IEEE Lesson Plan:

# Basic Electric Transformers

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## Lesson Focus

This lesson focuses on transformers as one of the most important components in any electrical system. Students engage in a hands-on activity where they build and test a simple but working transformer, using inexpensive materials.

## Lesson Synopsis

The lesson begins by outlining the work of some of the early experimenters and the sequence which eventually led to the realization of how a changeable electro-magnetic field could be harnessed to do real work. From there the lesson goes on to outline the advantages offered by alternating current (ac) power systems over the direct current (dc) systems. A hands-on activity in which the students can build and test a simple but working transformer, using inexpensive materials obtainable in any hardware store, at a cost of only a few dollars and are re-usable. The lesson ends with a section in which the students are invited to discuss with the teacher, various ways in which they think their demonstration transformer could be improved. A glimpse of a very large "real world" transformer is also provided.

## Age Levels

14 to 18

## Objectives

*Students will:*

- Learn about what transformers do.
- Learn about how transformers are made.
- Make small demonstration transformers.

## Anticipated Learner Outcomes

*Students will gain:*

- Ability to understand and articulate what transformers are, what they do and where they can be found.
- The importance of disciplined team work.
- Problem solving.

## Lesson Activities

- It is suggested that the first (45-minute) session be devoted to the teacher explaining to the class the text material and diagrams contained in this lesson. Teams of students then build and test their transformers in subsequent sessions.
- Desirably the class should have enough sets of components to provide an activity for all students working in groups of, say, four or five to a team. The students can decide for themselves whether they help assemble the transformer "core" or to help wind the two coils. (Note that all these components can be re-used many times over, so there is no wastage). See Figs 8 – 13. Depending on the age and manual dexterity of the students, one or maybe two further sessions should be allowed for them to build their demonstration transformers.
- The core is made from 24 small (2" x 2") steel corner brackets, available in any hardware store. These can, of course, be re-used over and over again.
- The formers on which the coils are wound are short pieces of 1-1/8" inside diameter plastic water pipe, cut to a length of 1" as accurately as possible. To save time, it is suggested the teacher prepares these pieces ahead of time. The wire used should be "magnet wire", meaning that it is insulated with varnish. It is suggested that #30 AWG be used (or a wire of about 0.25 mm diameter). (AWG stands for "American Wire Gage). Anything smaller is difficult to handle, and anything larger takes up too much room on the former. (A 1lb. spool of #30 magnet wire contains about 2,000 ft of wire, sufficient for at least 10 pairs of coils). Two students are required to wind the coils; one to hold the spool of wire, while the other winds the wire onto the short lengths of plastic pipe. One coil should have 150 turns and the other 300 turns. This should be done slowly and deliberately, with both students counting, to avoid errors! Wrap each coil with green masking tape and mark each with the number of turns.

## Resources/Materials

- Teacher Resource Documents (attached).
- Student Resource Sheets (attached)
- A list of items required for the hands-on exercise, plus some helpful photographs showing the assembly process, are included at the end of this lesson

## Alignment to Curriculum Frameworks

- See attached curriculum alignment sheet.

## Internet Connections

- TryEngineering (www.tryengineering.org)

## Recommended Reading

- Wikipedia "How transformers are made".

## Optional Writing Activity

- Having discussed the obvious limitations of this very simple demonstration unit, students should be asked to set out ways in which they think it could be improved.

## Source

- This lesson contributed to TryEngineering by Dave Hepburn, IEEE Canada.

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IEEE Lesson Plan:

# Basic Electric Transformers

## *For Teachers:*
## *Teacher Resource*

### Lesson Goal
Students will learn that transformers are one of the most important components in any electrical system. Students engage in a hands-on activity where they build and test a simple but working transformer, using inexpensive materials.

### Lesson Objectives
*Students will:*
- Learn about what transformers are.
- Learn about what transformers do.
- Learn about how transformers are made.
- Teams of two or three make small demonstration transformers

### Materials and Costs
See the Transformer Parts List at the end of this lesson. In most instances, if the hardware store understands that the materials are for a school project, they will give a substantial discount.

### Additional Safety Note:
Students should be clearly warned that on no account should they attempt to connect this simple apparatus to the 120 volt ac domestic supply.

### Time Needed
- Two to three 45-minute sessions

## *For Teachers:*
## *Teacher Resources*

**Let there be no misunderstanding!**
If the electrical transformer had never been invented, life as we know it today would still be back where Thomas Edison left it in 1880. Without the transformer, we would still be using "direct current" (DC) for all domestic and industrial purposes. There would be no long distance transmission of energy and no large scale power generating stations, either thermal, hydro or nuclear. In short, there would be no economies of scale and no major industries. Direct current is fine for sending relatively small amounts of electricity (say, 1,000 kW) relatively short distances, (say a mile or two). But beyond that, either the voltage at the user's premises would have to be too high for safety (say 1,000 volts) or the transmission losses ($I^2R$) would become unacceptably high (say 30% or more).

Fig. 1

And as if all that were not enough, transformers have two additional advantages:

- They have no moving parts and are therefore robust, cheap and very long-lived. 50 years is normal and some go to 100 years.

- Similarly, because they have no moving parts, they are astonishingly efficient. Even the small grey cylindrical things you see on hydro poles outside your house, (Fig 1) have efficiencies of 97% or better, while the really big ones in major substations (see Figs 12, 13, & 14) have efficiencies of 99.9% or better.

Figure 1, above, shows a typical single phase distribution transformer. The size is probably 10 or 15 kVA and would be enough for maybe 3 or 4 houses, depending on whether or not they have electric heating. Voltage would be the standard North American figure of 120 Volts. For more details, see Figures 9, 10 & 11 below.

**The Basics**
**Flux-Turn Linkages, Rate of Change of Flux-Turn Linkages, and Induced Voltage**

This effect was first discovered by Michael Faraday in 1830. His original equipment seems to have been lost, but the engraving in Figure 2 below was published in a book entitled Magnetism & Electricity by a Professor Poyser in 1893. Note the following components:

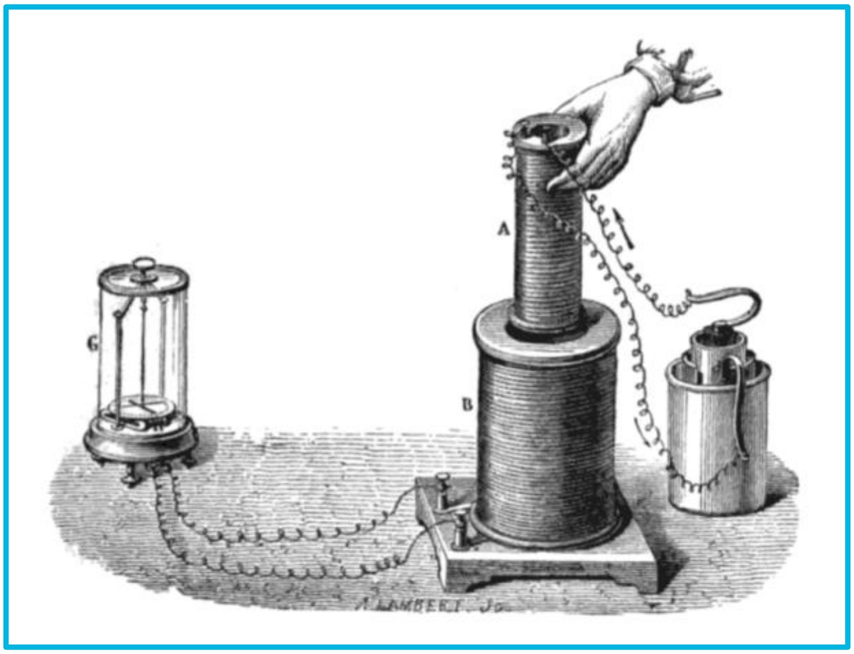


Fig. 2

A is the slightly smaller of the two coils of wire. This coil is connected to a battery (presumably some improvement on Volta's Pile). Coil A is therefore carrying a current (note the arrows) and is producing a magnetic field. The strength of this field is not known and is not important. Coil B is slightly larger than coil A and is connected to a small coil of wire and a magnetic needle.

