Online Radio & Electronics Course

Reading 18

Ron Bertrand VK2DQ
http://www.radioelectronicschool.com

TRANSFORMERS

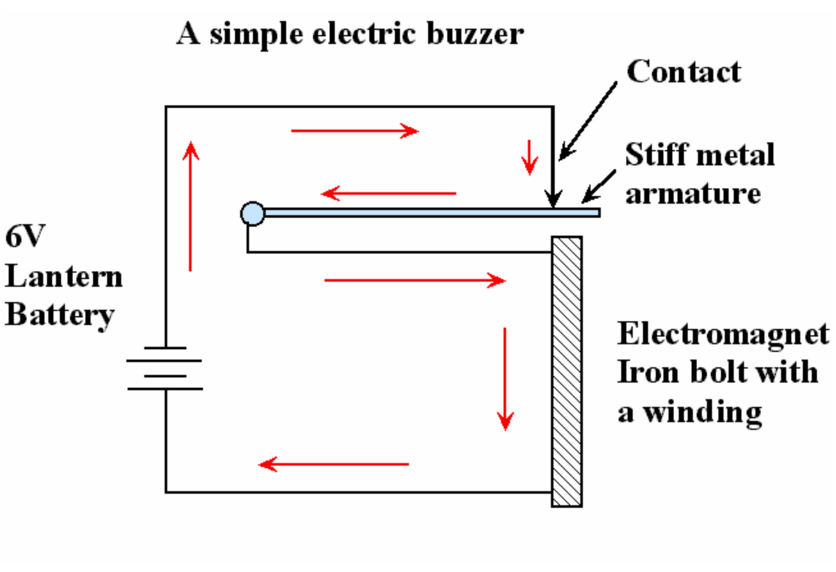
One of the most common components, or parts, used in electricity, electronics, and radio is the transformer. The name itself indicates that the device is used to transform, or change, something. In practice a transformer may be used to step up or step down AC voltages, to change low-voltage high-current ac to high-voltage low current ac, or vice versa, or to change the impedance of a circuit to some other impedance in order to transfer energy better from a source to a load.

A BUZZER

A buzzer has nothing to do with transformers. However, I am going to describe how I introduce transformers in a classroom environment. This will provide us will a little bit of revision and lead us quickly into transformers.

Take a close look at the pictorial diagram of a buzzer in figure 1. It is so easy to make one of these on a piece of board. No need for you to make one though, but it will be good if you can picture how it is made and how it works. The electromagnet is just a soft iron bolt (any bolt would do) about 75mm long. I wind as many turns of single strand telephone wire on the bolt as I can get. You could use any thin insulated wire. The armature is just a strip of tin about 5mm wide and 75mm long. A nail holds it on the board on the left-hand side. The contact on the right hand side is just another nail.

Figure 1.



The red arrows show where the current will flow when the battery is connected. The strip of tin (the armature) forms part of the circuit for current flow. However, after the battery has been connected for a fraction of a second the magnetic field builds up around the electromagnet and the electromagnet pulls the armature towards it. When the armature moves towards the electromagnet the circuit current is broken. The magnetic field about the electromagnet collapses and the armature springs back to the contact. Current can now flow again and the whole cycle is repeated over and over. The result is that the motion of the armature hitting the electromagnet makes a buzzing sound. We have a buzzer! If the armature was extended with a rod and on the end of the rod we had a small weight (hammer) which is set up to strike a bell, we would have an electric bell.

What type of current would flow in this circuit?

