

Design tips for linear and switched-mode power supplies

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Introduction

Energy transmitted through the electric grid is transmitted at very high voltages to reduce the amount of copper lost as heat in the wires; however, most electrical and electronic applications use much lower voltages.

One of the main reasons why the power grid uses AC currents and voltages is that it is relatively easy to use transformers to convert AC power from one voltage to another. This technology was readily available during the initial development and deployment of power grids in the late 19th and early 20th centuries.

To convert the typical grid voltage of 90 V_{AC} to 240 V_{AC} (depending on global location) down to a lower voltage, early electronic applications used a linear power supply, shown in Figure 1.

The line voltage is applied to a transformer, which converts the input voltage down to a lower voltage. This low-voltage AC is then rectified by the diode bridge and applied to a capacitor, which smooths the voltage and provides a DC voltage with ripple on it. The ripple is removed by the linear regulator, which provides a well-regulated low-voltage DC output from the supply.

How advanced semiconductors changed power supplies

The linear regulator is a reasonable approach, and indeed was widely used during the early and middle 20th century. But the development of fast (tens to hundreds of kilohertz) semiconductor switches that could tolerate the high voltage of the input line led to a major shift in the power-supply market during the 1960s and 1970s.

To understand why improved semiconductors made a difference, consider Faraday's law, which states that the voltage induced in a single conductor is proportional to

the rate of change of flux in that conductor.

$$V = N \frac{d\Phi}{dt} \quad (1)$$

where N is the number of turns of the conductor subject to the change in flux, Φ .

The magnetic flux in a single-conductor loop = $B \times A$, where B is the flux density/unit area and A is the area of the loop. The relationship of induced voltage to induced flux density is shown by Equation 2.

$$\int V \times dt = N \times \Phi = N \times B \times A \quad (2)$$

Because the inductance (and hence impedance) of the transmission lines used in the AC grid increases with frequency, the operating frequency of grids around the world was standardized in the 50- to 60-Hz range. This frequency, in conjunction with the rms grid voltages dictate the voltage-time product. For a sinusoidal voltage,

$$\int V \times dt = \int V \times \sin(\omega t) \times dt = -\frac{1}{\omega} \times V \times \cos(\omega t) \quad (3)$$

Therefore, over half a line cycle, the maximum volt-second product is defined by Equation 4.

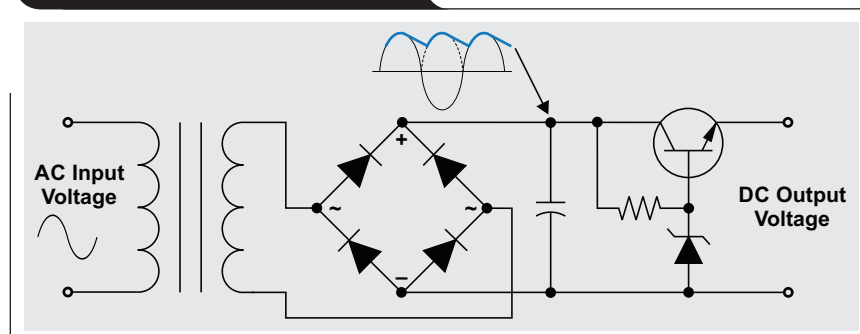
$$\frac{V}{2\pi \times f_{\text{Line}}} = V \times \frac{T_{\text{Line}}}{2\pi} \quad (4)$$

where f_{Line} is the line frequency and T_{Line} is the line-cycle time period. This is equivalent to the peak of the line voltage applied to the transformer primary for approximately one-sixth of the line period. Therefore,

$$N \times B \times A = V \times \sim 3 \text{ ms} \quad (5)$$

As previously mentioned, high-voltage semiconductor switches that could switch several thousand times a line cycle became available in the 1960s and 1970s. By putting a switch like this in series with the transformer, it was

Figure 1. Linear Power Supply



possible to reduce the maximum amount of time the equivalent peak line voltage was applied to the transformer primary from about 3 ms to the order of 10 μ s. This several-hundred-fold reduction in the volt-time product results in the same reduction in the $N \times B \times A$ product of the transformer.