What Faraday noted was that when he lowered coil A into coil B, the magnetic needle "twitched" in a certain direction. When coil A was pulled back out, the needle twitched in the opposite direction. When coil A was not moving, the needle did not move either. He probably also noticed that the faster he moved coil A, the more briskly the needle twitched.

This exercise was intended to demonstrate – in Faraday's own words - "the fact that an induced voltage is proportional to the rate of change of flux-turn linkages". Note here also the use of the term "Induced" voltage. The word induced is used here to distinguish between a voltage arising from some sort of magnetic interaction, and a steady voltage coming from a battery or other source. Double the number of magnetic lines and the voltage will double. If you double the rate of change, you double the voltage. Or if you double the number of turns on one or both coils you will get twice (or four times) the voltage.

The original of this demonstration seems to have been lost. But from the engraving done many years later it would seem that a remarkably high standard of quality was maintained. Consistently good quality copper wire would also have been difficult and expensive to obtain. It was insulated with silk (yes, silk). Today copper wire is readily available, insulated with varnish. Both coils were carefully wound onto wooden cylinders. As a matter of interest, if you could arrange a mechanism which could smoothly insert and withdraw the coil A, (a slow speed steam engine perhaps), you would have immediately made yourself an alternating current (AC) generator. As a matter of interest, some early experimenters did in fact attempt to make generators this way, but a rotating magnetic field was soon found to be better.

## A Very Interesting Piece of History

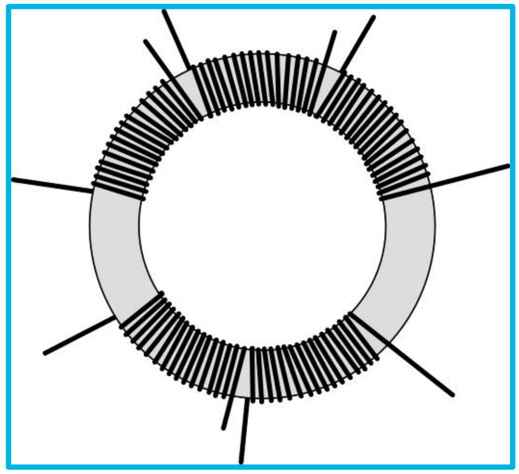

Fig. 3

Figure 2 was extracted from the present author's personal copy of a book by a Prof. Poyser of Trinity College, Dublin, published in 1893. In the normal course of events, one does not quote extensively from such material, but in this particular instance it was thought that the historical interest of the conjunction of Dr. Poyser's book with the notes written by Michael Faraday, should override protocol. The title of the book is Magnetism and Electricity and was published by Dr. Poyser, in 1893, 26 years after the death of Faraday. As will be seen from the quotation below, Poyser stated clearly that the first transformer was invented by Faraday in 1831, a year after his experiment with electromagnetic induction shown in Figure 2. You will see from Figure 3 that Faraday made himself a "donut" of soft iron wire around which he wound two smaller coils of copper wire. However Faraday did not say how big was the central donut. But remember that when Poyser wrote his book, he was writing about cutting edge technology.

Faraday's original notes mentions 5 separate coils seemingly distributed around the perimeter of the Donut.

Quote from Dr. Poyser:

> "The first transformer was invented by Faraday in 1831, and consisted of two separate coils wound on a soft iron ring. He wound 72 feet of bare copper wire (of about 18 B.W.G., or British Wire Gage) in three helices, one over the other, and insulated by layers of calico. The ends of each helix were brought out so the coils could be used either together or separately. On another part of the ring he would 60 feet of wire in two helices, which were then connected in series with a galvanometer. When the three helices were joined in series, and connected with a battery so they formed the primary, there was a sudden deflection of the galvanometer needle in the secondary. The needle soon came to rest, but when the circuit was broken, it suddenly deflected in the opposite direction.
>
> In any transformer, it is immaterial whether one coil be wound over the other or separately, or whether a straight bar be used, instead of a ring: in practice all these forms were used.
>
> If a steady current be sent through one coil, the inductive effect in the second coil will be at the making or breaking only; but if an alternating current be used, a current will be induced in the other at each alternation, without using a circuit breaker."

There are a few modern comments to be offered here from the above quote:

- The wording here is presumably that of Poyser and not Faraday.
- The term "galvanometer needle" is not used today. Usually we speak of either a "Mirror galvanometer" or compass needle. From the sketch in Figure 2, it would appear that a compass needle was used.

In the last line of the above quote, the word "alternation" is found. It is interesting to note that there are today still in use, many generators built in the late 1890's which carry nameplates rated in "Alternations per Minute", rather than Hertz or Cycles per second. Note also that one complete cycle comprises two alternations. One has to wonder where Faraday thought he would get alternating current in 1831.The history of industrial equipment can be interesting, n'es'ce-pas?

## Moving On A Bit

### Permeability, Saturation and Hysteresis
### Magnetic Permeability:

By this point the concept that ferrous metals make good magnets should be relatively clear. By experiment over the years, metallurgists have found that different grades of iron make different, i.e. stronger or weaker, magnets. Similarly that some grades of iron can retain their magnetism over very long periods. This can be measured and is calculated in terms of the number of lines of magnetic force per square inch (cm) of cross- section of the iron used. By way of illustration, a common figure for a maximum flux density in ordinary soft iron or mild steel is about 15.000 lines per square cm. In other words the iron mentioned above would be said to have a permeability of 15,000. By contrast, and as a standard reference, the permeability of air is taken as 1.00. This is a very important concept to keep in mind, because it tells us that if you have a coil of wire with air inside, you will need 15,000 times more effort to produce a magnet of the same strength. This is a huge difference. Or conversely, with a coil of wire having an iron core inside it, you can get the same strength using 1/15.000 (0.000066) the amount of effort! The student should appreciate, however, that the matter of "lines of magnetic force per square cm" (or square inch) is purely a concept to facilitate calculation. They cannot be seen with the naked eye.

### Saturation:

Following on from the above, most steels exhibit a marked tendency resist additional flux density beyond a certain point. In other words, the steel simply does what the word implies – it saturates, and cannot be further magnetized.

