Transformer Theory

A service guide to troubleshooting transformers in electronic gear

By Christopher H. Fenton

As long as they don't burn up or obviously malfunction, transformers are usually the last item to be checked out in ac-line-operated electronic equipment. Deceptively simple, the basic principles behind the transformer haven't changed very much since these devices were first put into service. So by understanding a few basic principles, it's possible for you to quickly determine whether or not the transformer is a cause of trouble in a circuit.

Let's explore these principles in detail, with the object of providing useful troubleshooting information to help you in isolating transformer problems. Though relatively technical (some elementary algebra is used to get the point across), our discussion is geared to *practical* transformer troubleshooting procedures.

Some Preliminaries

Despite the transformer's innocent appearance, it can be a very dangerous device. Therefore, a few words of caution are in order before getting into actual theory.

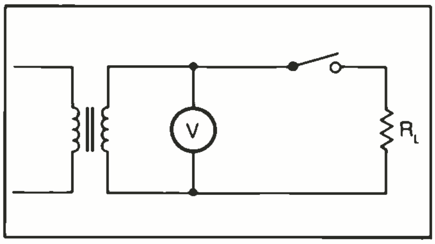

Fig. 1. An example of a test setup for checking a transformer. This arrangement is not very useful in practical testing situations because R_L often must have a very low ohmic value and very high power rating.

A typical current transformer may have a harmless voltage across its secondary winding and applied to the load, but when the load is removed, this can dramatically increase by several hundred times the load voltage. In most cases, the secondary winding of a low-power, low-voltage transformer will not give you a shock if you touch both secondary leads simultaneously. An exception is if the secondary winding is joined to the primary winding in the style of an autotransformer or if a short circuit exists that electrically connects the transformer's primary and secondary windings together.

The real electrical danger is not so much voltage but the current behind it. A short circuit that appears across the output winding of a transformer can cause an overload of current in the secondary winding that could immediately "fry" the load circuit. With this type of malfunction, the current drawn by the transformer will rarely "pop" a circuit breaker in your ac power line and, as a result, can often go undetected until the load circuitry has been damaged.

A power transformer that converts 117 volts ac into 6 volts ac has as much as 250 amperes flowing in the secondary winding, while the current in the primary winding remains 12.5 amperes, which is insufficient in magnitude to trip a standard 15-ampere circuit breaker. For this reason, transformers often have built into their primary windings fuses whose elements blow at a current that is based on "normal" operating current.

A transformer's internal fuse is not replaceable without completely disassembling the transformer—a task that is beyond the scope of most service technicians' abilities. Therefore, a transformer with a blown fuse must be scrapped and replaced with a new unit.

As a general rule, the most common way to check a transformer is to measure the output voltage across its secondary winding while the primary is being driven by the ac power source. Readings should be taken both at initial start-up and after the transformer has run continuously for a period of time as you check out whether or not excessive heating is taking place.

If the transformer doesn't smell like it is burning up and no smoke is curling off it, the service technician generally declares it to be "good" and proceeds to check out the rest of the circuits in a malfunctioning piece of electronic gear. While this approach may be okay if a transformer is being used for a simple application, a more accurate way of determining a transformer's specifications is needed when it is being used in such applications as powering microchips and other devices where strict control of the output voltage is needed.

Output voltage regulation is the most critical measurement one can make on a transformer. Regulation is usually expressed by the formula: Regulation = (No-Load Voltage − Full-Load Voltage)/Full-load voltage. In this formula, regulation is expressed as a percentage figure. The

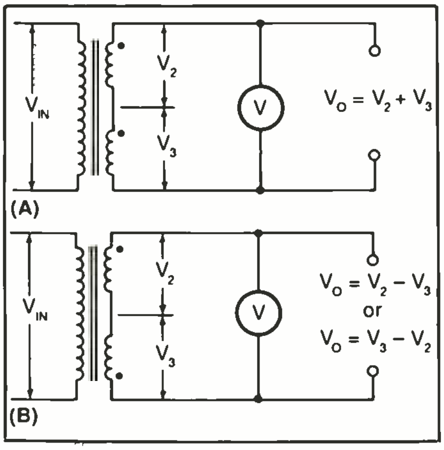

Fig. 2. Setups for determining relative polarities of transformer's secondary windings: (A) illustrates additive-coil arrangement, (B) subtractive arrangement.

higher the figure, the better the performance of the transformer.

Troubleshooting Theory

In Fig. 1 is shown a simple circuit in which load resistance R_L is used to pass the rated secondary current of the transformer at the predetermined voltage. This arrangement is fine for example purposes only. In real application, however, this setup can lead to a problem. That is, if the rated current is 10 amperes and secondary potential is 12 volts ac, the resistance is 10/12 = 1.2 ohms, based on the equation $R_L = V/I$ where *V* and *I* are the rated voltage and current, respectively. By extension, R_L will dissipate 120 watts, based on the equation P = IV, where *P* is power in watts. Therefore, the problem with the Fig. 1 test arrangement is that 1.2-ohm, 120-watt resistors are virtually nonexistent.

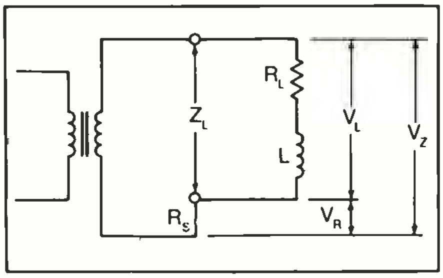

Fig. 3. Test setup for determining the inductance of L.

