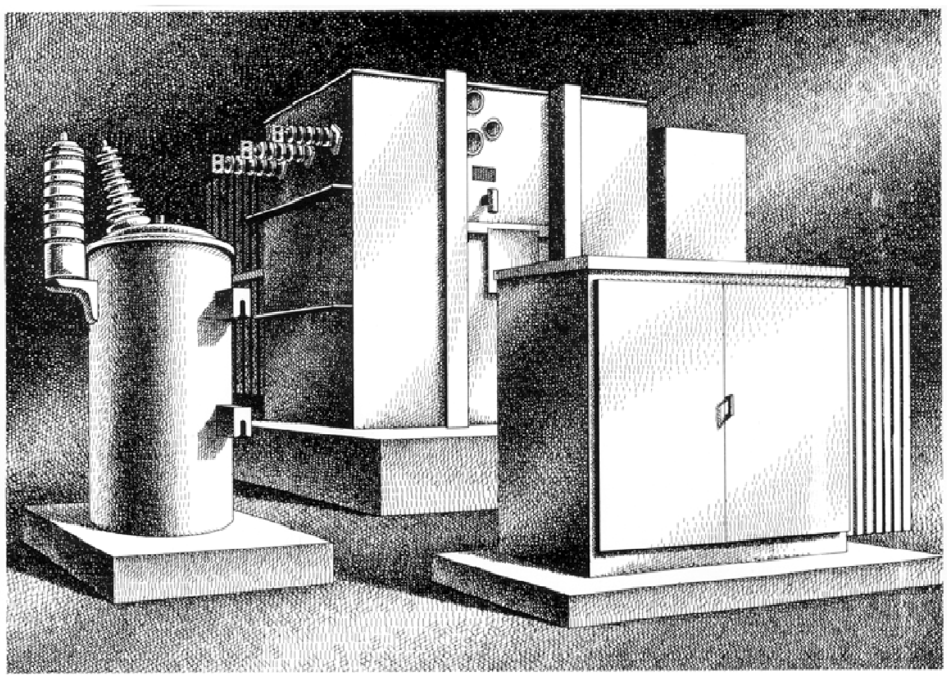
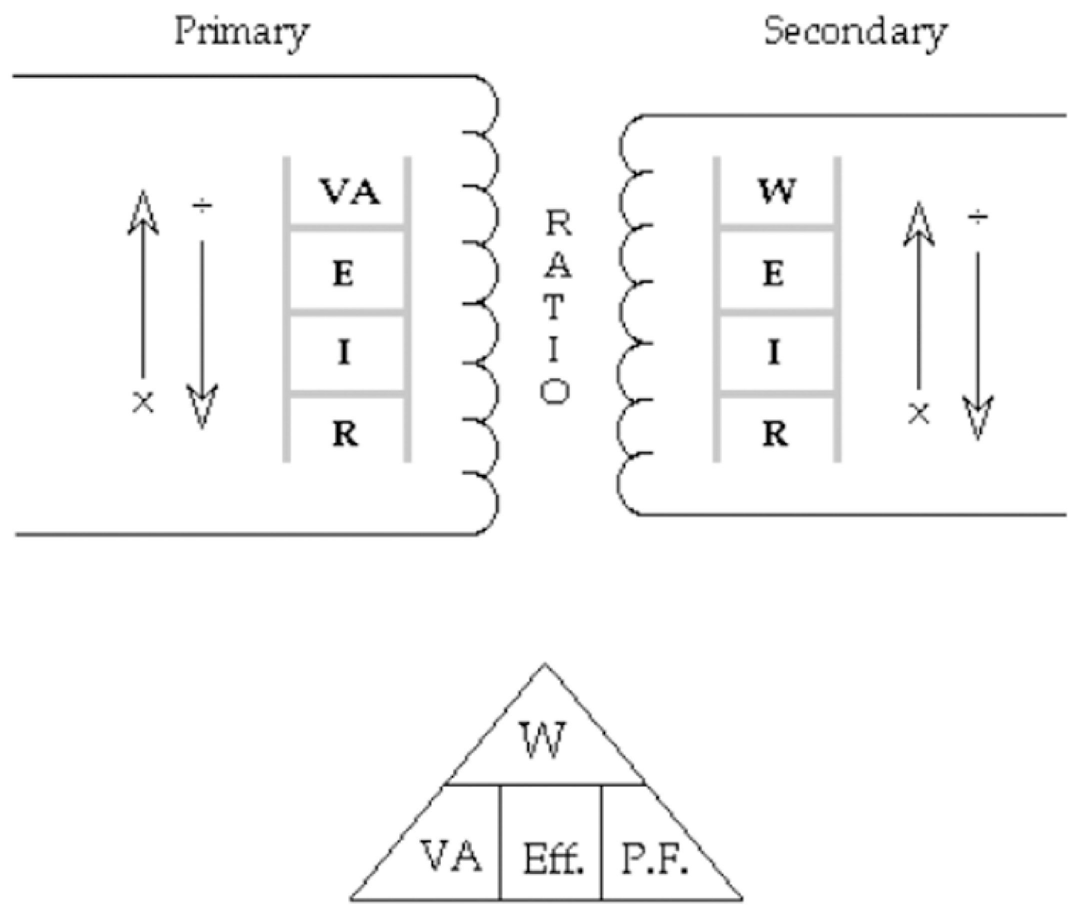
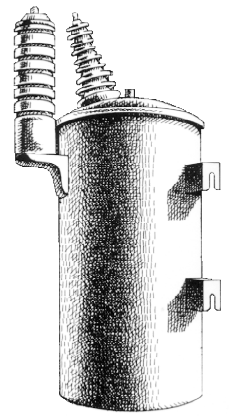
Transformer Calculations



Transformers



Transformers

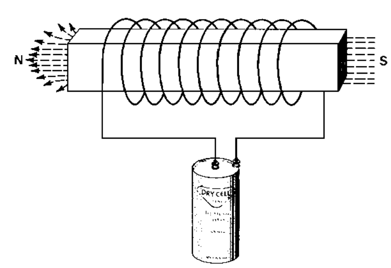


Transformers are one of the most basic yet practical devices used today. No matter where you are there is always a transformer nearby. They are used throughout *alternating-current (ac)* systems from generating plants to the doorbell at your home. Power companies use transformers to increase the voltage for their long distance power lines, the voltage is than reduced by other transformers before the power enters your house.