**Visualizing Magnetic Hysteresis and Saturation:**

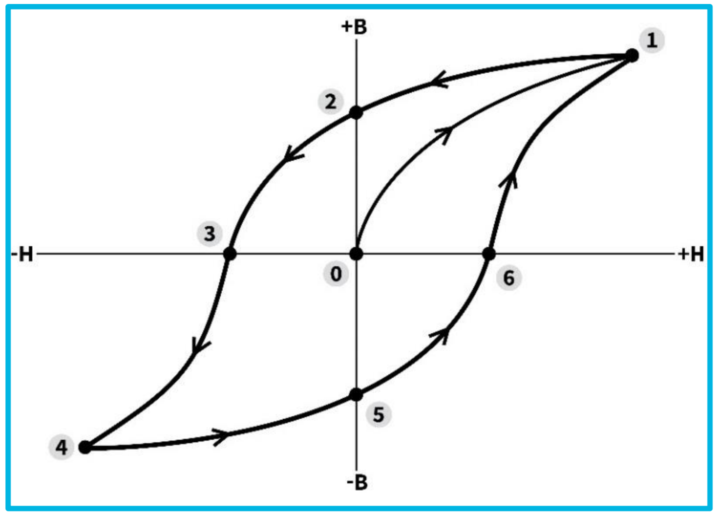


Fig. 4

During their early investigations, the pioneers in this field made another interesting discovery. They plotted a graph of the flux density (lines/sq. cm) versus current in the coil. This current, was of course DC from a battery. See Figure 4 and examine it in the following sequence:

The horizontal axis represents the force which is producing the magnetization, in this case a coil of wire surrounding a steel core. The international symbol for magnetizing force is H and is measured in Oersteads after the early Danish experimenter Hans Christian Oerstead. The international definition of an Oerstead is obscure, but in practical terms what you would be measuring would be the current (amps) in the coil of wire. You would of course, switch on the current and gradually increase it, taking measurements as you go.

The vertical axis represents the flux density in the magnetic material. This is measured in lines per square inch of the material, or lines per square cm, as the case may be. The international symbol for magnetic flux density is B. The international units for flux density are obscure. But think of it as the strength of the magnet. Obtain a series of small steelwashers. The stronger the flux the more washers it can lift. Then as you reduce the flux, the washers will begin to drop off.

1. Examine now the central point of the diagram where the two axes intersect. It is intentionally marked as zero because at that point there is no current and no magnetic flux. However the first time you attempt to magnetize a new core, you would obtain a curve similar to the line from zero to 1. Point 1 represents the point at which, even though you increase the amperes, you get no more flux. This is known as the saturation point.
2. Then, as you gradually decrease the current in the coil, the flux density would also go down. But surprisingly, even at point 2, when the MMF (Oersteads) is zero, you will find there is still some magnetism left. This is known as the Remainance point.
3. Next you could reverse the connection of the battery and begin gradually increasing the current in the opposite direction. At point 3 on the curve you would reach zero magnetism. The length of the line between zero and 3 represents the Coercion force, because that is the MMF required to “coerce” the magnetic flux in the steel back to zero.
4. Then from point 3 to 4, as you keep increasing the MMF, you will get more magnetic flux until the steel saturates again, but in the opposite direction. So point

4 would be the saturation point in the reverse direction. This would normally be the same value as in the positive direction.

5. As a point of interest here, note that in many applications there is no practical difference between a +B and a –B. A magnetic crane for example, would lift just as well either way. But in other applications, such as DC and AC motors for example, a reversal of polarity would tend to reverse the rotation of the motor. See other "basic" lessons in this series.
6. From point 4 onwards, it is all downhill, so to speak, because you will find that as you decrease the current again, you will reach a point 5 where there is zero flux density, just as at point 2 previously, and then on to point 6 and back to point 1.

7. Finally, if you were to switch everything off while at points 3 or 6 and then start again, you would find you were in effect at point zero.

**Class Challenge:**
Debate item 7 above amongst yourselves. To shut down and then restart, would you be at point zero or either of points 1 or 3?

**The Practical Meaning of Hysteresis**

You will appreciate that "coercing" the magnetic flux from point 2 down to, 3 or from point 5 down to 6 requires a certain amount of energy. In practical terms what this amounts to is that the area inside the hysteresis curve is an indication of how much energy is consumed in what is practically a net loss to the equipment. And of course in North America this happens 60 times a second. (In other locations this figure is "only" 50 times per second. But it still mounts up. The steel used in electric motors and transformers is therefore specially blended to keep the hysteresis curve as narrow as possible. But in other applications such as electric heating, the hysteresis loss is less important and the hysteresis curve can be much wider.

Students should note that many other materials also generate internal hysteresis loss and heating. Automobile tires, for example often reach quite high temperatures, even in winter, due to hysteresis in the rubber. If allowed to reach a high temperature, the tire could burst. Remember also that tires are under about 30-40 psi internal pressure.

By way of illustration, a common figure for a maximum flux density in ordinary soft iron or mild steel is about 15.000 lines per square inch. In other words the iron mentioned above would be said to have a permeability of 15,000. By contrast, and as a standard reference, the permeability of air is taken as 1.00. This is a very important concept to keep in mind, because it tells us that if you have a magnet which has only a coil of wire with air inside, you will need 15,000 times more effort to produce a magnet of the same strength. This is a huge difference. Or conversely, with a coil of wire having an iron core inside it, you can get the same strength using 1/15.000 (0.000066) the amount of effort! The student should appreciate here that the matter of "Lines of Magnetic force" is purely a concept, to facilitate calculations. They cannot be seen or measured.

**Saturation:**

Following on from the above, most steels exhibit a marked tendency resist additional flux density beyond a certain point. In other words, the steel simply does what the word implies – it saturates, and cannot be further magnetized.

**How Does a Transformer Work?**

The operation of a transformer is really quite simple, and is the reason why transformers are cheap, robust and efficient. In 1830, Michael Faraday discovered the fact that electricity could make magnetism, and that magnetism could make electricity. The two are inextricably connected. His apparatus is shown in Figure 2 above. It was probably one of the most important discoveries in the history of science, and one for which he acquired international fame. This demonstration proved that electricity can make magnetism and that magnetism can make electricity. The two are inextricably linked. The following year, 1831, Faraday carried his research a stage further, when he assembled the simple device shown in Figure 3, and the workings of which are described in the text from Dr. Poyser quoted above. This was in fact the original transformer, although whether or not Faraday actually called it a "transformer" is not clear. Indeed even the word "transformer" probably had not been invented at that time. But 50 years or so later, when alternating current generators first became available (Siemens of Germany), it became apparent to experimenters that applying a comparatively low alternating voltage to the "Low Voltage" winding of a "step-up transformer", could produce significantly higher voltages in the other "High Voltage" winding, which in turn were ideally suited to long-distance transmission of electrical energy. Some of the early experimenters in this field were Gaulard and Gibbs in Europe, Ferranti in Britain, together with Stanley and Westinghouse in the United States, all in the period 1880 - 1885. In fact when Dr. Poyser published his text book in 1893, he was writing about cutting edge technology.