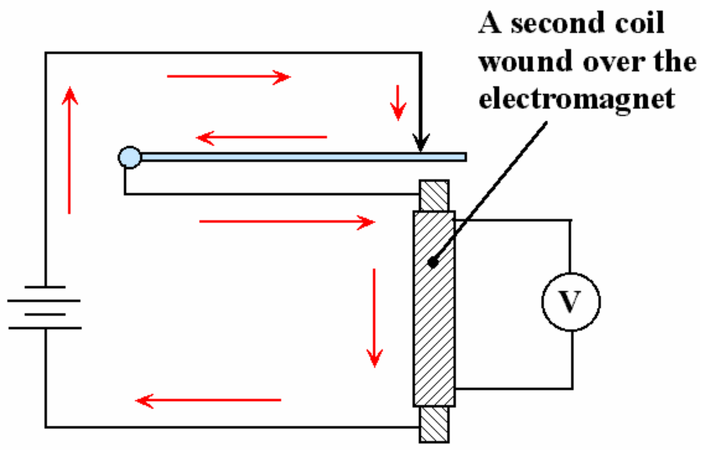
I hope you thought pulsating DC, or DC which is being turned on and off rapidly. Now think about the magnetic field around the electromagnet. It is a pulsating magnetic field, or perhaps more importantly, it is a magnetic field which is continually varying. It never stays still as it is either expanding when the current is on, or collapsing when the current is off.

Let's make a modification to our simple buzzer circuit to demonstrate the action of a transformer. Refer to figure 2.

All I have done is wound a second coil of wire around the electromagnet using insulated wire and connected it to a voltmeter. The two coils (inductors) are insulated from each other because of the insulation on the wire.

Now, do you remember when we discussed inductance and alternating current? We talked about Faraday's law of magnetic induction.

Figure 2.



Turning the electromagnet into a transformer

Faraday's law says: When relative motion exists between a conductor and a magnetic field an emf is induced into the conductor.

Is there relative motion between the conductors on the second coil and a magnetic field? Yes, there is. **An emf (voltage) is induced into the second conductor and this will be shown by the voltmeter**. We have created a simple, though very inefficient **transformer**. Generally a transformer has two windings. The **primary** winding is supplied with some type of current that will cause the magnetic field around it to vary. In our experiment the **primary** winding is the coil of wire around the electromagnet. The other winding of a transformer is called the **secondary** winding. In our experiment this is the coil of wire wound over the top of the electromagnet.

So a transformer is basically two windings (coils, inductors) wound on a common core or former. The primary winding is fed with some type of varying current so that a **moving magnetic field** is created around it. The moving magnetic field created by the primary winding causes an induced emf into the secondary winding.

For a transformer to work the primary winding must have a current through it that produces a varying magnetic field. This is virtually any current other than DC, such as AC, pulsating DC, varying DC, and the like.

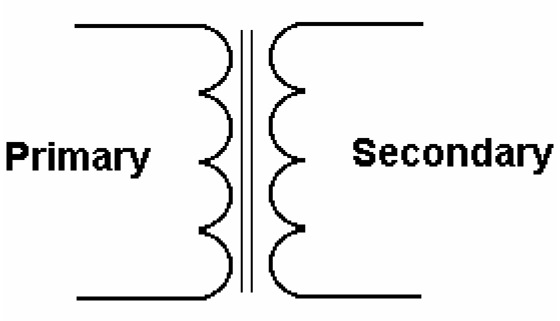
What we need to learn is the uses for a transformer and how we can determine the amount of induced voltage into the secondary.

Obviously we could reason that the amount of induced voltage into the secondary would have something to do with the voltage on the primary and the ratio of the number of turns on the primary and secondary. We will discuss this relationship in more detail shortly.

Transformers do not have to have a magnetic material such as iron for a core. The core can be air. The basic function of a transformer is to step voltage up or to step voltage down, which is also a way of matching unequal impedances.

Schematic symbol of a transformer

Figure 3.



The schematic symbol for a transformer is shown in figure 3 (excluding the writing which I have added). The two vertical lines between the two windings indicate that this transformer has a laminated iron core. If no lines were shown it would be an air-core transformer.

Transformer construction

The picture above shows a common construction method for a laminated iron core transformer.

Laminated iron core

Winding the primary and secondary on an iron core improves the efficiency of the transformer since the iron core concentrates the magnetic lines of force.

The problem with iron cores is that the core is also a conductor. Go back to Faraday's law again. The core of a transformer (iron) is in a moving magnetic field. This means that small currents will be unwittingly induced into the core. These unwanted core currents are called Eddy Currents. These currents are given this name because they flow in circles in the iron core much like eddies of water around a propeller.

