Chapter 18

Transformers

Chapter Starters

We have come to the last chapter of this book, the study of transformers. These very useful devices are all around us, in all shapes and sizes, some small enough to rest comfortable on your finger nail, others large enough to require a two-foot thick concrete pad.

Transformer theory is one of those subjects that can seem almost limitless. Certainly you could specialize in this topic and spend the next two years just learning about transformers and magnetics. It can be that complex and that absorbing. For most of us, such detailed knowledge is not required, although everyone will need at least some basic transformer theory. This chapter will cover the territory sufficiently for most people, but you should be aware that there is a huge body of knowledge about transformers and magnetics that will not be found here, as it is beyond the scope of this text.

So make a little room for transformer theory in your toolbox of knowledge that we started some time ago. It will prove very useful to you. After this chapter, your basic electricity toolbox will be full. That toolbox will assist you in your future studies, and in your day-to-day work. You should probably start a second toolbox for solid state devices and theory. That will very likely be your next electronics course, if you haven't begun it already. I hope your experience with basic electricity and with this text has been enjoyable and that I have helped you along your chosen path. Even after all of the years that I have been involved in electronics, I still learn new things often, and I still enjoy all of it. I hope that will be your experience also. Good luck with your future studies, and keep adding to your toolbox!

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18.1 Transformer Principles

A **transformer** is a component which utilizes the characteristics of magnetic fields to increase or decrease an AC voltage. A transformer operates on the principle that an AC voltage applied to a coil of wire, called a **primary winding**, will produce a varying magnetic field which, in turn, can induce a voltage across another coil, called a **secondary winding**, if it is placed within the same magnetic field. The magnitude of the voltage induced across the secondary winding depends on the number of turns in the secondary winding as well as the strength of the magnetic field shared by the two windings. A basic transformer is illustrated in Figure 18-1.

Chapter Objectives

Upon completion of this chapter, the student will be able to converse in the terminology used in discussion of transformers, explain the concept of an ideal transformer model and list the advantages of using an ideal model, solve problems related to non-ideal transformers which produce some losses due to heat, determine the effect of and uses for multiple primary or secondary windings, use transformers as impedance matching devices, calculate unknown transformer quantities, solve transformer fusing problems, and troubleshoot transformer circuits.

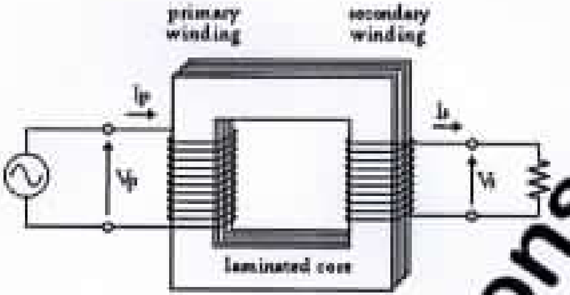


Figure 18-1. A Basic Transformer

A voltage source is connected to the primary winding yielding the **primary voltage**, V_P, and the **primary current**, I_P. The fluctuating voltage and current in the primary winding produce a magnetic flux in the laminated core. This flux is coupled, or shared with the secondary winding, inducing a **secondary voltage**, V_S, and a **secondary current**, I_S. A transformer designed to increase voltage is called a **step-up transformer**. A step-up transformer will have more turns in the secondary than in the primary. A **step-down transformer** will decrease the voltage. The primary and secondary windings are wrapped around a forming piece often called a **bobbin**. The **core** of the transformer is the inside the bobbin or the center of the windings. The core material may simply be air, in the case of an **air-core transformer** or laminated iron in an **iron-core transformer**. Ferrite cores are also widely used. Lamination and core materials were described in Chapter 9. Cores may also be variable, which is normally accomplished by moving the magnetic core material within the core area of the bobbin. Such movable cores are often called **slugs**.

The transformer action can be demonstrated very easily by using two inductors, a voltage generator and an oscilloscope. If you have these available, you would find it interesting to connect them as shown in Figure 18-2. The generator could be set to a few volts at 1 kHz. The magnetic field produced in L_1 will be expanding and contracting at the rate of 1 kHz. As the field expands and contracts through L_2, it induces a voltage across L_2 due to the principles of Faraday's Law. If all of the magnetic flux in L_1 was linked to, or shared by L_2, and if both inductors were the same, the voltage appearing at the scope would be the same as that across L_1. But you will quickly observe that the voltage across L_2 is very small compared to that across L_1. **Flux linkage** describes the sharing of a magnetic field between two coils. The **coefficient of coupling**, k, is a measure of how much flux produced in a primary winding, ϕ_P, is linked to or shared by the secondary, ϕ_S. This is defined in Equation 18-1.

