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COLUMNS

Transformers 101 (Part 2)

Transformer Design

In the first part of this article series, George presented the transformer and its essential characteristics. In this article, he covers the basics of transformer design.

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Last month, I covered the fundamental theory behind transformers. Now let's continue by considering the basic aspects of transformer design.

In low-power supplies—such as those for laptop computers, radios, battery chargers, and so forth—built-in transformers as we've known them are a dying breed. Manufacturers of electrical appliances have been, whenever possible, replacing their internal transformers with plug-in "wall wart" adapters. Those are either transformers with AC output (see **Figure 1a**) or DC supplies containing a rectifier and a capacitor (see Figures 1b–c).

One reason for this trend has been the avoidance of the costly safety certification of every equipment model, required in every country where the product was to be sold. Low-volume, high-mix product and slightly different regulations among countries cause the cost of certification to be a major issue. A mass-produced plug-in wall wart supply, already certified, is the answer. The traditional DC wall wart supplies (see Figures 1b–d), notorious for their poor power factor, are being replaced by high-frequency switching regulators with many benefits. Their design is not the subject of this series. Because their transformers operate at high frequencies, they are smaller, lighter, and less expensive. A wide range of input voltage, output voltage regulation, and excellent power factor provide additional benefits. The power factor correction (PFC) is now mandatory in many countries.

One disadvantage of the switching wall wart supply as compared with a traditional transformer type is its inherently lower reliability, due to the number and type of components in it. However, I have found those supplies to be of excellent quality and reliability, while I have seen far too many "classic" wall wart supplies fail due to their cheap design or shoddy workmanship.

At one time, engineers designed and built their own transformers. Today, there are so many off-the-shelf options that the need for "rolling your own" has virtually disappeared. When you need a transformer not readily available, you should have it designed. It takes a lifelong experience to become a competent transformer designer, but there are many expert companies to help you.

With that said, it is nevertheless a good idea for an engineer to be familiar with transformer design basics. At the very least, you'll be knowledgeable enough to interface with your supplier and will appreciate the potential design constraints. What transformer requirements do you need to specify?

REQUIREMENTS

Apart from the mechanical issues—such as the size, weight, mounting arrangement, and environmental conditions, including operating temperature range, vibration, and so forth, which are generally up to the mechanical designers to address—the electrical engineer's responsibility is to define the transformer's electrical characteristics. First, you need to know the primary voltage and frequency. Then, you must know the secondary windings' requirements. How many secondary windings? What are their voltages and maximum currents? What is the required regulation (i.e., the secondary voltage fluctuations caused by a varying load)? Any taps? Windings' insulation voltages. Primary to secondary insulation. Maximum parasitic capacitive coupling. Are there any shielding requirements to contain the electromagnetic field within the device?

All these requirements affect how the coils are designed, the type of the permeable core used, additional magnetic shielding, and so forth.

The secondary windings are expected to deliver power: $P = V_2 \times I_2 + \ldots + V_n \times I_n$. P is the total maximum power to be drawn from the secondary windings. The input power to the primary winding P_T is then: $P_T = P/\eta$, where η stands for the transformer efficiency. This is always less than 100% due to the magnetization current as we saw in the first part of this article series, parasitic capacitance, losses caused by the ohmic resistance of the windings, and so on. Having established the input power P_T and the operating frequency, an appropriate core can be selected. Here's where experience becomes crucial. For one, magnetic induction B needs to stay within the optimum range. The core size is also affected by the expected size of the bobbins to hold the windings, high voltage and electrostatic insulation, wire size to carry the required current, etc. Core manufacturers' data sheets are rarely exhaustive enough for a beginner to make the right choice.

Once the core has been selected, its characteristics determine the required number of turns per one volt. Then the turns for each winding based on their required voltages can be calculated as: $n = k \times V \times V_V$, where n is the number of turns. V is the desired voltage in volts. V_V is the number of turns per volt. k is a constant, which is to compensate for the secondary losses caused by the magnetic flux dispersion and ohmic losses at the maximum rated output power. For the primary winding k = 1. Therefore, the primary winding is not changed to avoid modification of the established magnetic flux in the core. Once again, transformer specialists have experience, historical data and establishing k is usually not much of a problem for them. For a transformer design novice, establishing k means a lengthy process of trial and error.

The wire sizes are based on the windings' currents and the current density s, which in turn depends on the operating temperature and cooling effects of the core. Old, conservative design tables recommended s to be in the range of 2 to 3 A, sometimes 4 A per 1 mm^2 of the wire cross-section. Modern designs—usually to cut cost, weight, and size—sometimes exceed this by more than an order of magnitude, relying on the better quality core materials, reliability sacrifice caused by the higher operating temperature and acceptance of higher ohmic losses. These are sometimes intentional to limit the