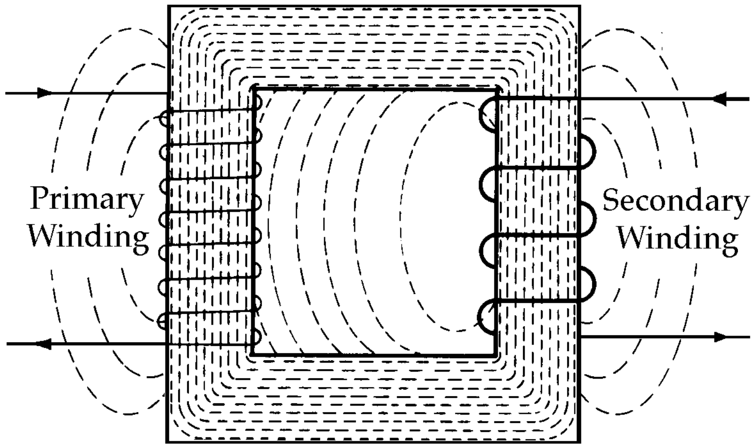
The method of transferring electrical energy by a transformer is done indirectly. Electrical energy is first converted into magnetic energy, then reconverted back into electrical energy at a different voltage and ampacity. Because of this conversion process, the transformer can perform duties which have made it invaluable in the field of electricity.

Mutual-Induction

Transformers are based on the principle of "mutual-induction." When current flows through a wire a magnetic field is produced. A good example of this is an "electro-magnet." By wrapping an insulated wire around an iron bar and hooking this wire to a battery, a magnetic field is induced in the iron bar making it a magnet - temporarily !



This principle also works in reverse. When a conductor passes through a magnetic field, a current flow will be induced through the wire. Interesting ! So, it seems that magnetism and electricity are closely related. You can't have one without the other. However, this relationship can be very useful.



A transformer uses both of these methods of "induction" at the same time. A basic transformer consists of two separate windings of insulated wires wound around a common iron core. The power source or supply is hooked to the primary winding, the load to be served is hooked to the secondary winding. When the primary winding is energized an electromagnetic field builds up and then collapses in the iron core, this field cuts through the secondary coil winding inducing power to the load hooked to the secondary. This power buildup and collapse is called magnetic flux and occurs at a frequency of sixty times a second (60 hz) in an a.c. circuit.

If the transformer is running perfectly, the power introduced on the primary will be equal to the power used on the secondary. You might be saying, "What good is a transformer if it uses as much power, or wattage, as it produces" ?

Now, here's the magic ! By altering the number of windings on the primary and secondary, we can alter the amount of volts and amps between the source and the load. If we have a motor rated 240 volts, but a source voltage of 480 volts, we can use a transformer to reduce our source voltage by one-half. Or, we can even increase our amps if needed.

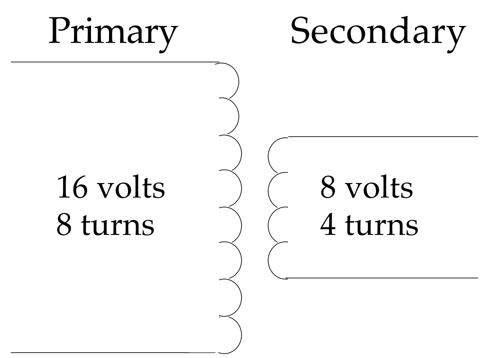
The current in the secondary coil always changes by the inverse of the ratio by which the voltage changes. If the voltage is doubled, the current is halved. If the voltage is raised to 10 times its original value by the transformer, the current in the secondary coil will be reduced to one-tenth the value of the current in the primary coil.

Transformer Ratio

Here's how it works ! Every winding on the primary side will cause voltage to be induced in each winding on the secondary. By altering the number of wind-ings (or turns) on either the primary or secondary side we will automatically alter the voltage ratio. Check this formula:

$$\frac{\text{Primary Volts}}{\text{Secondary Volts}} = \frac{\text{Primary Turns}}{\text{Secondary Turns}}$$

Here's an example:

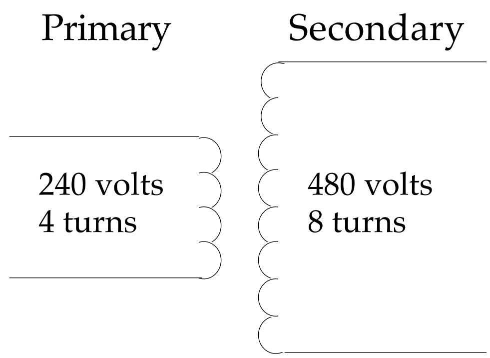


Notice that there are twice as many turns on the primary side (16/8 or 2:1) than the secondary side. Also, there are twice as many volts on the primary side (8/4 or 2:1) than the secondary side. We call this a 2:1 step-down transformer because we are stepping the voltage down by a two to one ratio.

Using the same turns ratio of the above transformer (2:1) calculate the following voltages:

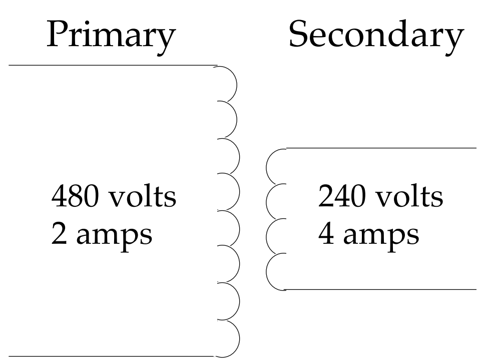
Primary Volts = 24	Secondary Volts = ________
Primary Volts = 48	Secondary Volts = ________
Primary Volts = 120	Secondary Volts = ________
Primary Volts = ________	Secondary Volts = 24
Primary Volts = ________	Secondary Volts = 48
Primary Volts = ________	Secondary Volts = 120

It's also possible to step-up voltages by increasing the number of turns on the secondary side if we need a higher voltage.