As a historical note here, Edison, whose early experiments were all with direct current, was bitterly opposed to alternating current – for personal and commercial reasons – and fought it for many years, before more or less capitulating in the early 1900's.
Figure 5 illustrates how a simple transformer works. Assume the primary winding has 100 turns and the secondary winding has 50 turns. Assume also that the primary winding is connected to a source of AC voltage. This voltage will send an AC current through that winding. The current then induces an alternating magnetic flux in the steel core. Assuming the core has no significant air gaps, this flux will permeate right round the closed loop of iron. In doing so, each time the flux alternates from "North" to "South" and back again, it will induce a change of flux-turn linkages in the secondary winding. Assuming that the magnetic flux is uniformly distributed throughout the core, the flux-turn-linkages in both windings will be the same. In this example, if the primary winding has 100 turns and that 100 volts is applied to it, that will represent (100 Volts/100 turns) = 1.0 volt per turn. And then assuming all flux created in the primary winding links with the 50 turns in the secondary winding, this will produce (1 volt/turn x50 turns) = 50 Volts in the secondary winding.

## Leakage Flux

In actual fact not all the flux produced by the primary winding will link with the turns in the secondary coil. And some of the flux produces by the secondary coil will not link with the coils in the primary coil. Some of it leaks away, as shown in Figure 6. This is known as flux leakage and is largely dependent on how loosely the two coils can be situated together. Leakage flux results in a slight (maybe 3% - 5%) reduction in the voltage ratio of the transformer. But it does not materially reduce the efficiency, because the voltage ratio can be adjusted upwards slightly by adding a few turns in the secondary coil to compensate for this. And as a matter of fact leakage flux can be looked upon as a measure of "Magnet Efficiency", although it is never referred to as such.

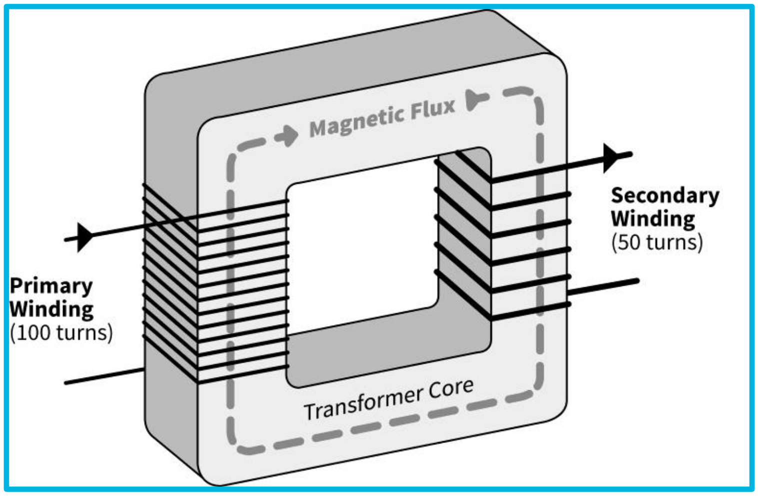


Fig. 5

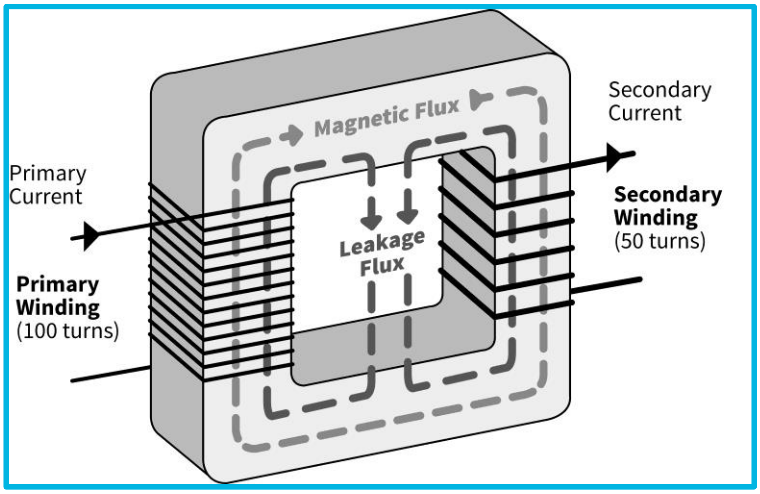


Fig. 6

## Eddy Currents

The last major characteristic which affect almost all electrical equipment is what are known as "Eddy Currents". Supposing you had a really large diameter solid iron bar, say, 6" in diameter. And supposing you then wound a large coil of magnet wire around the outside. The exact number of turns doesn't matter for the moment. And then again suppose you applied even a small AC voltage to the coil. That voltage would immediately set up an alternating current in the coil, which in turn set up an alternating flux in the iron bar. Two things would immediately happen: (a) The AC flux would cause some (quite small) hysteresis losses. These would probably not be very large. But (b) the flux inside the iron bar would also induce a voltage inside the iron, just as it does in the secondary coil outside the bar. With nowhere else to go, this induced flux would set up an induced voltage in the iron. And these induced voltages would cause induced currents to flow in the iron. And here lies the main problem. Iron has a comparatively low resistance (more than copper and aluminum, but much less than glass, for example). Thus these induced currents, with very little resistance to limit them, could reach very high values, with correspondingly very high heat losses. Even as late as the late 1880's Edison did not realize this in his early machines, and they soon ran very hot. The solution, however, was fairly easy. Instead of using solid iron components, he hit on the notion of building them from layers of very thin steel, (known as "laminations"). Each lamination was coated with a very thin layer of insulating varnish. This was a very satisfactory solution which is still used today. Because each lamination was/is very thin, about 0.015" or 0.5 mm thick, the resistance was correspondingly high, and the voltage in each lamination was low, so the loss was reduced to a small fraction of the solid material.  (See the hands-on demonstration at the end of this lesson). It is not known how Faraday made the "soft iron" core of his conceptual transformer shown in Figure 3, but probably he used multiple turns of uninsulated iron wire.

**Transformer Development**

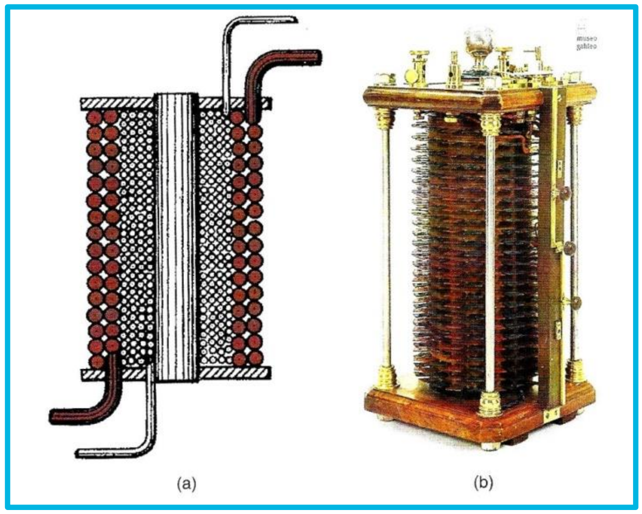


Fig. 7

Figure 3 shows a sketch of the "conceptual" transformer developed by Michael Faraday in 1831. It is not known for sure, however, whether or not Faraday used the term "transformer", because in his day there were no AC power systems on which to use it. However, as time went by and an understanding of electric power systems developed, different people developed their own ideas of how their AC equipment should look. Figure 7 shows one such possibility. In 1884, a Swiss/American firm called Gaulard & Gibbs introduced their concept of how a distribution transformer should look.  It was in fact a very early version of the modern unit shown in Figure 9.  Refer to the cross section drawing on the left hand side of Figure 7.  The soft iron core is the tall thin item standing vertically.  The large number of small circles represent the multiple turns of small wire in the primary (HV) winding.  The larger circles represent the larger diameter copper wire used in the secondary (LV) winding. The four items which look like pipes are actually the HV and LV pig-tails of the windings (somewhat over-drawn. These transformers apparently sold quite well for 4 - 5 years, but eventually were overtaken by better designs.  One significant weakness evident in Figure 7 is the central iron core.  It would seem that the designers had based their unit on their experience with bar magnets.  In other words the magnetic flux would have to exit the core at the top and travel all the way down to the bottom through air. Thus the leakage flux would have been extremely high and the so called "Magnetic Efficiency" (author's term) would have been extremely low. In other words more