To sustain the high $N \times B \times A$ product required at the grid frequency, line transformers typically:

- Have a high number of turns, resulting in a high winding resistance and thus requiring a significant amount of copper [high in this context is relative to the transformer required in a switched-mode power supply (SMPS)].
- Use laminated silicon steel cores, as steel has a high saturation flux density (B) of 1.5 to 2 T. The core is split into laminated sections to reduce the high eddy currents induced in the steel core.
- Have a large cross-sectional area (again, large is relative to the transformer required in an SMPS).

These factors combine to make the transformers much larger than the kind of transformers that can be used at higher frequencies.

The switch-mode power supply (SMPS)

A SMPS uses semiconductor switches to switch the voltage across the transformer (see Figure 2) that typically has these features:

- Fewer turns.
- Ferrite cores with a lower saturation flux density, but a higher resistance to eddy currents and thus does not need to be laminated.
- A smaller cross-sectional area.

The SMPS can greatly reduce the size and weight of the power supply. The following four categories compare the significant performance differences between linear power supplies and SMPSs

1. Comparison of input-voltage ranges

Linear

Linear power supplies have a limited voltage range. As shown in Figure 1, the peak voltage of the DC bulk capacitor is $V_{\text{Line_pk}} / N_{\text{PS}}$, where N_{PS} is the transformer turns ratio. The load and the capacitance value dictate the minimum voltage on the capacitor. This voltage must be higher than V_{OUT} plus the voltage drop across the linear regulator, but the higher the capacitor voltage, the greater

the dissipation in the pass element of the regulator, where

$$\text{Power} = (V_{\text{bulk}} - V_{\text{OUT}}) \times I_{\text{OUT}}$$

For this reason, the minimum bulk voltage is typically designed to be about 10% above the minimum voltage required to keep V_{OUT} in regulation. The upshot is that if V_{IN} falls by more than 10%, V_{OUT} will fall out of regulation.

Linear power supplies designed for one grid voltage (such as 230 V in Europe) sometimes have taps on the transformer that change the number of turns connected to the input to allow them to be used at a different grid voltages (such as 110 V in the U.S.). A user-adjustable switch can change the input voltage range, but forgetting to change the switch could result in the unit not operating correctly, or worse, becoming damaged.

SMPS

A SMPS can cope with a much wider range of input voltages by adjusting the duty cycle of the primary switch based on output-voltage feedback. Many offline power supplies can handle input voltages from around 85 V_{AC} to 265 V_{AC} in order to accommodate operation from any grid voltage in the world.

2. Comparison of light-load efficiency

Linear

The voltage across the primary winding of the transformer causes a current (called the magnetizing current) to flow in the winding. Equation 6.

$$V = L \frac{di}{dt} \Rightarrow I_{\text{MAG}} = \frac{1}{L} \int V(t) \times dt \quad (6)$$

This current is not load-dependent, and is in addition to the reflected load current.

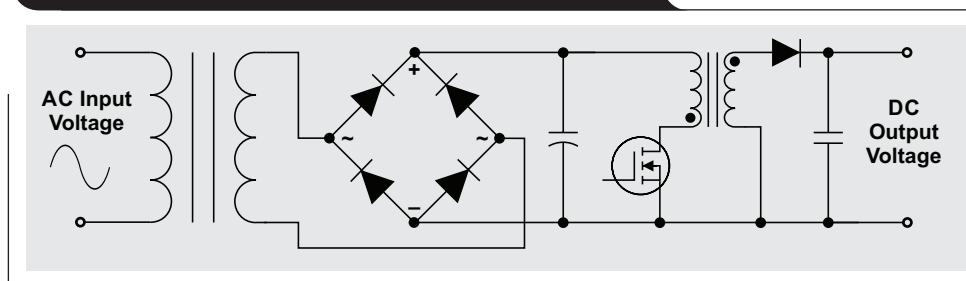
$$I_{\text{Reflected_Load}} = I_{\text{Load}} / N_{\text{PS}} \quad (7)$$

Therefore, total primary current flow is represented by Equation 8.

$$I_{\text{Pri_Total}} = I_{\text{MAG}} + I_{\text{Reflected_Load}} \quad (8)$$

Because of the high volt-seconds across the primary of the transformer in a linear power supply, the magnetizing current can be large, hence, there will be significant primary current even if the load is light. The losses created by this current will result in the unit dissipating significant power, even if the load is not consuming any power, and so the efficiency at both light load and no load will be poor.