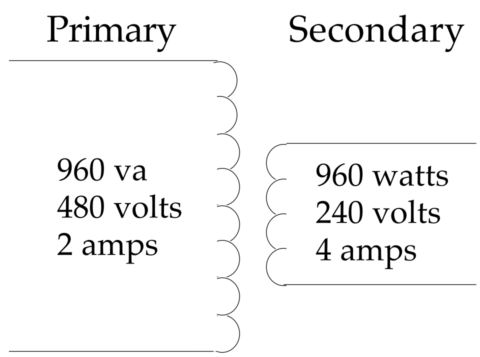
Notice that we can determine transformer ratio by either: (1) counting the number of turns on either side, or (2) by determining voltage on either side. We don't really need to know both.

OK ! We can transform the ratio of volts with a transformer, so what about transforming amps ? The ratio of current is also changed in a transformer, but in the opposite direction. Watch this:

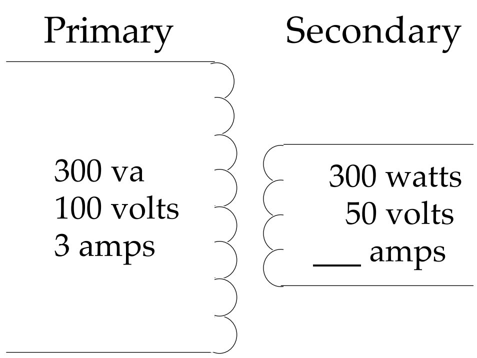


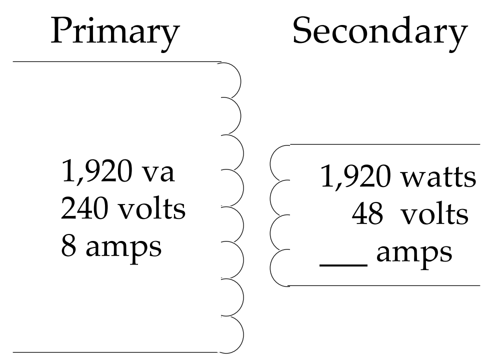
In the above model transformer, the voltage is stepping-down by a ratio of 2:1 (or 480 to 240 volts) while the current increases by a ratio of 1:2 or (2 to 4 amps). So, what is actually changing in an ideal transformer is the ratio of volts to amps.

What doesn't change in a transformer is wattage. Look at this:



To find primary watts, we'll call them volt-amps to differentiate them from secondary watts, we multiply primary volts times amps (480 x 2 = 960 va). To find secondary watts, we multiply secondary volts times amps (240 x 4 = 960 watts). Ideally, transformers do not alter power or wattage, again they only alter the ratio of volts to amps. Try a few on your own:

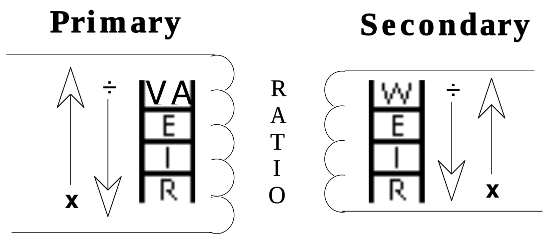




Since it is so easy to increase or decrease voltage and current (merely by altering the turns ratio of a transformer), one might assume that power, (or wattage) might be increased or decreased. This assumption is not valid, since it violates the law of conservation of energy. It's impossible to get as much power out of a transformer as is put into it, because no device can be made to operate at 100% efficiency; there is always some loss. If we can assume that a transformer runs at 100% efficiency, the amount of transformed power is neither increased or decreased, only the current to voltage ratio is changed.

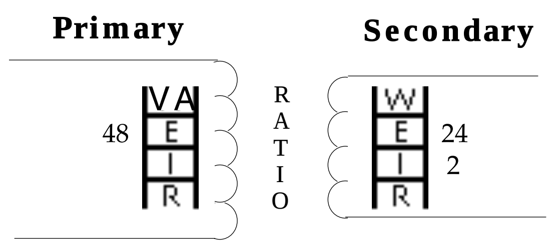
Transformer Ladder

Yes, we can utilize the Ohms Law Ladder to do transformer calculations.

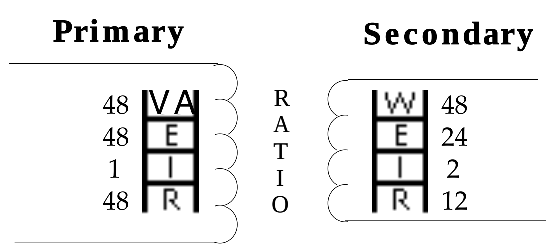


The ladder works on the primary side (replacing volt-amps for watts) by multiplying each step up the ladder and dividing each step down the ladder. This works the same on the secondary. The ratio of volts from primary to secondary can also be used.

Can you determine primary volt-amps, primary amps and secondary watts for the transformer below ?