Equation 18-1

$$k = \frac{\phi_S}{\phi_P}$$

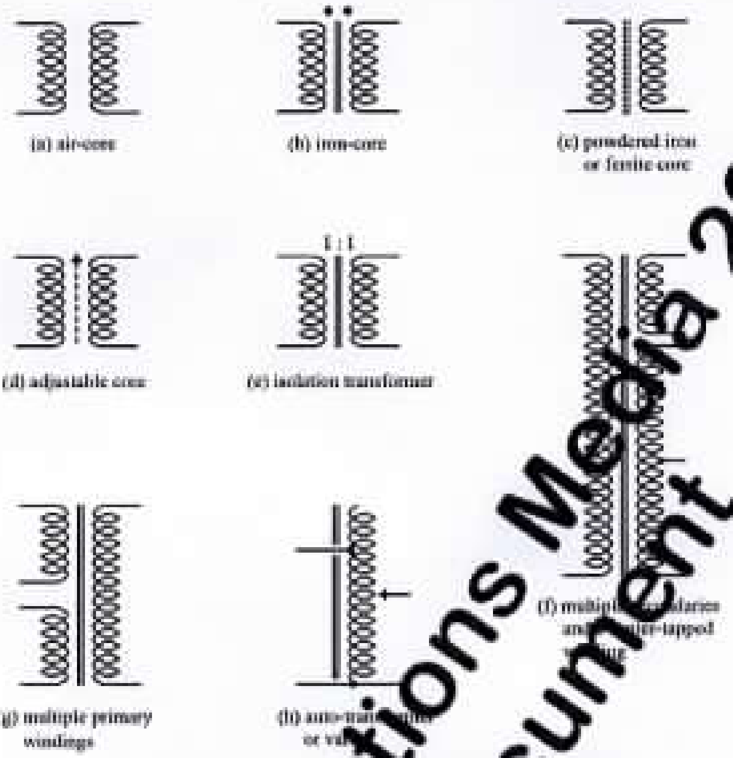
A transformer such as in Figure 18-1 will have a coefficient of coupling close to the ideal of 1. By contrast, k for Figure 18-3 will be much less than 1, because the coils do not share a common core and are said to be **loosely coupled**. You can experiment with the coefficient of coupling by moving the coils closer to each other and observing the effect on the scope display. Even with the coils on top of each other the coupling is still very small and the scope voltage is still very much less than that of the generator.

Figure 18-2. Magnetic Coupling

Transformers are made in many sizes as illustrated by the three shown in the photo of Figure 18-3. Ed Noble, a master electrician, holds a small air-core transformer in his right hand, an iron-core power supply transformer in his left hand, and is dwarfed by a 240 kV high-voltage transformer which he helped install over 30 years ago. The inset to the photo shows the small transformer enlarged. The high-voltage transformer has been in service continuously, which speaks volumes about the reliability of transformers.

Figure 18-3. Three Transformers

Figure 18-4 illustrates the schematic symbols for several different transformer types. The number of loops in the symbols is not significant. Even though one winding may have 200 turns and another 4000, it is quite correct to draw a symbol showing an equal number of loops on each side. Two solid lines between the loops indicate the presence of an iron core. Dotted lines indicate a powdered iron or ferrite core. The absence of lines defines an air-core transformer. Sometimes a winding may have a center tap, or may have several taps. The taps may be fixed in position or they may be movable.



(a) air-core (b) iron-core (c) powdered iron or ferrite core

(d) adjustable core (e) isolation transformer

(f) multiple secondaries and center-tapped winding

(g) multiple primary windings (h) auto-transformer or variac

Figure 18-5 Transformer Symbols

When a transformer steps-up or steps-down a voltage, it will simultaneously step-down or step-up (respectively) the current such that, ideally, the powers into and out of the transformer are the same. In reality, the output power is always less than the input power, so the efficiency is always less than 100%. Recall from Chapter 2 that efficiency was defined as: $\eta = P_o/P_i$. Transformers may operate with efficiencies up to 95%. Primary power, P_P, is that delivered to the primary winding, and $P_P = V_P I_P$. Secondary power, P_S, is that delivered by the secondary winding to the load, and $P_S = V_S I_S$. The efficiency of transformers can be expressed as defined in Equation 18-2.