Figure 2. Switched-mode power supply (SMPS)



SMPS

The shorter volt-seconds applied to the primary in an SMPS mean that the magnetizing current is much lower than in a linear power supply. Also, as the load reduces, so does the duty cycle of the primary switches; thus, the volt-time product and magnetizing current reduce with the load.

Many modern SMPS controllers stop switching the primary for a period of time when the load falls too low. They use either the burst mode or they reduce the frequency linearly, thus ensuring that the magnetizing current is only flowing when current is required from the output.

3. Output voltage ripple, noise and electromagnetic interference (EMI)

Linear

Other than high-frequency ringing from rectifying diodes, linear supplies generate much less in the way of high frequency signals that can interfere with other equipment. This is the most significant advantage of linear power supplies and is one of the main reasons that they are still chosen for some sensitive equipment.

SMPS

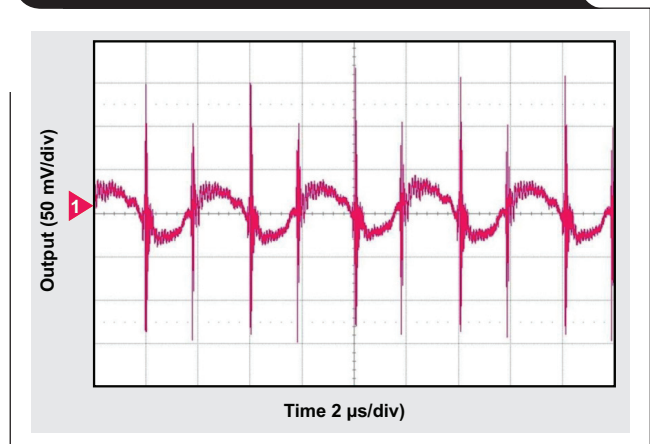
A SMPS converts the low-frequency input voltage into a high-frequency voltage, which is applied to the transformer and then rectifies and filters this high-frequency waveform to provide the DC output voltage. The output voltage tends to have a ripple component at the frequency of the transformer waveform. The magnitude of this component depends on the amount of filtering applied between the transformer and the output of the unit.

Another undesirable feature of the SMPS is that rapidly-switching high voltages across the transformer cause large voltage excursions on the switch nodes and high di/dt swings in the current loops. The sharp rise and fall times of these signals generate electromagnetic radiation from the unit, while the large amplitude voltages can inject high-frequency current into the AC line. The conducted and radiated emissions can interfere with other electronics in the vicinity of the power supply.

The Federal Communications Commission in the U.S. and European Union in Europe regulate the magnitudes of conduction and radiated signals that a unit can emit. Filtering these signals to conform to the regulations adds to the size, cost and development of an SMPS and is a significant drawback of the approach—one that reduced the rate of adoption of SMPSs. However, with sufficient filtering and shielding, it is possible to limit electromagnetic emissions from the unit. The other advantages of SMPSs have largely outweighed this drawback in most applications and SMPSs now dominate the power-supply market.

The sharp edges of the switching signals can also generate voltage spikes on the output of the unit. Figure 3 shows a common output voltage characteristic for an SMPS. There is a ripple voltage of around 50 mV at the switching frequency and much higher frequency perturbations when the switches turn on and off.

Figure 3: SMPS output voltage waveform



4. Comparison of transient response

Linear

Linear power supplies do not have large passive components between the reference (Zener diode) and the output and thus can respond almost instantly to changes in the load, which results in a superior transient response.

SMPS

The delay in the feedback loop and passive components in the power stage place an inherent limit on how quickly the unit can respond to changes in load.

Table 1: Linear and SMPS comparison summary

Linear power supply	SMPS
Heavy, bulky, dissipative transformer	Much smaller, lighter transformer
Narrow input-voltage range; only suitable for use on a single grid; requires a troublesome user-accessible switch	Wide (universal) input voltage range
Very poor light-load efficiency	High efficiency achievable at light loads
No output voltage ripple or switching noise	Some output voltage ripple and noise
Very low electromagnetic interference	Some electromagnetic radiation generated
No output voltage deviation under load transients	Some output deviation under load transients

Conclusion

Compared to their linear predecessors, switched-mode power supplies are not only much smaller and lighter, but they are more efficient and can handle far higher input-voltage ranges. They do generate more EMI, but it can generally be reduced to an acceptable level by filtering and shielding while still leveraging the advantages of higher-frequency operation.

Related Web sites

[Linear regulators product overview](#)

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