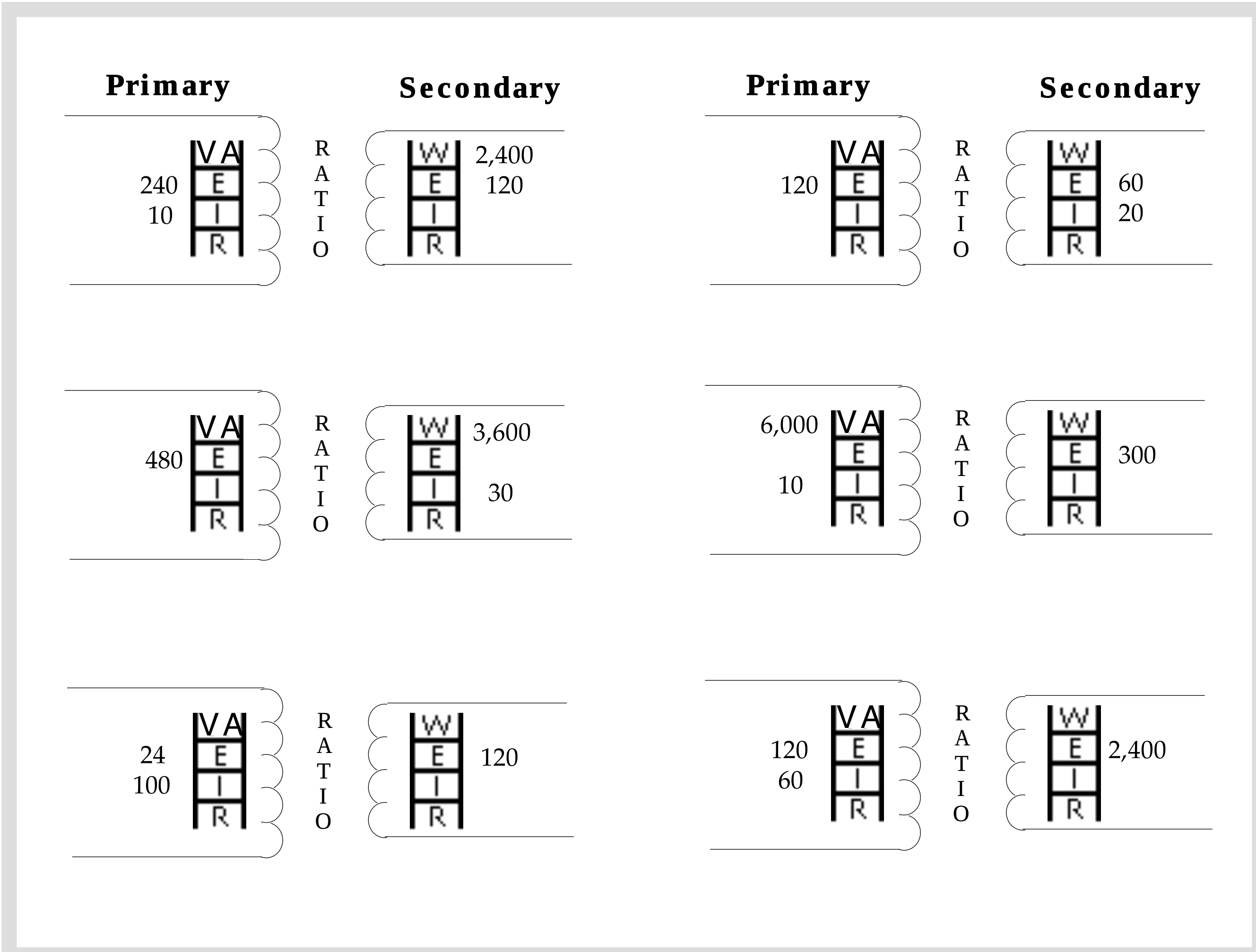


Remember, since the voltage ratio is 2:1, the amps ratio will be the opposite, 1:2. Also, the wattage will be the same on both the primary and secondary.



Although we can calculate resistance, it usually isn't very important (except for calculating the resistance of loads connected to the secondary).

Try these babies:



Efficiency

As we all know nothing works perfectly. Although transformers are pretty amazing there is some loss in power due to inefficiencies built into transformers. Here are the three main causes for power losses in the operation of a transformer:

<u>Eddy Currents</u> are local short-circuit currents induced in the iron core by alternating magnetic flux. In circulating in the core they produce heat. They are minimized by cutting the core into thin layers and laminating each layer.

<u>Hysteresis</u> is the lagging of the magnetic molecules in the core, in response to the alternating magnetic flux. This lagging (or out-of-phase) condition is due to the fact that it requires power to reverse magnetic molecules; they do not

reverse until the flux has attained sufficient force to reverse them. Their reversal results in friction, and friction produces heat in the core which is a form of power loss. Hysteresis is minimized by the use of special steel alloys properly annealed.

<u>The I^2R Loss</u> is sometimes referred to as "copper loss." It is power lost in circulating current in the windings. This represents the greatest loss in the operation of a transformer. The actual watts of power lost can be determined (in each winding) by squaring the amperes and multiplying by the resistance in ohms of the winding.

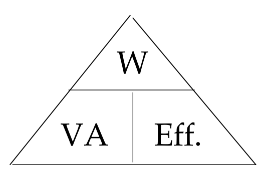
The intensity of power loss in a transformer determines its efficiency. The efficiency of a transformer is reflected in power (wattage) loss between the primary (input) and secondary (output) windings. Here are three formulas for determining power losses due to efficiency:

$$\text{Efficiency} = \frac{\text{Secondary Watts (output)}}{\text{Primary VA (input)}}$$

$$\text{Secondary Watts (output)} = \text{Primary VA (input)} \times \text{Efficiency}$$

$$\text{Primary VA (input)} = \frac{\text{Secondary Watts (output)}}{\text{Efficiency}}$$

Here's a simplified way of determining the Efficiency (Eff.) formulas above:



Just put your finger on the "W" to find Watts (output) = VA x Eff., or "VA" to find Volt-Amps (input) = W/Eff., or "Eff." to find Efficiency = W/VA.

Here's a sample problem:

Find the efficiency of a transformer with a primary of 3,000 va and a secondary of 2,400 watts.

$$\text{Efficiency} = \frac{\text{Secondary Watts}}{\text{Primary VA}} = \frac{2{,}400 \text{ watts}}{3{,}000 \text{ vA}} = .8 \text{ or } 80\%$$

Try these dudes:

- The efficiency of a transformer with a primary of 600 va and a secondary of 576 watts is _______ %.

- The secondary watts of a transformer with a primary of 1,200 va and an efficiency of 92% is _______ watts.

- The primary va of a transformer with a secondary of 1,600 watts and an efficiency of 88% is _______ va.

Power Factor

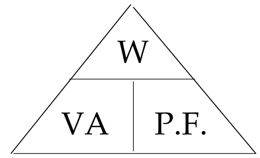
There is also some loss in power in transformers due to power factor. You remember that transformers use coils of wire. Whenever you wind a wire into a coil it automatically becomes an inductor. When you apply power to a coil, the magnetic effect (that is produced by the coil) tends to oppose the current flow so that it lags a bit behind the voltage. It may be said that voltage and current are out-of-phase with each other. When current lags behind voltage it's called "inductance," which causes a type of resistance in a circuit. Inductance causes loss of wattage in transformers similar to efficiency loss, and is calculated in much the same way.

$$\text{Power Factor} = \frac{\text{Secondary Watts (output)}}{\text{Primary VA (input)}}$$

$$\text{Secondary Watts (output)} = \text{Primary VA (input)} \times \text{Power Factor}$$

$$\text{Primary VA (input)} = \frac{\text{Secondary Watts (output)}}{\text{Power Factor}}$$

Here's a simplified way of determining the Power Factor (P.F.) formulas above:



Just put your finger on the "W" to find Watts (output) = VA x P.F., or "VA" to find Volt-Amps (input) = W/P.F., or "P.F." to find Power Factor = W/VA.