Equation 18-2
$$\eta = \frac{P_S}{P_P}$$

Dots are often used on transformer symbols, such as shown in Figure 18-5 (b), to indicate signal phase. With the dots both at the same end, V_P and V_S would be of the same phase.

Color Coding

Transformer leads are almost always color coded. The user may not know what the colors represent unless the manufacturer's data is available. In general, the primary wires are usually black. If there are two primary windings, the second one will often be coded with dark brown wires. Secondary colors may be just about anything, but each secondary winding will have its own color, so if you see two blue wires and two red wires, you will know that the two blue wires connect to one winding and the two red wires go to the other winding. A **center-tapped winding**, as shown in Figure 18-5 (f), has an extra wire connected to the center of the winding. This wire will have the same body color as the end wires, but with an added stripe of a different color. A typical center-tapped secondary might be colored red, red/yellow, red.

Transformer Resistances

Transformer resistances are simply the DC resistances of wire used in the windings. A larger number of turns equates to higher resistance, and larger diameter larger wire equates to lower resistance. The wire size for a winding is always a compromise between larger wire diameter, which allows conduction of higher current, and smaller wire diameter, which allows smaller transformer size. Some observations may, however, be made. Assuming no heat losses, a transformer which steps-up the voltage will step-down the current, so that $P_P = P_S$. To achieve an increase in voltage, the secondary winding must have a greater number of turns than the primary. Because the secondary will carry less current, it will be made from smaller diameter wire. More turns and a smaller diameter translate into more resistance in the secondary than in the primary. For similar reasons, a step-down transformer would likely have a lower secondary resistance compared to its primary.

In the case of multiple windings, some simple DC resistance measurements can often provide insights into expected terminal voltages. There is certainly no linear relationship between DC resistance and winding voltage, just the general trend of a higher resistance usually equating to a higher voltage. DC winding resistances are frequently very small, so careful measurement techniques are needed. Occasionally, transformers which have seriously overheated will have turned all of the winding colors to black, yet the transformer will still function after the fault is corrected. DC resistance measurements might be the only way to determine which windings are which, or to find a center tap along with its two ends.

18.2 Ideal Transformers

For our purposes, an **ideal transformer** is one in which the primary power is equal to the secondary power. If $P_P = P_S$, then $\eta = 1.00$ or 100%. Since the coil voltage induced in a changing magnetic field is directly related to the number of turns in the coil, the **transformer turns ratio**, [illegible], is used to describe the relationship between the number of turns in the primary winding, designated N_P, and in the secondary winding, designated N_S. The turns ratio is expressed in Equation 18-3.

Equation 18-3 [illegible] $= \frac{N_P}{N_S}$

In an ideal transformer, the turns ratio also describes the voltage ratio between primary and secondary, in accordance with Equation 18-4.

Equation 18-4 $$\frac{N_P}{N_S} = \frac{V_P}{V_S}$$

Since $P_P = P_S$ in an ideal transformer, then $V_P I_P = V_S I_S$. This may be expressed as in Equation 18-5.

Equation 18-5 $$\frac{V_P}{V_S} = \frac{I_S}{I_P}$$

The circuit of Figure 18-5 illustrates a transformer with an input voltage source and a load connected to its secondary. Because of the transformer, the generator will see a different load impedance than if it were connected directly to the load. This impedance seen by the generator is called the **reflected impedance** and is designated Z_R. Its value depends on the load impedance and the transformer turns ratio. Similarly, the generator impedance as viewed from the load will appear as a different value when a transformer is connected between the load and the generator.

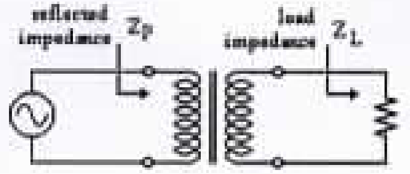


Figure 18-5. Reflected Impedance

For an ideal transformer, $P_P = P_S$ and since $P_P = I_P^2 Z_P$ and $P_S = I_S^2 Z_L$, then $I_P^2 Z_P = I_S^2 Z_L$. Rearranging,

$$\frac{I_S^2}{I_P^2} = \frac{Z_P}{Z_L}$$

$$\frac{I_S}{I_P} = \sqrt{\frac{Z_P}{Z_L}}$$

Equations 18-3 and 18-4 show that $r = I_S/I_P$, therefore we can define the turns ratio in terms of the load and reflected impedances as in Equation 18-6.