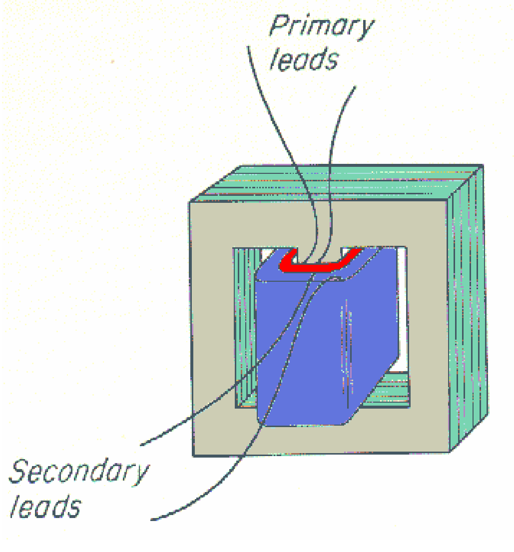


Figure 4.

Eddy currents are bad because of $P=I^2R$ losses. What this means is that current flowing through any resistance produces heat. This is fine if you want to make heat. However, the function of a transformer is not to make heat but to transform from one voltage to another. By the way, you may hear the term "I squared R losses" used. This means exactly the same thing, though "I squared R losses" can occur other ways besides eddy currents.

What is the product of the current and voltage in a circuit? Power = E x I. A transformer should ideally have no losses. This means the power in the primary circuit should be equal to the power in the secondary circuit. The power in each circuit is the product of the voltage and current in the respective circuit.

In practical transformers, particularly iron core ones, the major form of loss of power is due to eddy currents, otherwise known as "I squared R losses".

If we could increase the electrical resistance of the core without changing its magnetic properties, we would reduce the size of the eddy currents. When we discussed the properties that determine the resistance of a conductor, one of these properties was the cross sectional area, as expressed in RhoL/A. This is what we are doing when we laminate the iron core.

Imagine taking a solid iron core and slicing it into lots of thin sheets. Each sheet (lamination) will have a higher resistance to current flow than the solid iron core. We now spray each sheet with an insulating lacquer and bolt or glue the entire iron core back together again. We now have a laminated iron core, which will have less power lost in it due to eddy currents.

Eddy currents are not a problem if the core of a transformer is made of air or some other insulating material.

Another construction method for a transformer is shown in the diagram of figure 5.

Eddy currents are reduced in amplitude by laminating the core.

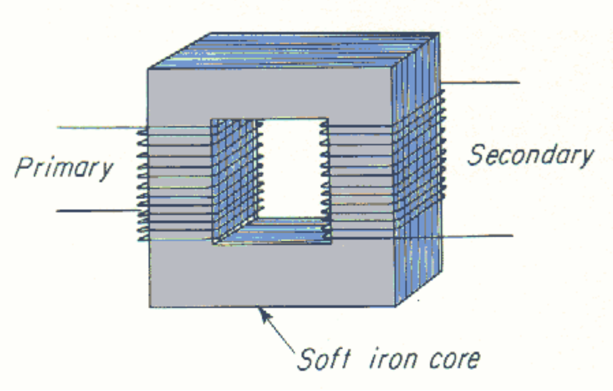
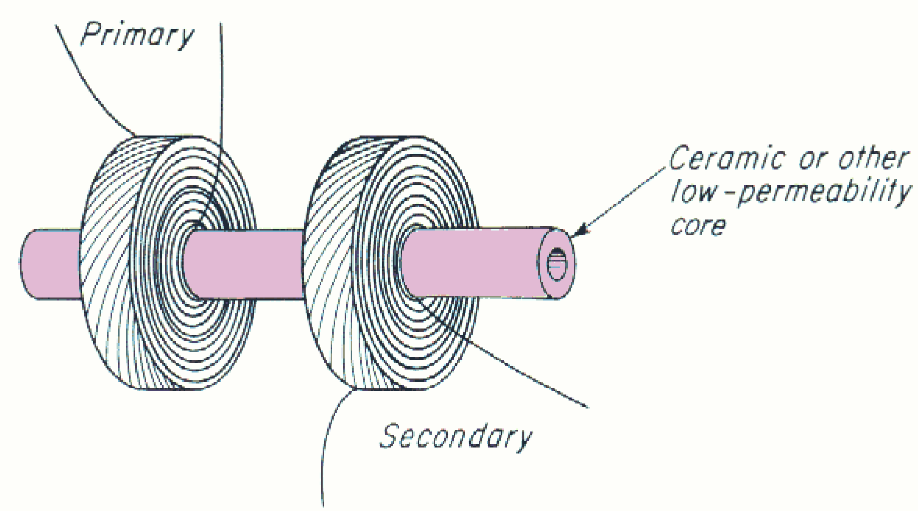