Here's a sample problem:

Find the power factor of a transformer with a primary of 2,500 va and a secondary of 2,425 watts.

$$\text{Power Factor} = \frac{\text{Secondary Watts}}{\text{Primary VA}} = \frac{2{,}425 \text{ watts}}{2{,}500 \text{ va}} = .97 \text{ or } 97\%$$

Efficiency And Power Factor Losses

With the following formulas we can take into account both power factor and efficiency losses:

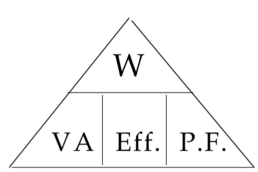
$$\text{Efficiency} = \frac{\text{Secondary Watts}}{\text{Primary VA} \times \text{P.F.}}$$

$$\text{Power Factor} = \frac{\text{Secondary Watts}}{\text{Primary VA} \times \text{Eff.}}$$

$$\text{Secondary Watts} = \text{Primary VA} \times \text{Eff.} \times \text{P.F.}$$

$$\text{Primary VA} = \frac{\text{Secondary Watts}}{\text{Eff.} \times \text{P.F.}}$$

Here's a simplified way of determining the formulas above:



Here's a sample problem:

The primary va of a transformer with a secondary of 941 watts, an efficiency of 98% and a power factor of .96 is ______ va.

$$\text{Primary VA} = \frac{\text{Secondary Watts}}{\text{Eff. x P.F.}} = \frac{941}{.98 \text{ x } ,96} = \text{1,000 va (close)}$$

Here's some problems for you to try:

- The efficiency of a transformer with a primary of 300 va, a secondary of 256.5 watts, and a power factor of .95 is _______ %.
- The power factor of a transformer with a primary of 1,000 va, a secondary of 810 watts, and an efficiency of 90% is _______.
- The secondary watts of a transformer with a primary of 1,500 va, an efficiency of 92%, and a power factor of .9 is _______ watts.
- The primary va of a transformer with a secondary of 3,040 watts, an efficiency of 95%, and a power factor of .80 is _______ va.

Transformer Types

A byproduct of the efficiency and power factor losses is excessive heat. Several methods are used to dissipate this heat from transformer cores and windings to the outside. Some transformers are designed for air-cooling. This type is known as dry-type transformers. They are designed with sufficient air spaces (in and around the coils and core) to allow sufficient air circulation for cooling. Some dry-type transformers depend on a blower for air circulation.

Most transformers use a coolant for heat transfer. Oil is the most commonly used coolant, but in applications where oil would present a fire hazard, askarel coolants must be used. Askarel is a term for coolants that includes all the synthetic noncombustible insulating coolants manufactured under different trade names. A coolant conducts heat to the sides of the tank, and the tank conducts it to the outside. To aid in dissipation of heat to the outside, some tanks are corrugated or equipped with fins to increase the radiating surfaces.

Large transformers use additional methods for cooling. Some are equipped with vertically spaced outside tubes (around the tank) which enter the tank at the bottom and below the coolant level at the top. The warm coolant has a natural circulation in the tank and tubes, which vents heat to the outside.

Power Distribution Transformers are used to efficiently distribute electricity from generating plants to industrial, commercial and residential areas. Step-up transformers boost voltages up to 765,000 volts for easy transmission, using small sized conductors. Step-down transformer are use to meet local higher current demands at 480, 277, 240, 208 and 120 volt requirements.

Autotransformers use one continuous winding through both the primary and secondary on the same iron-core. The primary and secondary serve in the same magnetic circuit causing current to flow in parts of the same winding. The main advantage of autotransformers are economical construction, and operating efficiency in low ratio situations like reduced-voltage motor starters.

Current Transformers (CT's) are used when the a.c. currents are too large for measuring instruments such as power company kilowatt-hour meters. They work on the same principle as the clamp-on ammeter by sensing current flow through a conductor without having to break the circuit.

Constant-Current Transformers produce a constant secondary amperage to a load even though the primary input amperage changes. By using a movable primary coil, air space between coils can be varied. This causes magnetic leakage between the coils, and varies current flow in the secondary. A typical example of the use of these transformers are series street-lighting systems.

Transformer Size Chart

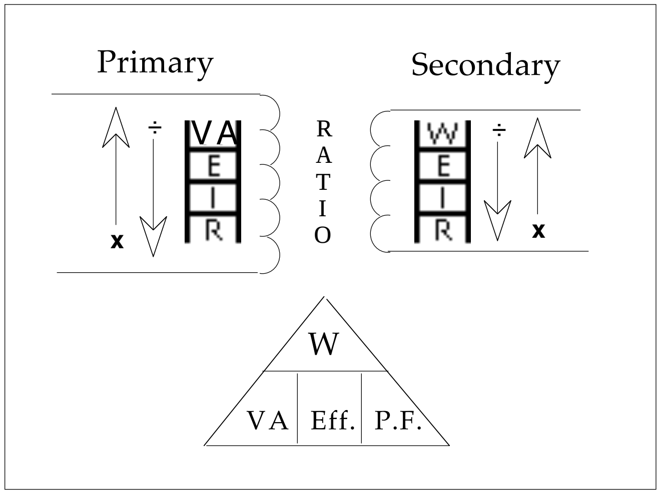
Full-Load Current In Amps At The Line Voltages Listed Below

kVa Rating	120 volts	240 volts	480 volts	600 volts	2400 volts	4160 volts
1/2	4.2	2.1	1	.8		
1	8.3	4.2	2.1	1.6		
2	16.7	8.3	4.3	3.2		
3	25	12.5	6.1	4.8	1.2	.7
5	41	21	10.4	8.3	2	1.2
7-1/2	62	31	15.6	12.5	3.1	1.8
10	83	42	21	16.5	4.1	2.4
15	124	62	31	25	6.2	3.6
25	208	104	52	42	10.4	6
37-1/2	312	156	78	62	15.6	9
50	416	208	104	84	21	12
75	624	312	156	124	31	18
100	830	415	207	168	42	24
167	1390	695	348	278	70	40

kVa = (full load current x voltage) ÷ 1,000

Transformer Calculations

Here's a simple chart that can be used in transformer calculations. Using this chart will save us from having to look-up or memorize all of the previous formulas we have used so far.