Equation 18-6

$$r = \sqrt{\frac{Z_P}{Z_L}}$$

It is often useful to combine Equations 18-3 through 18-6 to show the relationship of turns ratio to voltage, current and impedance. This is done in Equation 18-7

Equation 18-7

$$r = \frac{N_P}{N_S} = \frac{V_P}{V_S} = \frac{I_S}{I_P} = \sqrt{\frac{Z_P}{Z_L}}$$

Consider the following example which will illustrate some basic transformer calculations typically expected to be known by technologists.

Example 18-1

Assuming the ideal step-down transformer of Figure 18-6 has a turns ratio of 4.80, determine values for V_S, I_S, P_S, P_P and I_P.

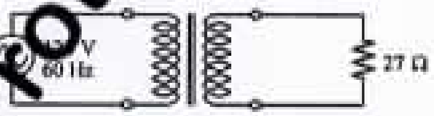


Figure 18-6. Circuit for Example 18-1

$r = V_P / V_S$
$V_S = 120\text{ V} / 4.80 = 25.0\text{ V}$
$I_S = V_S / R = 25.0\text{ V} / 27\ \Omega = 926\text{ mA}$
$P_S = V_S \times I_S = 25.0\text{ V} \times 926\text{ mA} = 23.1\text{ W}$
Since $\eta = 1.00$
$P_P = P_S = 23.1\text{ W}$
$I_P = P_P / V_P = 23.1\text{ W} / 120\text{ V} = 193\text{ mA}$

18.3 Non-Ideal Transformers

Of course there is no such beast as an ideal transformer so we must try to deal with real devices as accurately as we can. It must be said that a transformer, while appearing to be such a simple device, is actually quite complicated electrically. Higher-level mathematical equations can describe the electrical phenomena very accurately, but at a cost of considerable learning energy and time. Some excellent computer programs can also predict electrical performance quite accurately, but even these programs are difficult to master and apply to the real world. These tools are best left to those whose career focuses on transformer design and application.

Typically, technologists needs are simpler and can be made much easier at the sacrifice of some accuracy in the predictive capability of calculations. These sacrifices will not have any serious consequences.

Magnetization Current

Consider the circuit of Figure 18-7 where the secondary of the transformer is unloaded. Even though the secondary of the circuit is unloaded, a current still flows in the primary circuit. Under these conditions, that current is called the **magnetization current** and will be designated as I_m. This magnetization current flows as a result of the inductive reactance of the primary as seen by the generator. If a resistive load was then connected to the secondary there would be additional current flowing in the primary which we can call **primary current due to secondary loading**. This has already been designated as I_P.

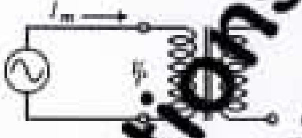


Figure 18-7. Magnetization Current

If we wish to consider the effects of the magnetization current, we must realize that the total current in the primary is an addition of the magnetization current and the primary current due to secondary loading. This sum will be called the total primary current and will be designated as I_{Pt}. This is slightly complicated by the fact that I_P is a real current but I_m is imaginary because it is due to the inductive reactance of the primary. You will recall from "ELI the ICE man" that the inductive voltage leads the inductive current by 90°, This results in the relationship illustrated in Figure 18-8 where it can easily be seen that I_{Pt} is actually the vector addition of I_P and I_m. In most practical cases I_m is very small compared with I_P and thus I_{Pt} is approximately the same as I_P. Differences can become more noticeable when a transformer secondary is lightly loaded, that is, when a secondary draws little current. Consider the following example.

Figure 18-8. Total Primary Current

Example 18-2

The transformer in Figure 18-9 has a turns ratio of 6.50 and has a magnetization current of 12.8 mA. What would be the expected total primary current?