Figure 5.

Figure 6 - A non-iron-core (air-core) transformer



The type of transformer shown in figure 6 is generally used at high frequencies. Iron core transformers are **not used at radio frequencies,** as the eddy current losses become too high.

HYSTERESIS - LOSSES

If iron is in an un-magnetised state, its domains are not arranged in any particular manner. The domains are randomly orientated. When a magnetising force is applied to them, the domains rotate into a position in line with the magnetising force. If the magnetising force is reversed, the domains must rotate into an opposite position. In rotating from one alignment to the opposite, the domains must overcome a frictional hysteresis, or resisting effect, in the substance. In some materials the resisting effect is very small, in others it is appreciable. The energy converted into heat overcoming hysteresis is known as hysteresis loss.

Hysteresis occurs in iron cores of transformers. As frequency is increased, the alternating magnetising force will no longer be able to magnetise the core completely in either direction. Before the core becomes fully magnetised in one direction, the opposite magnetising force will begin to be applied and start to reverse the rotation of the domains. The higher the frequency, the less fully the core magnetises.

Transformers operated on low frequency AC may not have much hysteresis, but the same cores used with a higher frequency have more hysteresis and may also be less efficient.

COPPER LOSS

Iron-core transformers are subject not only to eddy-current and hysteresis losses in the core but also to a **copper loss** which occurs as heat is lost in the resistance of the copper wire making up the windings. The current flowing through whatever resistance exists in these windings produces heat. The heat in either winding, in watts, can be found by the power formula $P = I^2R$. For this reason the copper loss is also known as the I^2R loss. The heavier the load on the transformer (the more current that is made to flow through the primary and secondary), the greater the copper loss.

With one layer of wire wound over another in a transformer, there is a greater tendency for the heat to remain in the wires than if the wires were separated and air-cooled. Increased temperature causes increased resistance of a copper wire. As a result it becomes necessary to use heavier wire to reduce resistance and heat loss in transformers than would be required for an equivalent current value if the wire were exposed to air during operation.

EXTERNAL-INDUCTION LOSS

Another loss in a transformer is due to external induction. Lines of force expanding outward from the transformer core may induce voltages and therefore currents into outside circuits. These currents flowing through any resistance in an outside circuit can produce a heating of the external resistance. The power lost in heating these outside circuits represents a power loss to the transformer, since the power is not delivered to the transformer secondary circuit. Actually, in a well designed transformer, the amount of power lost in this fashion is usually very small.

THE VOLTAGE RATIO OF TRANSFORMERS

One of the main uses of transformers is to step up a low voltage AC to a higher voltage. This can be accomplished by having more turns on the secondary than on the primary.

The turns ratio of a transformer is the ratio of the number of turns on the primary to the number of turns on the secondary.

If a transformer has equal number of turns on the primary and secondary (it happens) then the turns ratio is 1:1.

If a transformer has 100 turns on the primary and 10 turns on the secondary then the turns ratio is 100:10 which is the same as 10:1.

If a transformer has 300 turns on the primary and 900 turns on the secondary then the turns ration is 300:900 which is the same as 1:3.

The shorthand for primary turns is usually N_p and for secondary turns N_s.
The voltage of the primary is usually designated E_p and for the secondary E_s.