Notice the ladder on the primary is only useful with primary side values (va, volts, amps and resistance). The secondary side ladder values (watts, volts, amps and resistance) are only useful on the secondary side.

With the triangle, at the bottom of the chart, we can cross-over between the primary and secondary taking efficiency and power factor into account. Remember that with 100% efficiency and unity power factor (1), primary volt-amps and secondary watts would be exactly the same.

Let's go ahead and use this chart in working out future problems !

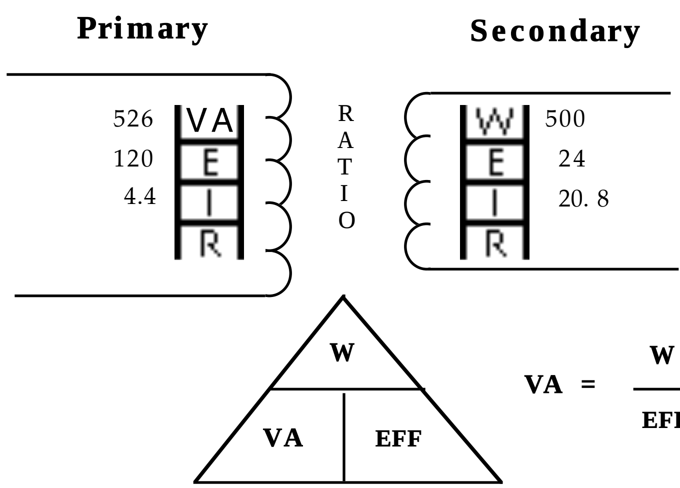
Transformer Sample Problem

Problem

A single-phase transformer has 120 volts on the primary with 24 volts on the secondary. The transformer is feeding a 500 watt load with an efficiency of 95 percent

Find: (1) Secondary Amps ?
(2) Primary Volt-Amps ?
(3) Primary Amps ?

Solution



$$VA = \frac{W}{EFF} = \frac{500}{95\%} = 526$$

(1) Secondary Amps	500 watts/24 volts	=	20.8 amps
(2) Primary Volt-Amps	500 watts/.95 eff.	=	526 watts
(3) Primary Amps	526 va/120 volts	=	4.4 amps

Transformer Problems

(1) The transformer is based on the principle that energy may be effectively transferred (by induction) from one set of coils to another (by a varying magnetic flux) provided both sets of coils _______.

(a) are not on a common magnetic circuit
(b) have the same number of turns
(c) are on a common magnetic circuit
(d) do not have the same number of turns

(2) Oil is used in many large transformers to _______.

(a) lubricate the core
(b) lubricate the coils
(c) insulate the coils
(d) insulate the core

(3) When a step-up transformer is used, it increases the _______.

(a) voltage
(b) power
(c) current
(d) frequency

(4) The turns ratio of a transformer with a primary of 120 volts and a secondary of 24 volts is ?

(a) 120:1
(b) 12:1
(c) 6:1
(d) 5:1

(5) A transformer has a primary of 120 volts, a secondary of 15 volts. A 150 watt buzzer is connected to the secondary. The resistance of the buzzer is _______ ohms.

(a) 1.5
(b) 10
(c) 15
(d) 150

(6) If the input to a 5-to-1 step-down transformer is 100 amps at 2,200 volts, the output will be _______.

(a) 100 amps at 500 volts
(b) 500 amps at 440 volts
(c) 20 amps at 11,000 volts
(d) 500 amps at 2,200 volts

(7) When the input to a 1-to-6 step-up transformer is 12 amps at 120 volts, the output is approximately _______.

(a) 72 amps at 20 volts
(b) 2 amps at 20 volts
(c) 2 amps at 720 volts
(d) 72 amps at 720 volts

(8) The primary volt-amps of a 40 amp, 230 volt, single phase transformer is _______ volt-amps.

(a) 8,800
(b) 9,200
(c) 9,600
(d) 10,200

(9) The secondary watts of a single-phase transformer with a primary of 40 amps, 230 volts, and a .85 power factor is _______.

(a) 7,480
(b) 7,820
(c) 8,160
(d) 10,823

(10) A transformer has a primary of 50,000 volt-amps with 42,000 watts of true power at 100 percent efficiency. What is the power factor ?

(a) 1.19
(b) .92
(c) .84
(d) .76

(11) The efficiency of a transformer with an output of 400 watts, an input of 440 volt-amps is ______ .

(a) 1.1
(b) .99
(c) .91
(d) .86

(12) For a transformer with an efficiency of 60%, for every 100 watts output, there would be _______ watts input.

(a) 166.6
(b) 100
(c) 60
(d) 40

(13) For a transformer at 90% efficiency, for every 100 vA input, there would be _______ watts output ?

(a) 110
(b) 100
(c) 99
(d) 90

(14) A load of four 100 watt light bulbs at 12 volts is tied to a transformer at 95 percent efficiency with a .9 power factor and an input voltage of 120 volts. What is the primary current of the transformer ?

(a) 3.9
(b) 3.3
(c) 3.1
(d) 2.8

(15) What is the primary current of a 3.75 kVA, 120 volt transformer ?

(a) 28.35
(b) 31.25
(c) 33.31
(d) 34.45

(16) What is the secondary current of a transformer with four 100 watt light bulbs at 12 volts ?

(a) 33.3
(b) 31.3
(c) 28.3
(d) 24.0

(17) What is the output wattage of a transformer if the secondary current is 12 amps at 120 volts ?

(a) 444
(b) 1,040
(c) 1,440
(d) 1,800

(18) What is the output wattage of a 25 kVA transformer rated at 92% efficiency with a .9 power factor ?

(a) 25,000 watts
(b) 20,700 watts
(c) 2,700 watts
(d) 2,500 watts

(19) Compared to the secondary of a loaded step-down transformer, the primary has ______.