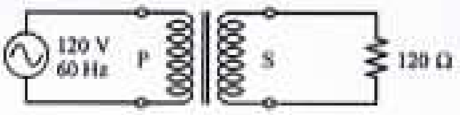
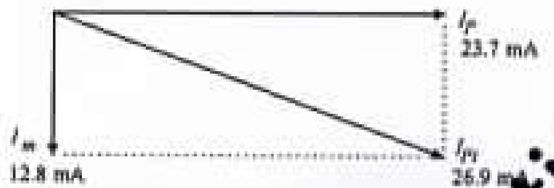


Figure 18-9. Circuit for Example 18-2

$V_S = V_P / r = 120\text{ V} / 6.50 = 18.5\text{ V}$
$I_S = 18.5\text{ V} / 120\ \Omega = 154\text{ mA}$
$P_S = V_S \times I_S = 18.5\text{ V} \times 154\text{ mA} = 2.84\text{ W}$
$P_P = P_S = 2.84\text{ W}$
$I_P = P_P / V_P = 2.84\text{ W} / 120\text{ V} = 23.7\text{ mA}$



$I_{Pt} = \sqrt{(I_P^2 + I_m^2)} = \sqrt{(23.7\text{ mA}^2 + 12.8\text{ mA}^2)} = 26.9\text{ mA}$

It is valuable to remember that in an energized circuit, a magnetization current always exists and, although it is often insignificant compared to the current drawn when the load is connected, it still represents energy being consumed. When one considers the effect of millions of "wall warts" constantly connected to the power line, the result is a significant quantity of wasted energy, so unplug those items when they are not in use!

Transformer Heat Losses

The most significant transformer loss is that evidenced by the fact that transformers get warm when in use. That heat produced is lost energy and we may easily account for such losses in our calculations by describing the transformer's efficiency. The general efficiency of a transformer was described earlier in Equation 18-2 where P_S represents the power delivered by the secondary winding to the load, and P_P represents the power delivered to the input of the transformer primary winding. Two examples of calculations considering losses are provided below.

Example 18-3

A transformer has a primary voltage of 120 V, a primary current of 278 mA and supplies a secondary voltage of 24.0 V to an 18 Ω load. Determine the transformer efficiency in percent.

$P_S = V_S^2 / R = 24.0\text{ V}^2 / 18\ \Omega = 32.0\text{ W}$
$P_P = V_P \times I_P = 120\text{ V} \times 278\text{ mA} = 33.4\text{ W}$
$\eta = P_S / P_P = 32.0\text{ W} / 33.4\text{ W} = 0.959$
$\eta = 95.9\ \%$

Example 18-4

Assuming an efficiency of 97 % for the transformer in Figure 18-10, and a turns ratio, r, of 2.50, determine V_S, I_S, P_S, P_P and I_P for the circuit.

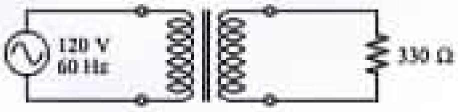


Figure 18-10. Circuit for Example 18-4

$V_S = V_P / r = 120\ \text{V} / 2.50 = 48.0\ \text{V}$
$I_S = V_S / R = 48.0\ \text{V} / 330\ \Omega = 145\ \text{mA}$
$P_S = V_S \times I_S = 48.0\ \text{V} \times 145\ \text{mA} = 6.98\ \text{W}$
$\eta = 0.97 = P_S / P_P$
$P_P = P_S / 0.97 = 6.98\ \text{W} / 0.97 = 7.20\ \text{W}$
$I_P = P_P / V_P = 7.20\ \text{W} / 120\ \text{V} = 60.0\ \text{mA}$

18.4 Multiple Secondary or Primary Windings

As explained earlier, transformers often have multiple secondary windings or multiple primary windings, and sometimes both. To deal with calculations, each winding may be dealt with on its own however several statements will help you see the whole picture. One, **total secondary power**, designated P_{St} will always be the sum of all individual secondary winding powers. Two, **total primary power**, designated P_{Pt} will always be the sum of all individual primary winding powers. And three, transformer efficiency will be defined as P_{St} / P_{Pt} and will always be less than 1.00 except for the case where you might assume an ideal transformer with 100 % efficiency. Two examples will illustrate typical calculations.

Example 18-5

For the circuit of Figure 18-11, assume a transformer efficiency of 100 % and a turns ratio of 4.50 to secondary 1 and a turns ratio of 6.50 to secondary 2. Determine V_{S1}, I_{S1} , P_{S1} , V_{S2} , I_{S2} , P_{S2} , P_{St} , P_P and I_P.

