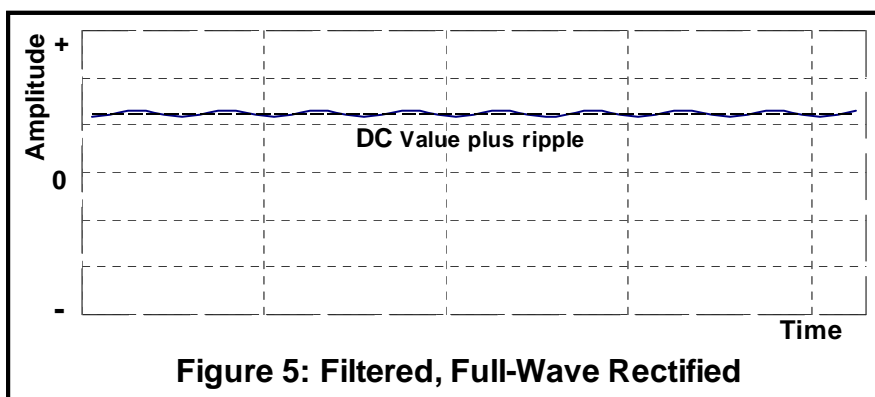
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Filter

The pulsating DC as shown generally is not suitable for powering circuits, because they need a more constant voltage. A simple filter will smooth out the DC by storing energy briefly in "reactive" components (inductor and capacitor) during the peak part of the wave then releasing that energy when the DC starts dropping, resulting in the waveform of Figure 5. Instead of a widely varying DC voltage, the filter leaves only a small ripple on the DC value. Another way of describing the filter effect is that it suppresses the AC components in the waveform, leaving the DC and some residual AC (ripple). For light loads, a capacitor alone may be sufficient. Like the transformer, filter components for 50/60 Hz frequency and high power can be large and heavy.



Regulator

An electronic regulator is usually required. Its purpose is to sense the output voltage, compare that to an internal, accurate voltage reference, and control its circuit to keep the output DC voltage constant, within some allowable limits. Without a regulator, the DC voltage could vary by as much as 5% (or more in some locations) from just the specified variation of the AC voltage supplied by a power company. Moreover, nominal home and

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office voltage may be different, e.g., 115 VRMS, in some localities. The load can also vary significantly in many applications. For example, in a computer tower, each disk and DVD/CD drive as well as other devices use 5 VDC, but they may not all be installed at the same time. As others are added, the load current changes accordingly, which could cause large changes in the nominal 5 VDC without regulation. The regulator controls a voltage "reserve" allowing it to increase or decrease the DC energy as necessary to maintain a constant DC output value. Simple regulators reduce the total DC variation to a few percent while more stringent requirements need better regulation to a fraction of a percent. The regulator action also reduces ripple.

Linear Regulator

A simple regulator circuit shown in Figure 6 can utilize a power transistor as a "series pass" element. By sensing the instantaneous DC output, the regulator can vary the transistor drive to compensate for changes in input voltage or load. It acts like a variable resistor in series with the load. While some variation in output always remains, it can be reduced to arbitrarily low values. The voltage control circuit can have a variable setting to change the output voltage while maintaining regulation at the new setting.

This circuit is a "linear" type of regulator. The transistor is made to respond proportionately to the demand for voltage correction. It must dissipate the heat caused by its current and its effective resistance, both of which can be significant in certain ranges of operation.. For even moderate output power, a heat sink may be needed to efficiently transfer heat to the air and sometimes forced-air cooling is required. A DCPS with linear regulator (LRDC) can have good regulation, i.e., small changes in output voltage, relatively low ripple, and fast response to sudden load changes.

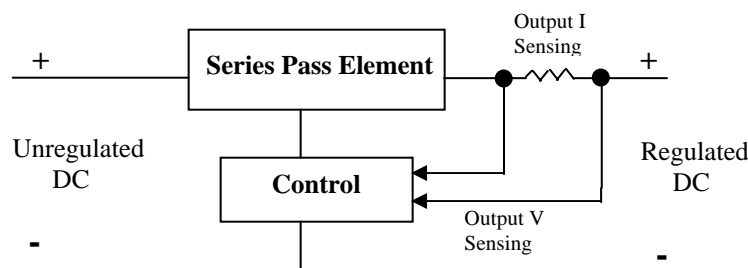


Figure 6: Linear DC Regulator Diagram

Switching Regulator

"Switching regulators" offer great improvement in some important ways over the linear designs. A transistor is switched on and off, never operating in its linear region except during the brief transition from one state to the other. The output waveform, Figure 7, shows two conditions of the resulting voltage. In one condition, the voltage is "on" from time 1 to time 2 and "off" from time 2 to time 4. In the other, the voltage is "on" from