(a) higher voltage and lower current
(b) lower voltage and higher current
(c) lower voltage and current
(d) higher voltage and current

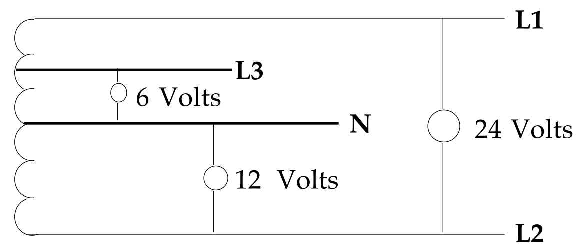
(20) If a transformer is rated at 1 kVa, with an efficiency of 85% and a power factor of .85, the input is ______ volt-amps.

(a) 680
(b) 1,000
(c) 1,470
(d) 1,500

Transformer Taps

There are ways to derive other voltages from a transformer by tapping into the windings at various locations. This is helpful when different voltages levels are required by different loads. Some low-voltage transformers come with taps at 24, 12 and 6 volt taps for flexibility.

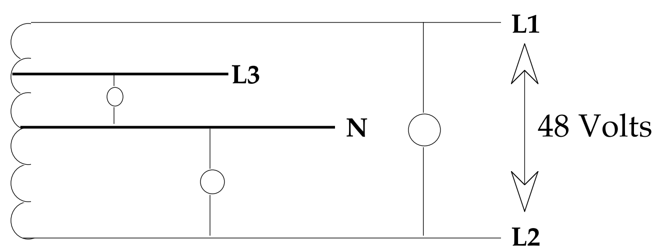
Secondary



Notice the connections: **L1 - L2** = 24 volts
L2 - N = 12 volts
L3 - N = 6 volts

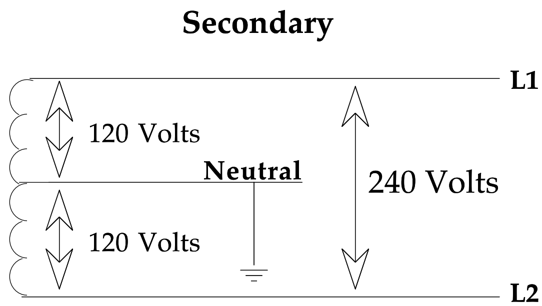
See if you can locate the taps of this transformer secondary !

Secondary



Make the connections: **L1 - L2** = _____ volts
L2 - N = _____ volts
L3 - N = _____ volts

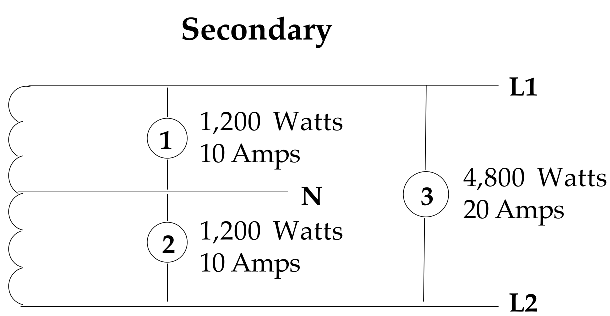
Residential (single-phase) 240 volt transformer secondary windings are commonly center-tapped in order to derive 120 volts. The center-tap in this situation may be called the common, neutral, or identified conductor, and if we connect it to ground it can be called the grounded conductor. Connecting the neutral to ground diverts unwanted fault currents to the earth, and not through persons like you or me.



With the normal three-wire connection to our house panel, we get the benefits of 240 volts (L1-L2) for our heavy loads (like air-conditioners, water-heaters and motors), and 120 volts (L1-N or L2-N) for our general lighting and receptacle circuits.

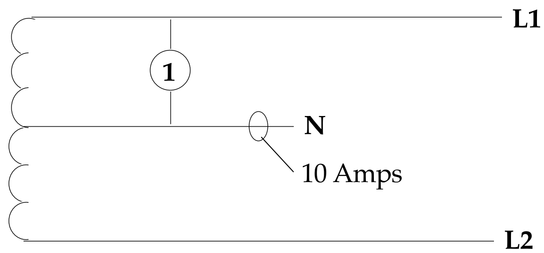
Balancing

It may be said that our 120 volt loads are balanced on the neutral in the above transformer. That is because the neutral only carries the difference or unbalanced current between the loads connected to the hot conductors (L1 or L2).

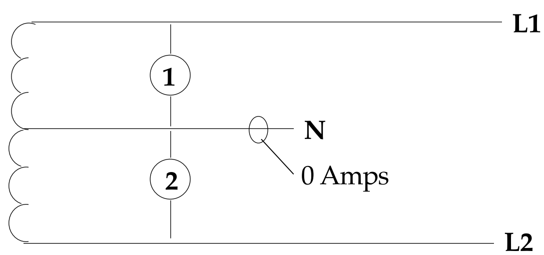


The above transformer secondary consists of three conductors: two hots or phase-conductors (L1 and L2) and a neutral (N). As before, the secondary has two voltage levels; 240 volts (L1-L2) and 120 volts (L1-N) or (L2-N).

Load #1 is a 1,200 watt, 120 volt load connected (L1-N). If we put an amprobe (current tester) around the neutral in this situation, we should get a reading of 10 amps (1,200w/120v).

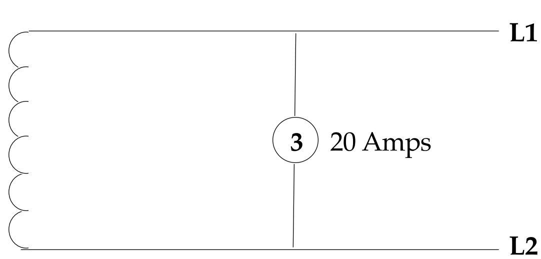


Load #2 is also a 1,200 watt, 120 volt load connected (L2-N). The neutral in this situation should get a reading of 10 amps, right ! Sorry ! We would get a reading of "0" on our amprobe because the two 1,200 watt loads would be balanced. Remember ! The neutral only carries the difference or unbalanced current between the loads connected in this situation.

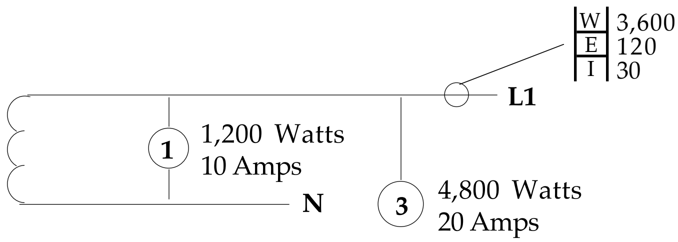


Now, if only one of the two 120 volt loads (#1 or #2) are turned on or running, our neutral would only carry the 10 amps of the other side. So, the maximum that our neutral would carry in this situation is 10 amps. We call this the "maximum unbalanced load" and must size our neutral conductor based on this assumption.