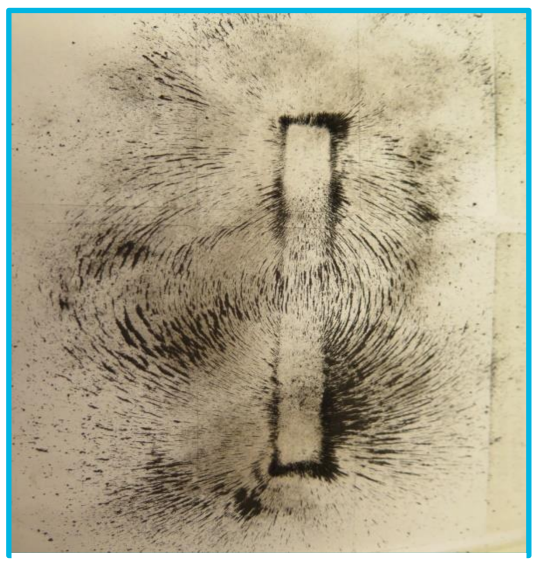

Fig. 8
Magnetic field around
a bar magnet.

material would be required than necessary, and the units were probably expensive – hence the demise of the company. Figure 8 shows the flux around a bar magnet, which probably influenced Gaulard & Gibbs.

Did this influence Gaulard & Gibbs?

Fig. 9

Figure 9, below, shows a modern "Distribution" transformer such as are seen in the thousands over all the world. Such transformers are almost always "single phase" and can be distinguished by only one HV bushing and a single tank. In the case where the customer, such as a small workshop or shopping mall, requires a 3 phase supply, three such single phase transformers can be seen grouped around the same wood pole. The electric safety code does not allow a 3-phase supply in a domestic residence.

For those interested in the details in Figure 9, the thin wire at the top left is the incoming HV lead – probably about 15 kV single phase.

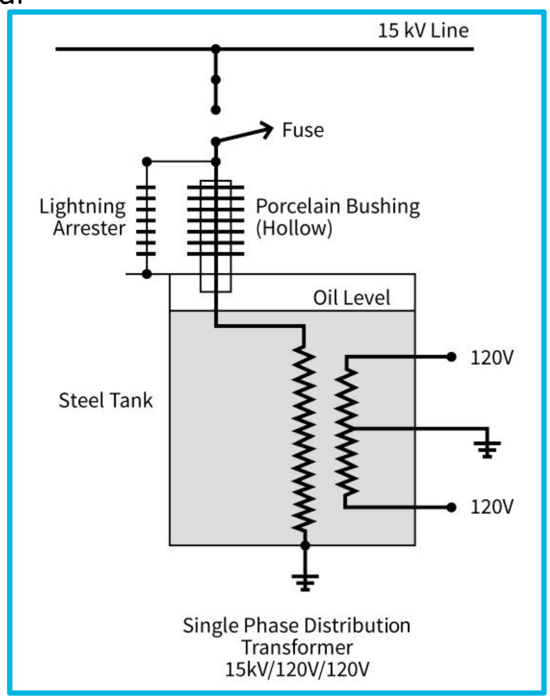


Fig. 10

Just beneath that, the cylindrical object (not very clear unfortunately) is a lightning arrester. There is also an HV fuse to protect the transformer from accidental overloads. These fuses are opened and closed from ground level by a linesperson (man or woman) using a long pole with a hook on the end. In the event that there is work to be done on the houses served by this transformer, the lines person will first open the fuse to isolate the transformer and the houses served by it. Not only will this isolate the transformer, but the open fuse, hanging down will provide "Visible Evidence of Isolation". The matter of "Visible Evidence of Isolation" is one of the most important safety rules in electric systems.

Just below the top of the transformer can be seen three objects pointing towards the left. There are the low voltage terminals. Almost all North American distribution transformers have two secondary windings rated at 120 Volts each. The two can be connected in series to give 240 Volts if required. (Electric cook stoves and dryers use 240 Volts, but still Single Phase). The terminal in the middle is the "Neutral/Ground" connection which joins the two 120 Volt sections of the transformer and to ground. Even Ben Franklin in 1750 had the good sense to have a safety ground!

Figure 10 shows a simplified electrical diagram for a single phase distribution transformer.

But What if a Small Customer needs a Small 3-Phase Supply?

Easy! You can hang three single phase transformers in a cluster on the same pole as in Figure 11. Student Note: This photograph is interesting, because if you look closely you will see three clusters of 3 transformers on each of 3 adjacent poles. Not pretty, but it works.

Fig. 11

**A Supplementary Note about Michael Faraday**

There can be no question that Faraday had a remarkable gift for "getting things right first time". Look at his donut transformer in Figure 3. This was put together 1831, many years before Gaulard & Gibbs came on the scene. And yet Faraday "got it right first time" with regard to an efficient magnetic structure. Look at Figure 6 above, and even Figure 21 below in the hands-on demonstration at the end of this lesson, and you will see that both large and small transformers have a closed magnetic circuit as in Figure 3.

**A "Real" Transformer**

Real transformers come in a wide range of sizes, from those producing milliamps for use in electronic circuits, to huge units producing hundreds of Mega Volt- Amperes (MVA). The latter are known as "Power Transformers".

Student Note:

- Upper case M stands for Mega.
- Lower case k stands for Kilo.
- Upper case K stands for Kelvin, on what is known as the absolute temperature scale.

A really large "power" transformer would look something like that shown in Figures 12, 13 & 14. The exact MVA rating of this unit is not known but is probably in the 200 MVA to 300 MVA range. (200,000 to 300,000 kilovolt.amperes or kW.

There would a substantial steel "core", rectangular in shape and looking rather like a large picture frame.

Surprising as it may seem. The whole of this core is made up with thousands of thin steel "laminations" of many different dimensions mentioned above. One side of each lamination is covered with a very thin coating of insulating varnish to prevent "eddy currents" as mentioned above. As might be expected, with a core of this size, made with thousands of individual laminations, it would probably take a team of 5 – 6 experienced people 4 -5 weeks to assemble – with all laminations lying horizontally.  The whole is kept together by a series of large steel bolts passing right through the core, just as in the demonstrator.  These bolts have to be carefully insulated, because if they accidentally touch even one lamination, it would cause a short circuit strong enough to ruin the core.  So these people have to be experienced! (They are probably also well paid).