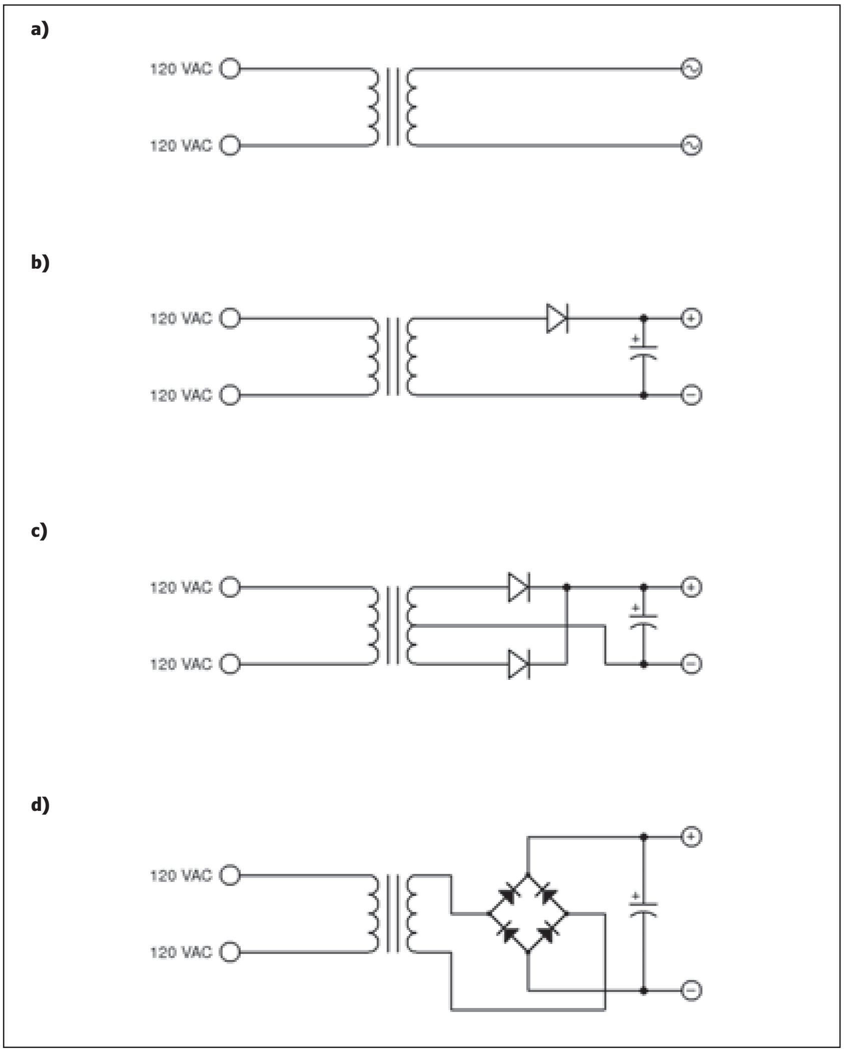

FIGURE 1
Common wall wart power supplies. While the first **(a)** is still very much in use, the other power supplies **(b–d)** are gradually disappearing.

maximum output current, such as in cheap battery chargers or due to expectations that the voltage fluctuations caused by a varying load will be compensated for by a following voltage regulator.

Most signal and low-power transformers in electronics work as single-phase devices, although there are special applications in power distribution where multiple phase primary or secondary or both windings are needed. Once I participated in design of a relatively high-power (60-kVA) control system supplied from a three-phase, 200-V/400-Hz generator. Building a transformer with a nine-phase secondary, followed by rectifiers with capacitive filters, improved the power factor such that reduced the power quality requirement was satisfied without a PFC. Multiple phases were a smaller, lighter, and less expensive solution.

The same transformer design principles apply throughout the power and frequency spectrum. The major difference is made by the required core. Transformers working in the audio spectrum, for instance, require flat frequency response characteristics from typically 20 Hz to 20 kHz and a minimum harmonic distortion. Except for low, usually a single frequency, such as for 60-, 50-, or 400-Hz power supplies, transformers need specialized cores designed to optimally handle the given frequency spectrum of the signals and their waveforms.

SPECIALIZED DEVICES

There are also many specialized transformer-based devices, such as pulse transformers or transformers for switching power supply applications, whose input is not sinusoidal. Some must handle a DC bias. There are also magnetic amplifiers, ferroresonant voltage regulators, transformers using magnetic flux nonlinearity, including saturation to perform special functions too exotic to address in this short article series. Prior to the invention of the vacuum tube, transformers were the only component capable to modify signal levels.

It should be remembered that other than supplying desired voltages, transformers can match different impedances by the ratio of their turns. This, coupled with their primary to secondary insulation and suppression of common mode interference, is used in distribution of numerous data communication systems (e.g., Ethernet and MIL-STD-1553).

As the frequency increases, the magnetic cores become smaller and somewhere around 100 MHz can be eliminated. The obvious advantage of the air core, provided the frequency is high enough and the coils can be reasonably small, is their linear B/H relationship and, thus, no need to worry about its nonlinearity. At high-megahertz frequencies, transformers can be created by transmission lines and once we get into the gigahertz, with waveguides. But that, while interesting, is a different topic for another time.

For completeness I should mention "electronic transformers." These are similar to the DC-producing switching wall warts. Light, reasonably efficient and less costly to manufacture than magnetic transformers, their output is their internal switching frequency amplitude modulated by double the input AC (50 or 60 Hz) frequency. Popular with some appliance manufacturers, they have limitations. More about them next month in the final part of the series when we'll also look at some less common transformer types.

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RESOURCES

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