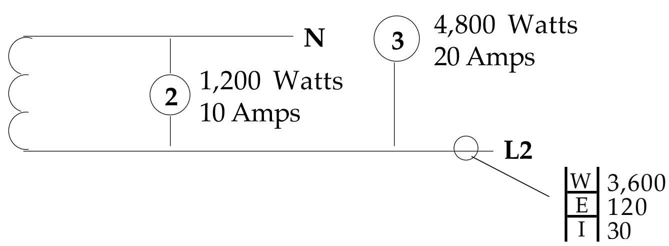
What about Load #3, this is a 4,800 watt, 240 volt load hooked-up (L1-L2). We don't really need a neutral for this load because it's a balanced load.



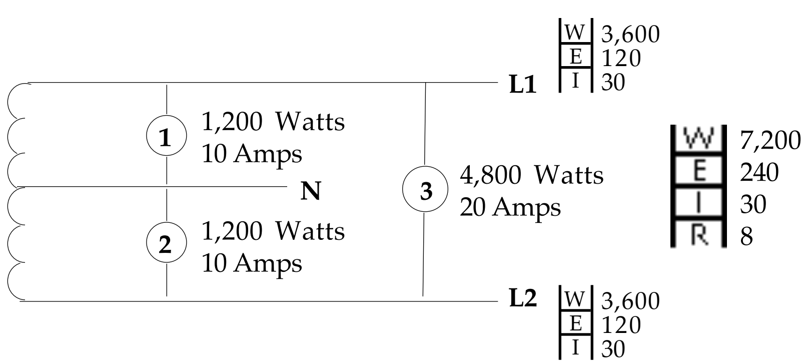
If we check the current on conductor (L1) we'll find that it is carrying 3,600 watts. That's one 1,200 watt, 120 volt load (#1) plus one-half of the 4,800 watt, 240 volt load (#3) for a total of 3,600 watts at 120 volts.



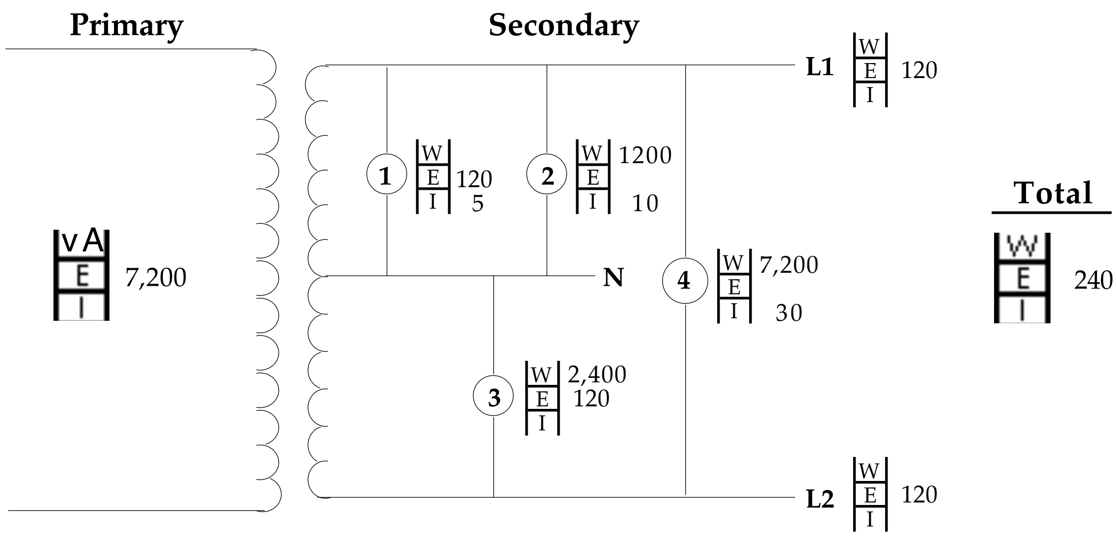
If we check the current on conductor (L2) we'll find that it is also carrying 3,600 watts. That's one 1,200 watt, 120 volt load (#2) plus one-half of the 4,800 watt, 240 volt load (#3) for a total of 3,600 watts at 120 volts.



Keep in mind that the two hot phase-conductors have to carry this load along with the two 1,200 watt, 120 volt loads. That's a total of 7,200 watts when you add up all of the loads (1,200 + 1,200 + 4,800). If we divide the total wattage by the total voltage (7,200/240) we get a total of 30 amps. So, assuming that we have no efficiency or power factor losses we'll require a 7.5 kVa transformer.



Remember the National Electrical Code (Article 220-4(d)) requires that we balance our circuits as evenly as possible when distributing our loads.



(1) The turns ratio for the above transformer is _______.

(a) 240 : 1
(b) 60 : 1
(c) 30 : 1
(d) 4 : 1

(2) The maximum current on Line 1 (L1) is ______.

(a) 65 amps
(b) 50 amps
(c) 48 amps
(d) 45 amps

(3) The maximum current on Line 2 (L2) is ______.

(a) 65 amps
(b) 50 amps
(c) 48 amps
(d) 45 amps

(4) The total wattage on the secondary is ______.

(a) 11,400 watts
(b) 6,000 watts
(c) 5,700 watts
(d) 5,400 watts

(5) The total current on the secondary is ______.

(a) 65 amps
(b) 50 amps
(c) 48 amps
(d) 45 amps

(6) The total wattage on the primary is ______.

(a) 11,400 watts
(b) 6,000 watts
(c) 5,700 watts
(d) 5,400 watts

(7) The total current on the primary is ______.

(a) 6.4 amps
(b) 3.2 amps
(c) 1.6 amps
(d) 1.1 amps

(8) The current flowing on the neutral with all loads on is ______.

(a) 20
(b) 15
(c) 5
(d) 0

(9) The maximum current that the neutral must carry is ______.

(a) 20
(b) 15
(c) 5
(d) 0