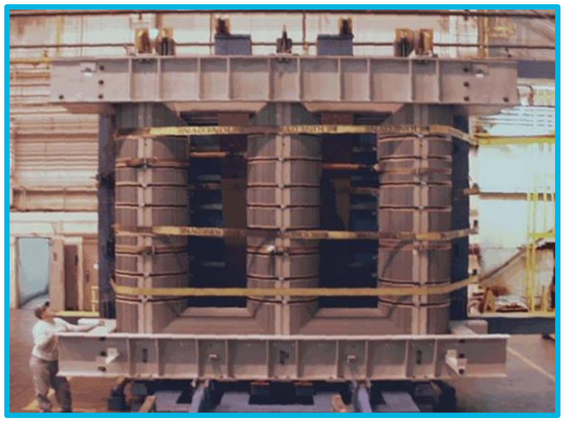

Fig. 12
Core of 3-Phase Unit. Note man in lower left-hand corner.

When finished, the core would be hoisted into a vertical position as shown. And then, believe it or not, all the laminations across the top of the core have to be removed so that the windings (cylindrical in shape) can be lowered over the vertical part of the core.  See Figure 20 in the hands-on.

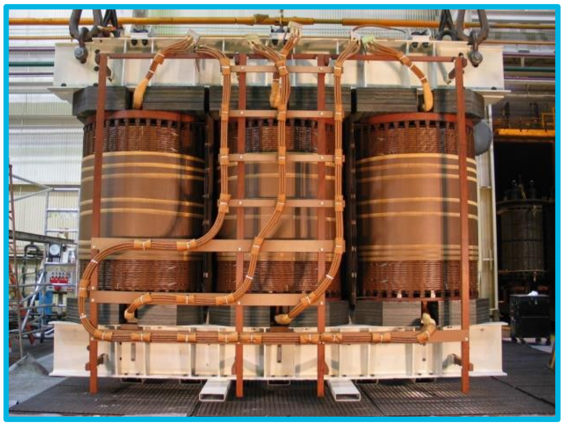

Fig 13
Core & Windings od 3-phase unit.

A much simplified but realistic example is shown in the hands-on example shown at the end of this lesson.

Once the coils have been secured in place, usually with specially treated wooden wedges bolted firmly into place, - you guessed it! – the laminations forming the top part of the core have to be put back into place.  Life gets tedious, doesn't it?

**Tanking Up**

The final stage of assembly will be to get the core and windings into the transformer tank.  See Figure 14.  First of all the core and windings will be placed in a large oven (a very large oven) where it will be kept at just over 100 C for 24 hours in order to drive off all moisture which may have been absorbed into the paper tape used to insulate the windings and the main terminals.  They will them be gently lowered into the transformer tank, the cover will be set in place and bolted down.  Then while still warm, a full vacuum will be "pulled" (jargon) on the whole assembly and transformer insulating oil will be pumped in until the tank is full.

Fig. 14

All main fittings including bushings, radiators etc. will be put in place and a full series of tests will be carried out, including measurement of losses and ability of the insulation to withstand high voltage surges etc.

And then …… you guessed it! All removable components will be taken off in readiness for shipping. No wonder such equipment is expensive.

**Moving on a bit, again.**

The text above has been a very much simplified outline of what a transformer is and how it does it. For good measure, however, the following notes may serve to amplify the present day technology.

**Hands-on Demonstration**

See the detailed parts list and cost estimate at the end of this lesson.

**The 8 Volt Power Supply**

Before proceeding to the practical demonstration, the teacher should obtain two principal items:

1. A "Bell Transformer" from the local hardware. Bell transformers are used to power domestic front door bells and door chimes. They step down the domestic voltage from 120 volts to 8 volts, which is a very safe voltage for students in a classroom, which normally set a limit at 12 volts. It should be noted however that some bell transformers also provide an alternative of 16 or even 24 Volts. In such cases it is recommended that the screw in the 16 volt position be removed. See Figure 15. These transformers are designed to fit snugly against the outside of a standard steel receptacle box.

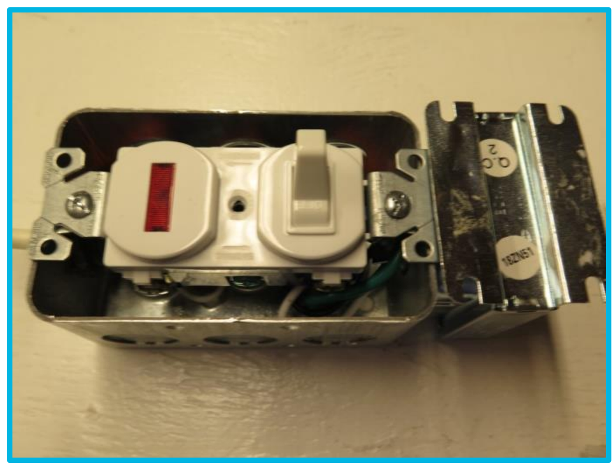

Fig. 15

2. A 120 Volt single pole light switch of the type which has a red pilot light in the other position. The red light can be arranged to come on only when the switch is in the "On" position. A warning to teachers: These switches are not the easiest to connect up. It is strongly recommended that you engage a qualified electrician to wire up this "Safe Power Box". See Figure 15.

Figure 16 shows a completed Bell Transformer "Safe Power Unit". Teachers should be aware that there are two or three different types of Bell Transformers, but all are designed to fit snugly against the outside of a rectangular steel receptacle box. All you do is take out one of the round "knock-outs" and the Bell Transformer will snap into place on the outside of the receptacle box, with the Black, White and Green wires inside the box. There is usually a screw or nut provided to keep the transformer securely in place. Leave the connection of these wires to a qualified electrician. In Figure 16, the switch is "On" and the pilot light is illuminated. In order to get reasonable contrast and show the pilot light illuminated, this photo was taken in poor light and focus.

Fig. 16

As mentioned previously, Bell Transformers usually provide optional outputs of 8, 12, 16 and sometimes even 24 volts. Some, such as the unit shown in Figure 17 also provide 24 Volts. Schools usually limit classroom voltages to 12 Volts, so it is a good plan to remove all screws except those which provide 8 Volts. Figure 17 shows an example. Note that the "step-up" demonstration unit the students will build here will produce about 13.5 Volts. It is difficult to see the School Board objecting to the difference between 12 Volts and 13.5 Volts. But if in doubt, ask the school maintenance staff.


Fig. 17
Close-up of Bell Transformer with 16 Volt screw removed.

## The Windings

The students should be divided into groups of 2 or 3. The first group should be given a length of plastic water pipe, inside diameter of 1-1/8" (2.75 cm). Cut two lengths 1" (2.5 cm) long. The class should be provided with a spool of insulated copper "magnet wire" size #30 AWG or similar. (AWG = American Wire Gage). With two students – one to hold the piece of plastic pipe and the other to wind on the wire, they should wind on 150 turns. Note that if there are plenty of students, a third should be employed to count the number of turns - it's easy to lose count!.

A second group should be given the other piece of pipe and told to wind on 300 turns of wire.

Secure both ends of the wire with green masking tape. See Figure 18. The varnish should be lightly scraped off both ends of the magnet wire.