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time 1 to time 3 and "off" from time 3 to time 4. The first waveform has a low effective DC value, V_1 , while the second waveform value V_2 is much higher. These result from the difference in "duty cycle", which is the ratio of on-time to the total cycle time, from time 1 to time 4.

$$V_{AV} = V_H \times T_{ON} / T_{CYC}$$

$$T_{CYC} = T_{ON} + T_{OFF}$$

Where:

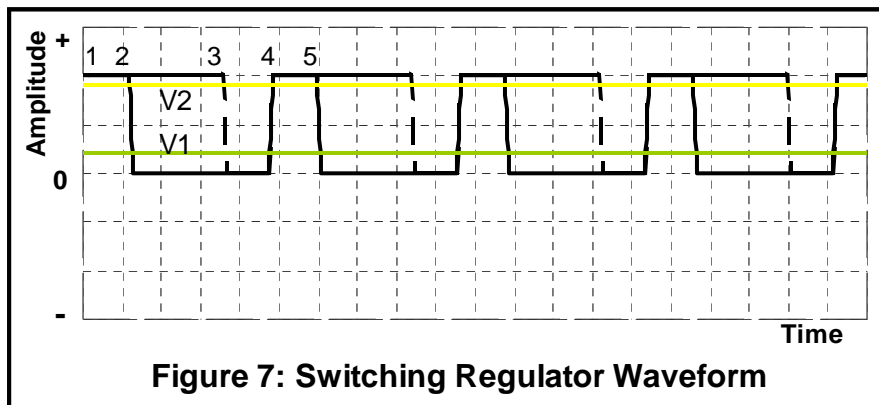
V_{AV} is the average voltage of the waveform.

V_H is the "on" voltage.

T_{CYC} is the time of one waveform cycle

T_{ON} is the "on" time.

T_{OFF} is the "off" time.



Example: $T_{12} = .001$ sec
 $T_{24} = .004$ sec
 $T_{13} = .0036$ sec
 $T_{34} = .0014$ sec
Duty cycle wave 1 = $.001 / (.001 + .004) = 0.2$
Duty cycle wave 2 = $.0036 / (.0036 + .0014) = 0.72$

The larger duty cycle causes a DC value 3.6 times greater than that of the lower duty cycle.

Therein lies the fundamental feature of a switching regulator: its control will vary the duty cycle of its waveform over a wide range according to the correction needed in output voltage. The transistor is either fully conducting, so that its effective resistance is low, or not conducting, so that it does not pass any current. Either way, the power it dissipates is low, much lower than that in a linear regulator. Power loss is lower and cooling is much less of an issue.

It may seem that the filtering problem has been made more complicated, but it is not, because the switching rate is very high, typically from 10 KHz to 100 KHz and higher. Much lower values of inductance and capacitance are needed to achieve low ripple.

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Integrated-circuit (IC) regulators are available in many circuit configurations, sizes, and capacities, greatly simplifying the once-challenging task of regulator design.

Switching DCPS, SMPS

A switched mode power supply (SMPS), shown in the functional block diagram of Figure 8, applies the concept of high-frequency switching to a complete DCPS. The 120 VAC is rectified by a diode bridge, resulting in a high DC voltage. That voltage is then filtered and switched by transistors so as to alternate the polarity of the DC voltage applied to a special transformer, creating an AC voltage drive on its primary and corresponding AC voltage on its secondary. Another rectifier converts the AC to DC and is followed by a filter to smooth the output. The DC output is compared to an accurate internal reference voltage, and any change causes the switching circuits to compensate, maintaining a constant output.

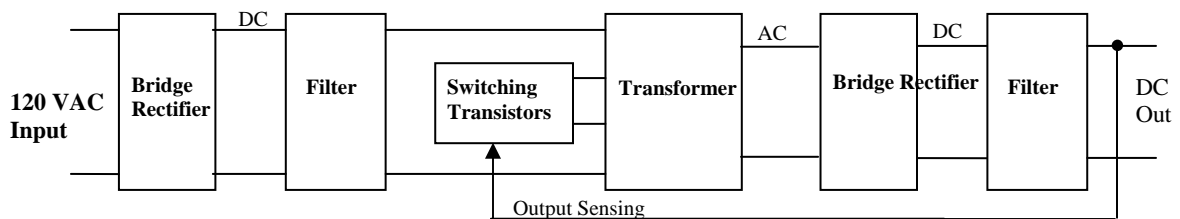


Figure 8: Switched Mode Power (SMPS) Supply Functional Diagram

Like the switching regulator described, this circuit switches at high frequency, so components are relatively small, performance and efficiency are high, and minimal heat is generated. Even with the apparent complexity, modern integrated circuits incorporating the solid-state devices and automated manufacturing techniques make such supplies economical. They are widely used today.