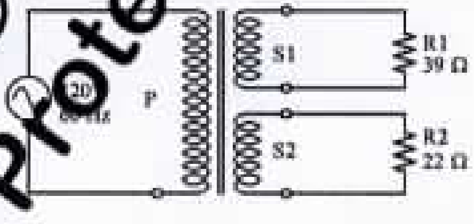


Figure 18-11. Circuit for Example 18-5

$V_{S1} = V_P / r_1 = 120\ \text{V} / 4.50 = 26.7\ \text{V}$
$I_{S1} = V_{S1} / R_1 = 26.7\ \text{V} / 39\ \Omega = 684\ \text{mA}$
$P_{S1} = V_{S1} \times I_{S1} = 26.7\ \text{V} \times 684\ \text{mA} = 18.2\ \text{W}$
$V_{S2} = V_P / r_2 = 120\ \text{V} / 6.50 = 18.5\ \text{V}$
$I_{S2} = V_{S2} / R_2 = 18.5\ \text{V} / 22\ \Omega = 839\ \text{mA}$
$P_{S2} = V_{S2} \times I_{S2} = 18.5\ \text{V} \times 839\ \text{mA} = 15.5\ \text{W}$
$P_{St} = P_{S1} + P_{S2} = 18.2\ \text{W} + 15.5\ \text{W} = 33.7\ \text{W}$
$P_P = P_{St} = 33.7\ \text{W}$ since $\eta = 1.00$
$I_P = P_P / V_P = 33.7\ \text{W} / 120\ \text{V} = 281\ \text{mA}$

Example 18-6

For the circuit of Figure 18-12, assume a transformer efficiency of 96 % and a turns ratio of 3.25 to secondary 1 and a turns ratio of 5.75 to secondary 2. Determine V_{S1}, I_{S1} , P_{S1} , V_{S2} , I_{S2} , P_{S2} , P_{St} , P_P and I_P.

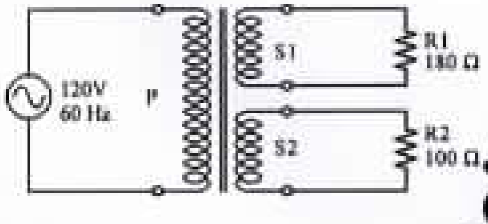
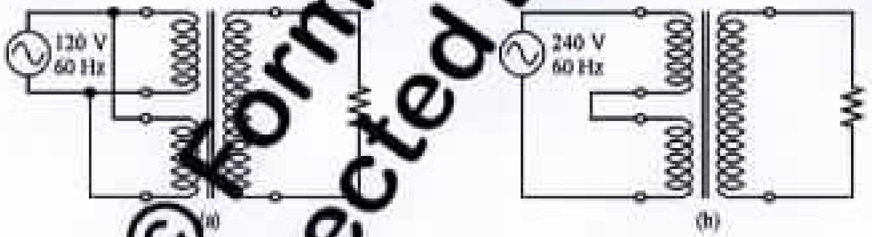


Figure 18-12. Circuit for Example 18-6

$V_{S1} = V_P / r_1 = 120\text{ V} / 3.25 = 36.9\text{ V}$
$I_{S1} = V_{S1} / R_1 = 36.9\text{ V} / 180\ \Omega = 205\text{ mA}$
$P_{S1} = V_{S1} \times I_{S1} = 36.9\text{ V} \times 205\text{ mA} = 7.57\text{ W}$
$V_{S2} = V_P / r_2 = 120\text{ V} / 5.75 = 20.9\text{ V}$
$I_{S2} = V_{S2} / R_2 = 20.9\text{ V} / 100\ \Omega = 209\text{ mA}$
$P_{S2} = V_{S2} \times I_{S2} = 20.9\text{ V} \times 209\text{ mA} = 4.36\text{ W}$
$P_{St} = P_{S1} + P_{S2} = 7.57\text{ W} + 4.36\text{ W} = 11.9\text{ W}$
$P_P = P_{St} / \eta = 11.9\text{ W} / 0.96 = 12.4\text{ W}$
$I_P = P_P / V_P = 12.4\text{ W} / 120\text{ V} = 104\text{ mA}$

Multiple primary winding are usually used to allow connections to 120 V or 240 V mains. Figure 18-13 (a) illustrates how 120 V may be applied to both primary windings in parallel. Figure 18-13 (b) illustrates how 240 V may be applied to both primary windings in series. The secondary voltage will remain the same for both situations.