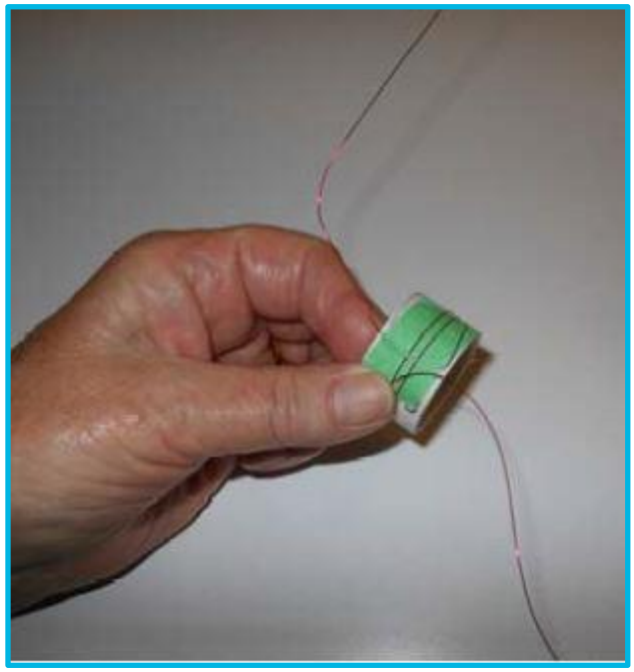

Fig. 18

**The Core**

The core will be built from 24 small steel corner brackets as shown in Figure 19. (Only 12 shown here). The brackets should be 2" x 2" size, held together with#6-32 size steel nuts and bolts, 1" long as shown in Figure 19. In this figure only the lower half of a single phase core is shown. Figure 20 shows a sample 3-phase core, for illustrative purposes only. It is shown here to give some relevance to the very large core shown in Figure 12, which is not easy to visualize with the upper half removed. As stated previously the Electrical safety Code does not permit 3-phase power systems in locations open to the general public (i.e. houses, schools and shops etc.).

The core is made from 24 small 2" x 2" (5 x 5 cm) steel corner brackets, available in any hardware store. These can, of course, be re-used over and over again.

Fig. 19
Typical "Laminations" for core of demonstrator unit. Only 12 shown here. 24 required total.

A separate group should be given the 24 small steel corner brackets shown in Figure 19 and used as "laminations". They should be assigned the title of "Assembly" teams and given the task of lightly assembling the transformer core. In the first instance the top part of the core should be left off. Secure the individual "laminations" with the small steel nuts and bolts provided. Note that the "Real" transformer shown in Figures 12, 13, & 14, which is a 3 - phase unit and has 3 legs as in Figure 20. But safety codes do not permit 3 phase power in houses, schools and other places open to the public. It is shown here for completeness. Single phase transformers usually have two legs for the sake of magnetic symmetry, as shown in Figure 19.

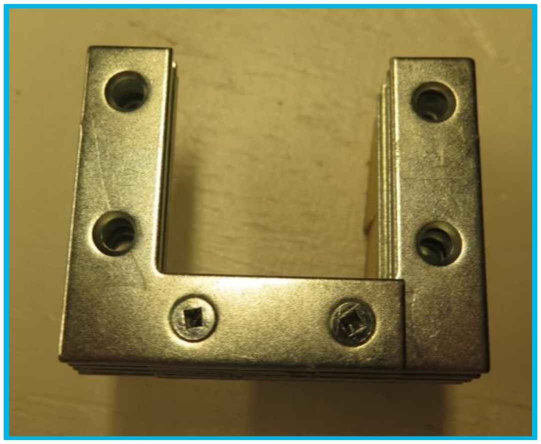

Fig. 20
Single Phase Core

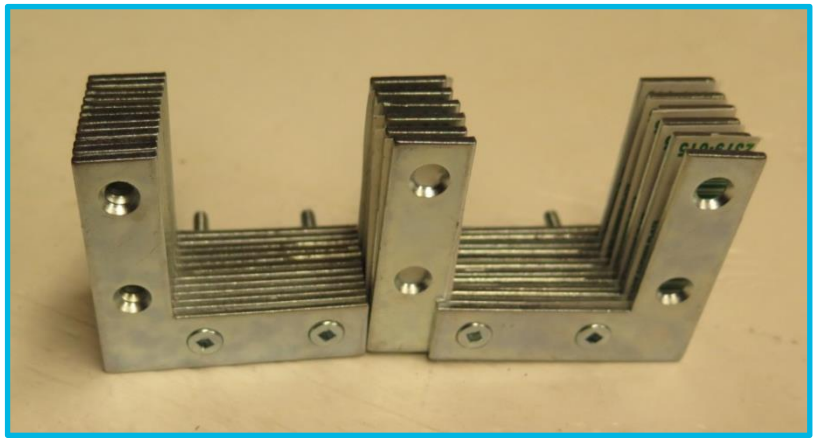

Fig. 21
3-Phase Core

**The Finished Assembly**

Once the "Winding teams" have finished two coils (one of 150 turns and one of 300 turns) they should drop them onto the two legs of the core and complete the core by inserting the top laminations.  Figure 22 shows our assembled single phase demo transformer.

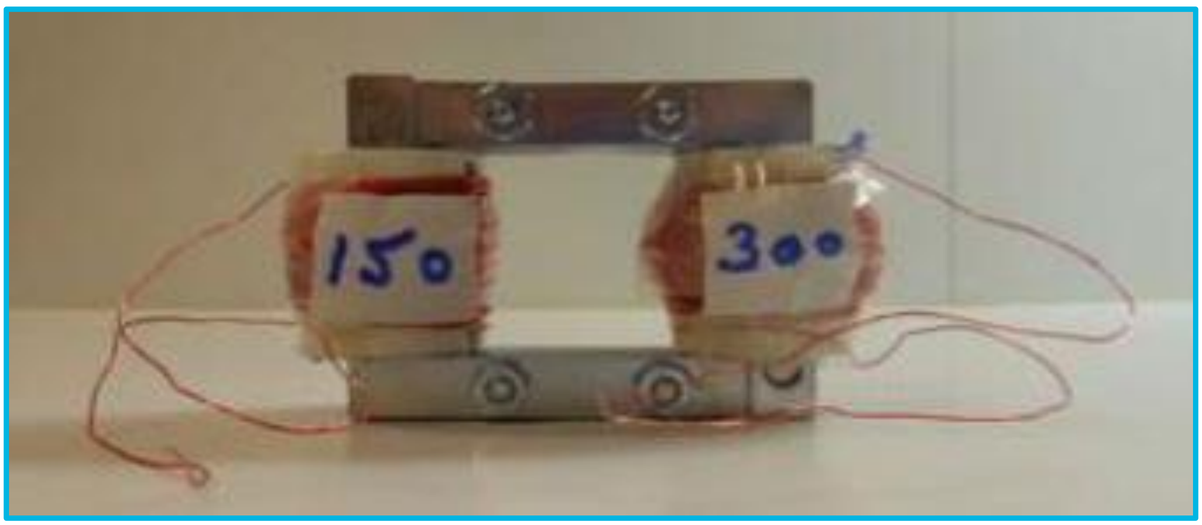


Fig. 22

**Final Testing**

Figure 23 shows the completed project under test. Connect the two leads from the 150 turn coil to the 8 Volt terminals of the "Power Supply". Connect the two leads from the 300 turn (16 V nominal) winding to the voltmeter. Last Step. Plug the "Power Unit" into a wall outlet and turn the switch to "ON". You should get a reading of only about 13.5 Volts, because of the imperfections in the test unit.