DCPS Specification Parameters

DCPS performance characteristics define the ranges of parameters and conditions over which the supply performs within the stated performance limits. Major specification parameters are listed and defined below.

Input Parameters

Voltage: $V_{rms} \pm V_{tolerance}$

Current: I_{max} , A

Frequency, Hz

Output Parameters

Voltage: $V_{DC} \pm V_{tolerance}$, V

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Current: I_{max} , A

Input regulation: Change (usually percentage) in output voltage for a specified change in input voltage amplitude.

Load regulation: Change (usually percentage) in output voltage for a specified change in load current

Ripple: Peak-to-peak amplitude of the ripple voltage, maximum

Power dissipation: Power lost in the DCPS and dissipated as heat, worst case or specified conditions, W

Environmental Parameters

Ambient temperature, max/min, degrees

Cooling air flow, cfm (cubic feet per minute), if required

Maximum allowable temperature on the DCPS case or at a specified point, degrees

Protection Features

In many applications, current limiting is a necessary function to prevent excessive load current, protecting both the power supply itself and the circuit being powered. The limit value may be fixed or variable. One technique uses a small-value resistor, shown in Figures 1 and 6, as a "current sensing" resistor. If the voltage drop across the resistor ($V = I \times R$) exceeds a threshold reference in the regulator, the current may be held at a safe maximum value or the regulator can shut off, waiting to be reset after the excessive load is cleared, depending on application requirements.

DCPS temperature is usually a concern when output power may be high, packaging is tight, air flow is restricted, or the DCPS is located close to hot devices. Electro-mechanical thermostats can be used to switch the DCPS off at a selected temperature. Electronic "shutdown" circuits can be used for the same purpose.

A fuse is sometimes located in the DC output line to protect against high current loads. It is simpler than an electronic circuit but does not react as quickly, an important consideration in some situations. A fuse in the AC input line is common, preventing the DCPS from drawing excessive power as a result of high DC load current or malfunction of the DCPS itself.

Electromagnetic Interference (EMI)

The use of high-frequency switching in SRPS and SMPS leads to generation of undesired signals in the RF (radio frequency) range, which may be radiated and cause interference with industrial, communication and entertainment devices. The switching frequencies themselves may interfere with certain low-frequency navigation and control systems. The fast "rise time" (low to high voltage) and "fall time" (high to low voltage) shown in Figure 7 indicate that there are much higher frequency components in the switching waveform. If not suppressed, these could interfere with a wide range of other systems and services. Interfering signals may also be conducted out of the DCPS via its AC power input cord.

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Stringent limits are imposed by the Federal Communication Commission (FCC), defining the maximum radiated signal levels allowed as a function of frequency or frequency band. Every device produced should have been acceptance-qualified by design or testing to insure conformance with FCC regulations.

The potential for interference increases with higher power and higher switching frequencies. Low-power supplies usually need only basic radiated-signal suppression provisions. The RF signal components may be controlled to some extent by "tailoring" the shape of the switching waveform with only small effect on performance. In most designs, interference is reduced by a combination of techniques including the following:

- Tight-fitting covers and joints, possibly with metallic or RF-absorbent gaskets.
- Transformer shields.
- High-frequency suppressors on the AC power cord.
- Short circuit paths (wires or printed circuits).
- Carefully-located capacitors to suppress stray radiation.
- Filters designed to suppress HF.
- Selection of components which yield the lowest EMI level.
- Screened ventilation openings

Summary

In this course, you have learned that a DCPS is used in virtually every electronic device powered by a wall plug, including many home and office appliances having electronic features.

You also have learned the functions of primary components in a DC power supply:

Transformers convert an AC voltage to another AC voltage level.

Rectifiers change AC to DC.

Filters smooth the pulsing DC to a more constant level.

Regulators automatically adjust the output DC voltage to compensate for changes in AC input voltage or DC load current.

You know the functions and differences of the basic regulator types:

Linear regulators are relatively simple and effective, offer low ripple, but can have problems with heat dissipation and efficiency. They may have lower ripple, better regulation, and faster response to transient loads.

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Switching regulators are relatively complex in functions, but are smaller, more efficient, and cooler.

You have learned that modern switched mode power supplies (SMPS) offer a more efficient and smaller unit which is easier to cool.

You are familiar with the protection features sometimes built into a DCPS:

Current limiting will control the maximum current which can be drawn from a DCPS.

Temperature of the DCPS can be limited to a specified maximum.

A fuse may be used on the AC input line or the DC output to prevent excessive load.

You understand that electromagnetic interference (EMI) characteristics of a DCPS must conform to signal radiation limits established and enforced by the FCC.