At the service bench, the transformer should be tested while it is operated with the load (circuitry) for which it was designed to be used. The circuit is substituted for R_L and the switch is temporarily connected between the two as shown in Fig. 1. Inclusion of the switch permits the person doing the testing to check on-load and off-load voltages. This arrangement is better than using an artificial load because the voltage parameter is the one actually used in the circuit.

When performing such a test, the transformer should be allowed to warm up and reach operating temperature because heat can change the resistance of the transformer's windings. Any change in winding resistance results in a corresponding change in output voltage from the transformer.

Another important point to take into consideration when troubleshooting a transformer is the relative polarity (phasing) of the secondary windings in a dual- or multiple-secondary winding transformer. By connecting together the secondary windings in series with each other, as shown in Fig. 2, it is possible to determine what the relative polarity of the output is simply by measuring the voltage with a voltmeter or multimeter set to the ac voltage function.

If the transformer's secondary windings are wired to be additive, the meter will indicate the sum of the voltages across the separate secondary windings. That is, $V_O = V_2 + V_3$, where V_O is the output voltage and *V2* and *V3* are the individual secondary voltages. If the windings are wired to be subtractive, the meter will indicate the difference between the potentials that appear across the secondary windings: $V_O = V_2 - V_3$ or $V_O = V_3 - V_2$. The two formulas reflect the fact that any two secondary potentials may not be the same magnitude; so whichever is the smaller is subtracted from the larger. If the two secondary windings are exactly balanced, the output potential indicated by the meter will be 0 volt.

When conducting an additive or subtractive test, it is important that you make sure the input voltage to the primary winding of the transformer is within required tolerance. If the input voltage is unknown, apply a small voltage from another transformer's secondary winding just long enough to obtain the required measurements. After the polarities of the secondary windings have been determined, label the transformer's leads accordingly so that you will know what they are later on when it comes time to install the transformer in the circuit.

In most servicing applications, bridge circuits are used to find inductance. Unfortunately, instruments to measure inductance are usually not found on the testbench. However, there are other methods that don't require an investment in yet another piece of expensive equipment. The simplest method one can use for determining inductance uses a high-impedance voltmeter, a resistor of known value and an ac power supply that delivers the required voltage.

The value of the resistor should be roughly the same as the impedance of the inductor, which is expressed as Z_L. Use the following formula to find the impedance of the inductor:

$$Z_L = \sqrt{X_L^2 + R_L^2}$$

The resulting inductive reactance, X_L, is calculated using the formula $X_L = 2\pi fL$, where π is a constant (approximately 2.14), *f* is frequency and *L* is inductance.

Let's assume *L* is about 50 Henrys and R_L is about 450 ohms. Using the formula for reactance (f = 75 Hz),

$$Z_L = \sqrt{(2 \times 3.14 \times 75 \times 50)^2 + 450^2}$$

Factored out, the result is approximately 19,370 ohms.

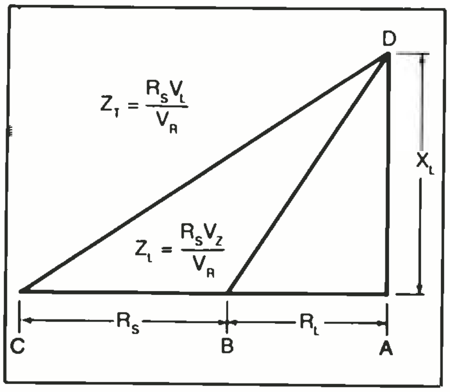

Fig. 4. An impedance triangle like this is a very helpful in determining the impedance of an inductor, given certain information.

Use an ac voltmeter and the test arrangement illustrated in Fig. 3 to determine the inductance of R_s, L and across both nodes to obtain the three values for the equation. To calculate the impedance, it's best to draw an impedance triangle (see Fig. 4).

After defining R_s as a set number of units, use $R_S V_L/V_R$ and the same number of units to strike an arc with its radius on the opposite end of the R_s line. Then calculate the result of $R_S V_Z/V_R$ ohms, convert the result into scale and strike an arc with its radius on the opposite end of the R_s line to intersect with the previously struck arc.

From the intersection of the two arcs, draw a perpendicular line to the base line of R_s. This line represents the reactance of X_L. By converting your units back into ohms and plugging the result into the equation $X_L = 2\pi fL$, you can calculate the inductance.

If R_L can be measured accurately, inductance can be found without drawing the impedance triangle because $Z_T{}^2 = X_L{}^2 + (R_L + R_s)^2$, and you can use the equation

$$X_L = \sqrt{Z_T{}^2 - (R_L + R_s)^2}$$

The same method can be applied if direct current is flowing through the transformer's windings. By applying the required voltage and measuring the results with a voltmeter, it's possible to determine the inductance of the secondary winding. When using a voltmeter, direct current should be prevented from entering the meter by placing a blocking capacitor in series with the meter's "hot" probe and the test point in the circuit.

Other Considerations

Leakage inductance is an important consideration with transformers used in audio-frequency applications. To measure leakage inductance, short together the secondary winding of the transformer and determine the primary's inductance. Direct current is not required because leakage inductance is independent of the saturation effects of the transformer's core. Leakage inductance is also frequency-independent; so you can use any input frequency.

By using an inexpensive RC bridge designed to measure inductance against a preset value and an inductor whose value is already known as a starting point, you can accurately determine small values of leakage inductance.

Simply by learning a few basic formulas, you can quickly solve transformer problems quickly and efficiently. A couple of minutes spent checking a transformer for a potential problem can save a great deal of time and effort and prevent costly mistakes. ME