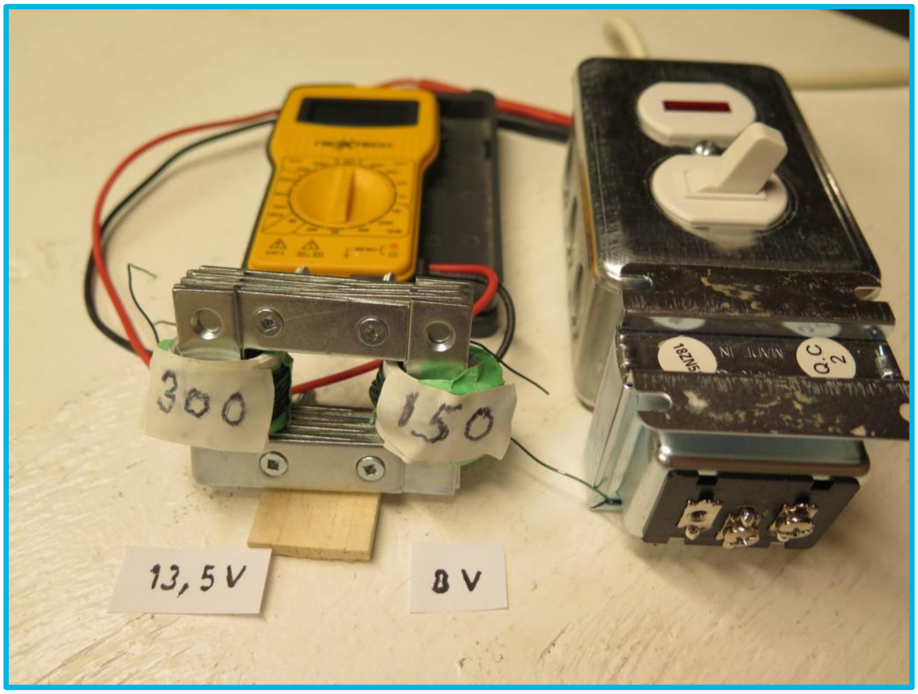


Fig. 23

**Class Challenge**

The teacher should debate with the class, why we have not got the full 16 Volts theoretically obtainable from a 2:1 setup.

**Summary**

The above has been a very much simplified outline of what a transformer is and how it does it. For good measure, however, the following notes may serve to amplify the present day technology.

In the jargon of the industry, what we have just assembled would be known as a "Step-up" transformer. If we had reversed the connections, and applied the 8 volts to the 300 turn coil and measured the voltage on the 150 turn coil, we would have measured rather less than 4 volts, (because of its' simplicity) and produced a "Step Down" transformer.

The above is a really basic example, put together to demonstrate the principle. In actual fact, the way in which the core is put together, especially around the corners, results in a good many lines of magnetic flux being lost to what is known as "Flux Leakage". Hence the voltage ratios illustrated above will be significantly less than the 2:1 suggested.

**Class Challenges**

1. Refer to the note about leakage flux above and try an experiment with the hands on demonstration in Figure 22. Remove the top yoke and measure the output voltage you get.

2. Note from Figure 19 that when new, the steel brackets used as laminations have small sticky labels. It is suggested that for the first try, you build the transformer with the labels still in place and record the output voltage. Then remove the labels (Varsol will do that) and try again. In theory the laminations with the labels in place should give a slightly higher voltage because the leakage flux and the eddy currents will be slightly less.
3. Ask the class for their views on what a DC transformer would look like?

But don't forget, if it looks like a transformer and hums at 120 Hz like a transformer, it must be a transformer.

## For Teachers:
## Materials

**DEMO TRANSFORMER PARTS LIST & COST ESTIMATE**

| Item | Source | Qty | Remarks | Unit Cost | Cost per set |
|---|---|---|---|---|---|
| **Core** | | | | | |
| Core steel | Home Hardware | 24 | 2" Flat corner | $0.35 | $8.40 |
| Core bolts | 1/8" x 32 tpi x 1-1/2" long | 4 | | $0.15 | $0.60 |
| **Coils** | | | | | |
| 1-1/8" id plastic pipe | Cut 1" long +/- 0" | 2 | Cut with pipe cutter | $5.00/ 8ft | $0.10 |
| 8 Volt winding | # 30 AWG 150 turns | 52 ft | Insulated magnet wire | 1lb = $55 = | 2,000 ft |
| 16 Volt | | 112 | | | |
| | | | Secure with | | |
| Small Robertson Screwdriver | | 1 | | | n/a |
| Small sharp knife to scrape varnish off wire. | | 1 | | | n/a |
| | | | Total per transformer | | $13.64 |

| "Safe" Power Supply | Qty | Remarks | | Cost |
|---|---|---|---|---|
| 8 Volt Bell Transformer (or the nearest equivalent small transformer in your area) | 1 | | | $13 |
| 120 V On/Off switch with red pilot light | 1 | | | $12 |
| Rectangular steel or plastic receptacle box | 1 | | | $1.50 |
| 3 Cond flexible cable 6 ft for power supply | ply | | | $5.00 |
| 3-pin plug for power supply | 1 | | | $6.5 |
| Small Crocodile clips | 6 | For jumpers | n/a | |
| Speaker wire or similar | 2 m | Ditto. For 8 Volt side ONLY NOT for use on 120 Volts | | |
| **Approximate Total.** | | One only, reqd. | $35.00 | |

## *For Teachers:*
## *Alignment to Curriculum Frameworks*

**Note:** Lesson plans in this series are aligned to one or more of the following sets of standards:

- U.S. Next Generation Science Standards (www.nextgenscience.org)
- U.S. Common Core State Standards for Mathematics (www.corestandards.org/Math)
- International Technology Education Association's Standards for Technological Literacy (http://www.iteea.org/TAA/PDFs/xstnd.pdf)
- Computer Science Teachers Association K-12 Computer Science Standards (http://csta.acm.org/Curriculum/sub/K12Standards.html)

**◆National Science Education Standards Grades 5-8 (ages 10 - 14)**

**CONTENT STANDARD A: Science as Inquiry**

As a result of activities, all students should develop

- Abilities necessary to do scientific inquiry
- Understandings about scientific inquiry

**CONTENT STANDARD B: Physical Science**

As a result of their activities, all students should develop an understanding of

- Transfer of energy

**◆National Science Education Standards Grades 9-12 (ages 14-18)**

**CONTENT STANDARD A: Science as Inquiry**

As a result of activities, all students should develop

- Abilities necessary to do scientific inquiry
- Understandings about scientific inquiry

**CONTENT STANDARD B: Physical Science**

As a result of their activities, all students should develop understanding of

- Interactions of energy and matter

**◆Next Generation Science Standards Grades 6-8 (Ages 11-14)**

**Motion and Stability: Forces and Interactions**

- MS-PS2-3. Ask questions about data to determine the factors that affect the strength of electric and magnetic forces.

**◆Next Generation Science Standards Grades 9-12 (Ages 14-18)**

**Motion and Stability: Forces and Interactions**

- HS-PS2-5. Plan and conduct an investigation to provide evidence that an electric current can produce a magnetic field and that a changing magnetic field can produce an electric current.

**◆Standards for Technological Literacy - All Ages**

**Design**

- Standard 2: Students will develop an understanding of the core concepts technology.
- Standard 7: Students will develop an understanding of the influence of technology on history.

**The Designed World**

- Standard 16: Students will develop an understanding of and be able to select and use energy and power technologies.