The turns ratio of a transformer is the same as the voltage ratio. In other words:

$$N_p/N_s = E_p/E_s$$

A Worked Example.

A transformer has 100 turns on the primary and 10 turns on the secondary. If 500 volts AC is applied to the primary what will be the secondary voltage?

$$N_p/N_s = E_p/E_s$$

We could transpose this equation for E_s but for exam purposes an easier approach is to see that the turns ratio of the transformer N_p/N_s is 100/10 or 10:1. For every 10 volts on the primary there will be 1 volt on the secondary. Therefore, the secondary voltage will be 500/10 or 50 volts.

This is a step down transformer because the secondary voltage is lower then the primary voltage. A step up transformer is where the secondary voltage is higher than the primary voltage

The turns ratio is equal to the voltage ratio.

A lot of beginners get confused, particularly with step up transformers. You can make a transformer to convert say 10 volts AC to 10,000 volts AC. At first sight it may appear that you are getting something for nothing - no such luck.

The power in the primary circuit is equal to the power in the secondary circuit (less losses).

No power is gained or lost (purposely) in a transformer. If a transformer steps voltage up, there is a corresponding decrease in secondary current. So we may get more secondary voltage, but at the sacrifice of secondary current.

Take an Arc Welder. This is basically a huge step down transformer. 240 volts AC to the primary and only a few volts on the secondary, but a huge amount of current for melting metals is available in the secondary circuit.

TRANSFORMER ISOLATION

One major advantage of transformers is the safety isolation they can provide. Small battery eliminators are really just small transformers. The primary connects to 240 VAC and the secondary may be 12 VAC (or converted to DC).

Because there is no metallic contact between the secondary and the primary, it means the user of the low voltage equipment is isolated from the mains power, providing a great safety advantage.

AUTO TRANSFORMERS

An autotransformer consists of a single winding with one or more taps on it, as shown in figure 7.

Auto transformers are not "automatic". The name "auto" is used for them as the first application of this type of transformer was the car ignition coil.

Everything we have discussed about other transformers (mutually coupled transformers) applies to autotransformers.

Autotransformers used on high voltages are dangerous, as they provide no isolation between the user and the supply. These transformers are not commonly used in radio and communications anymore.

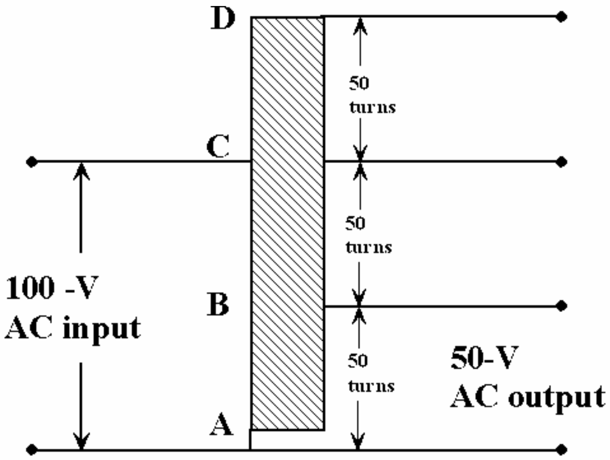


Figure 7 – Auto transformer.

IMPEDANCE MATCHING

We have not discussed the purpose of impedance matching yet, and I am not going to now. Suffice to say, in electronics it is important to connect components together which are of the same impedance (impedance is the total opposition to current flow in an AC circuit).

For example your stereo system may specify that you use 8 ohm speakers. If you use speakers other than 8 ohms on your stereo, you damage the stereo or at least get poor quality sound.

A transformer could be used to connect any impedance speaker to a stereo system. The impedance ratio of a transformer is again related to the turns ratio. All I will give you for now is the equation:

$$\frac{Np}{Ns} = \sqrt{\frac{Zp}{Zs}}$$

$$Zp = Zs\left(\frac{Np}{Ns}\right)^2$$

You will not have to use the equations in the exam but it is good to have them as a reference.

Z_p = impedance looking into the primary terminals from the power source.

Z_s = impedance of load connected to secondary, and

N_p / N_s = turns ratio, primary to secondary.