(a) (b)

Figure 18-13. Multiple Primary Windings

As will be seen in the previous section, it is an interesting exercise to see if you can figure out how to apply a DPDT switch to the circuit of Figure 18-13 such that you can have one input plug and either 120 V or 240 V may be applied to it with the switch being set appropriately to achieve constant secondary voltage for either chosen input supply voltage.

18.5 Impedance Matching

As stated earlier, transformers are used as impedance matching devices. As an example, a transformer might be used to match a low impedance speaker to a high impedance source such as an amplifier. There are also other methods by which this may be accomplished. In addition, the technologist may also wish to calculate reflected impedances caused by the use of a transformer. Some examples will illustrate these situations.

Example 18-7

For the circuit of Figure 18-14, calculate the reflected impedance seen by the generator assuming a turns ratio of 15.7 for the transformer.

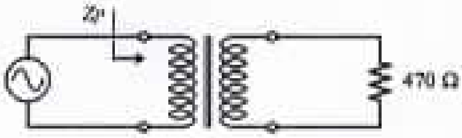


Figure 18-14. Circuit for Example 18-7

$r = \sqrt{(Z_P / Z_L)}$
$r^2 = Z_P / Z_L$
$Z_P = r^2 \times Z_L = 15.7^2 \times 470\ \Omega$
$Z_P = 116\ \text{k}\Omega$

Example 18-8

Determine the turns ratio required by the transformer of Figure 18-15 so as to match a 600 Ω generator to an 8 Ω load.

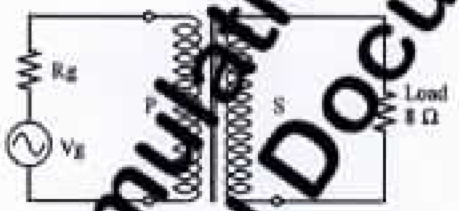


Figure 18-15. Circuit for Example 18-8

To match the generator, Z_P must appear to be 600 Ω
$r = \sqrt{(Z_P / Z_L)} = \sqrt{(600\ \Omega / 8\ \Omega)} = 8.66$
Therefore a step-down transformer is required with $r = 8.66$

An additional transformer matching application is where a transformer is resonantly tuned to a specific frequency. In this application, illustrated by Example 18-9, each side of the transformer appears as a parallel resonant circuit and consequently only those resonant frequencies achieve the amplitude and energy levels required to be transferred to the secondary. At the secondary the same selection happens again before the signals may be passed along to further circuitry. In this way frequencies off resonance are not passed and are thus filtered out of the system. The *Q* of the resonant circuits will control the width of the band of frequencies which are allowed to pass through to other circuits.

Example 18-9

Consider the transformer of Figure 18-16. The adjustable tuning slug is in the centre of its operating range. At this point, the primary inductance is 46.9 μH while the secondary inductance is 32.0 μH. Determine values for C_1 and C_2 which will allow the transformer windings to be resonant at a frequency of 60.0 kHz.

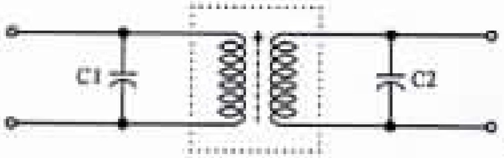


Figure 18-16. Circuit for Example 18-9

$f_r = 1 / (2 \pi \sqrt{L\,C})$
$f_r^2 = 1 / (4 \pi^2 L\,C)$
$C_1 = 1 / (4 \pi^2 f_r^2 L_P) = 1 / (4 \times \pi^2 \times 60 \text{ kHz}^2 \times 46.9 \text{ μH}) = 15$[illegible]
$C_2 = 1 / (4 \pi^2 f_r^2 L_S) = 1 / (4 \times \pi^2 \times 60 \text{ kHz}^2 \times 32.0 \text{ μH}) = 220 \text{ nF}$

18.6 Troubleshooting Transformer Circuits

Many problems occurring with transformers are associated with heat. As a consequence, the astute technologist will always look for signs that a transformer was subjected to overheating. Blackening of the wire colors is an obvious sign, but hardened or cracked wire insulation are sometimes not quite as visible.

On occasion the circuits supplied by a transformer, most often a power supply, may be the source of a transformer overload condition. It may be necessary to disconnect the load and replace it with a known load in order to assure the problem is not being caused by the transformer itself.