The basic equation tells us that the turns ratio is equal to the square root of the impedance ratio.

HOW IS A TRANSFORMER ABLE TO MATCH IMPEDANCE?

Suppose we had a transformer with 2400 turns on its primary and 150 turns on its secondary. The turns ratio of this transformer is 2400 / 150 or 16:1.

The turns ratio is 16:1. Let’s see if we can work out what the impedance ratio would be.

For the sake of this exercise lets apply a primary voltage of 240 volts. Since the voltage ratio is equal to the turns ratio, the secondary voltage must be 15 volts.

The turns ratio is 16:1 and this gives us the same voltage ratio, that is, 240 / 15 = 16:1.

Now for calculation purposes I have to nominate a maximum secondary current that the transformer can handle. This value is totally arbitrary and any value can be chosen for our purposes. The maximum secondary current I will choose is 1 ampere.

Our transformer is shown in figure 8.

Since we know the secondary current and voltage (for full load) we can work out the secondary power:

$P_{\mathbf{secondary}} = E_{\mathbf{secondary}} \times I_{\mathbf{secondary}} = 15 \times 1 = 15$ watts.

Since the power in the primary is equal to the power in the secondary (neglecting losses) we can, knowing the primary power is 15 watts, work out the primary current:

$I_{\textbf{primary}} = P_{\textbf{primary}} / E_{\textbf{primary}} = 15 / 240 = 62.5$ mA.

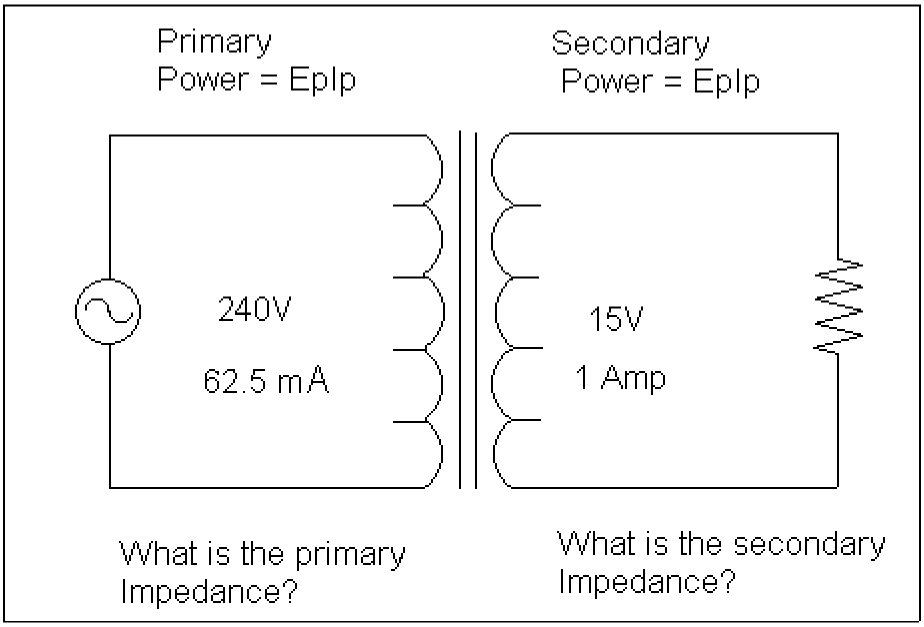


Figure 8.

Where is all this taking us? Well, impedance is the ratio of voltage to current:

$Z = E / I$.

We know what the current and voltage is in the primary and secondary circuit, what is the primary and secondary impedance?

Impedance of the primary = $E_{\textbf{primary}} / I_{\textbf{primary}}$ = 240volts / 62.5mA = 3840 ohms.

Impedance of the secondary = $E_{\textbf{secondary}} / I_{\textbf{secondary}}$ = 15 / 1 = 15 ohms.

In other words, the impedance ratio of this transformer is 3840:15 or 256:1. I have gone about it the long way just to show you how it works.

The rule you need to remember is that:

(a) The turns ratio is equal to the square root of the impedance ratio

or

(b) The impedance ratio is equal to the square of the turns ratio.

N_p / N_s = Square root of (Z_p/Z_s)

USING THE FORMULA

Let's work out the impedance ratio from the formula. From the last example we know the voltage ratio is 240:15 which is the same as the turns ratio N_p/N_s.

N_p / N_s = square root of (Z_p/Z_s)   (remember Z_p/Z_s is the impedance ratio)

240 / 15 = square root of (Z_p/Z_s)

16 = square root of (Z_p/Z_s)

We do need to get rid of the "square root" on the right hand side. To do this we "square" both sides, and we are left with:

16 x 16 = Z_p/Z_s

or

Impedance ratio = Z_p/Z_s = 16 x 16 or 256 : 1

This agrees with our earlier calculation.

If you have trouble using this equation ask your facilitator for help. Many people do, so don't be afraid to ask for help.

The type of question you need to answer in the AOCP exam is something like this.

What is the turns ratio of a transformer that is required to match a 600 ohm source to a 50 ohms load?

Z_p = 600 Z_s = 50

Turns ratio = N_p / N_s = square root of (600/50) = 3.464 to 1.

For every turn on the secondary there will be 3.464 turns on the primary.

Some practical transformers

Figure 9.

The large transformers in figure 9 are power transformers for use in power supplies. The smaller ones are for use in audio circuits, primarily to match impedance.

The picture in figure 10 is of a battery eliminator taken apart and showing the small transformer inside.

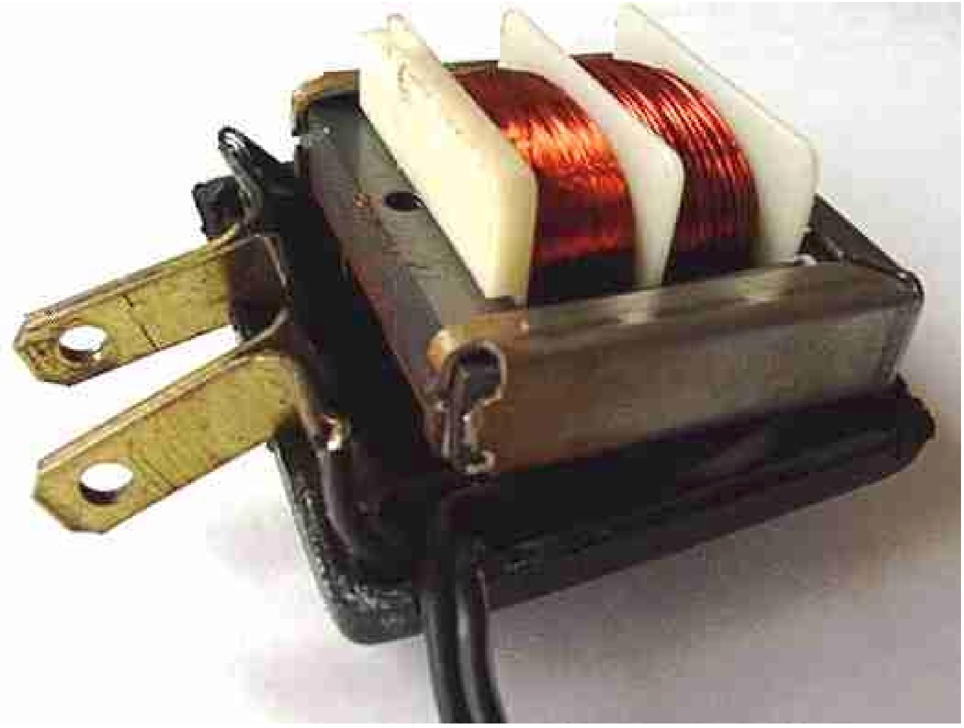


Figure 10.

Figure 11 is of a couple of power autotransformers wound on a toroid former.

Figure 11.

End of Reading 18.
Last revision: January 2002
Copyright © 1999-2002 Ron Bertrand
E-mail: manager@radioelectronicschool.com
http://www.radioelectronicschool.com
Free for non-commercial use with permission