Ask if the client has taken the cover off of the unit requiring repair and look for evidence of this, as clients will always say they haven't touched anything. In reality they might have opened it up and tried all sorts of things like shaking, banging, dropping and perhaps they shorted the output "just to see if it was working." Momentary lapses of intelligence such as this should only result in a blown fuse. But they might have bypassed the fuse because they knew it was blown. This, of course, is a major lapse in intelligence!

I'll choose to end this chapter by including one of my favorite stories that I always enjoyed sharing with my classes. One day during a lab class, a student asked for help with his circuit, saying that he didn't think his transformer was working. I asked if he had checked for the presence of a voltage on the secondary. He said there was no voltage there. I asked if he had checked the fuse on the transformer primary and he said he hadn't done that.

I accompanied him over to his position to observe if that was going to turn out to be the fault. He correctly unplugged the transformer from the 120 V receptacle before pulling out the fuse. He looked briefly at the fuse then, without saying anything, he held it up for me to see. In that instant I could see by the look on his face that he was unsure of what it should look like. I instantly and shamelessly decided I could exploit this and have a little fun, so I said, "There's your problem, the darn fuse is shorted." Handing it back to him I said, "See, take a close look, you can see the short." He looked and said, "Yeah, I can see it!" So I suggested he take it back to Technical Services in the next wing and ask for a good one.

He dutifully did that and asked the Technical Services people to replace a perfectly good fuse at a time when there happened to be several of them standing nearby. Needless to say they ragged him pretty good and he learned on the spot exactly what a good fuse looked like and why. Then he came back hoping for some chance to pull the carpet out from under my feet to pay me back!

All innocent fun really. No fault of his; a student cannot remember everything that is presented, nor can one be alert or even present all of the time. I simply capitalized on one piece of information that was missing from his toolbox, but I am sure it is there now, never to be forgotten. If he only knew how many students have learned from that story, he would know why I continued telling it to every class–simply to lock down one more piece of information because that was my job.

It was never just a job though. When you find a job you like it's not really like work anymore. It's more like professional baseball. Remember, the umpire says "Play Ball!" He doesn't say "Work Ball!" I hope you find the job you like doing. Good luck!

18.7 A Glance Back

New Quantities

A number of quantities have been introduced in this chapter, along with their formula symbols, units and unit symbols. Table 18-1 presents a summary of those items.

Table 18-1. New Quantities Introduced

Quantity	Formula Symbol	Unit	Unit Symbol
primary voltage	V_P	volt	V
primary current	I_P	ampere	A
secondary voltage	V_S	volt	V
secondary current	I_S	ampere	A
coefficient of coupling	k	—	—
primary flux	ϕ_P	weber	Wb
secondary flux	ϕ_S	weber	Wb
primary power	[illegible]	watt	W
secondary power	P_S	[illegible]	W
transformer turns ratio	[illegible]	—	—
primary turns	N_P	turn	—
secondary turns	N_S	turn	—
transformer efficiency	η	—	—

Equations

All of the equations introduced in Chapter 18 are listed below as a useful summary for the student.

Equation 18-1 $k = \frac{\phi_S}{\phi_P}$

Equation 18-2 $\eta = \frac{P_S}{P_P}$

Equation 18-3 $r = \frac{N_P}{N_S}$

Equation 18-4 $\frac{N_P}{N_S} = \frac{V_P}{V_S}$

Equation 18-5 $\frac{V_P}{V_S} = \frac{I_S}{I_P}$

Equation 18-6 $r = \sqrt{\frac{Z_P}{Z_L}}$

Equation 18-7 $r = \frac{N_P}{N_S} = \frac{V_P}{V_S} = \frac{I_S}{I_P} = \sqrt{\frac{Z_P}{Z_L}}$

Terms Explained

The following terms have been introduced and explained within this chapter. Can you explain the meanings of all of these terms?

air core transformer
bobbin
centre-tapped winding
coefficient of coupling
core
flux linkage
ideal transformer
iron core transformer
loosely coupled
magnetization current
primary current
primary current due to secondary loading
primary voltage
primary winding
reflected impedance
secondary current
secondary voltage
secondary winding
slugs
step-down transformer
step-up transformer
total primary current
total primary power
total secondary power
transformer
transformer turns ratio