A Set of Templates For Teaching About How Three Phase Electrical Power Really Works

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Abstract: Three phase circuits can be confusing unless we really look at them and see them in a different light. I have taken the laws of single phase and three phase circuits and developed a number of templates so that most three phase circuits can be looked at as single phase circuits. When the students learn to look at three phase circuits with the use of the templates, much of the confusion of solving for unknowns in three phase circuits goes away. It can be shown that almost every circuit can be seen as a group of single phase circuits. As a matter of fact, if the voltage sources are known quantities, most unknown voltages and currents can be found by the use of one or two equations. This paper shows examples of how these templates are utilized to solve for unknown quantities in four typical three phase circuits. Two other common circuits are also shown. Part of the reason for developing this approach is to help students understand how three phase circuits really work, and when and why to use the √3 factor.

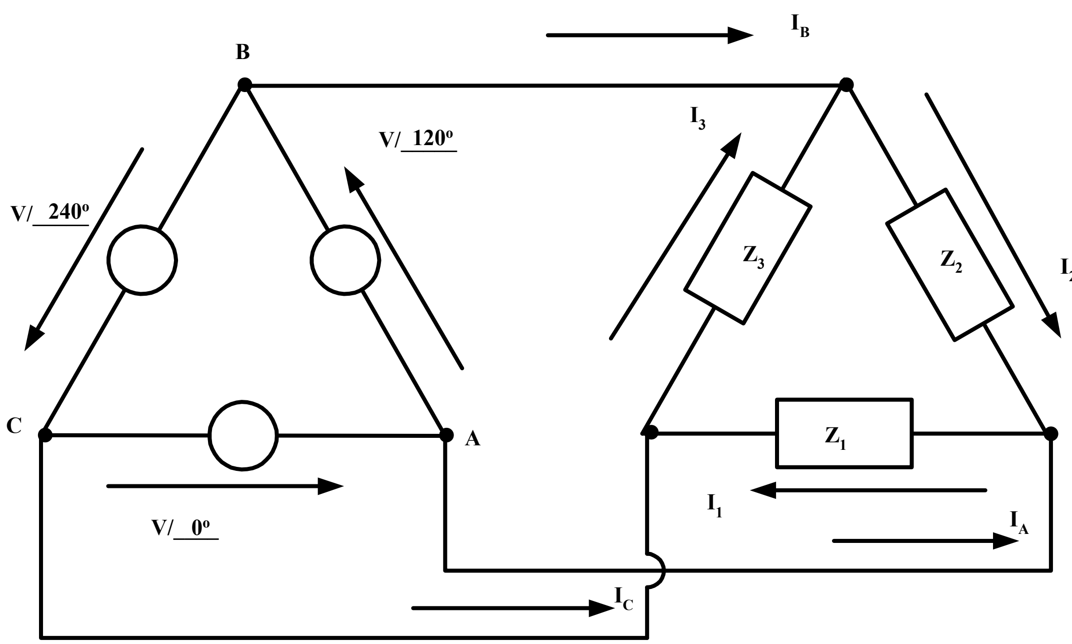

Figure # 1 Delta Delta Circuit

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How It All Got Started

After teaching the principles of three phase electrical power for a number of years, it became obvious that there had to be a better way to teach these principles. One day, when working with three phase circuits, I drew a series of templates that would help anyone understand these circuits easier. The first thing that was done was to draw the three phase input voltages, keeping the angles on the drawing the same as the actual vector angles of the voltages. Then, whatever loads existed would be drawn at the same angles as their respective voltages. Then, careful examination reveals that most three phase circuits are only a series of single phase circuits. If Ohm's Law, Kirchoff's Current Law, and Kirchoff's Voltage Law are applied to these three phase circuits, the whole problem becomes an exercise in the basics of single phase electrical circuits. Granted, the math, and especially the vector algebra, is a little more difficult, but not excessively so. The biggest difficulty occurs in keeping track of the phase angles and polarities of the various parameters of the circuits.

Three Phase Delta Delta Circuit

As an example, let's look at the delta delta circuit shown in figure # 1. Each of the three voltages has a magnitude and an angle associated with it. Notice, that the way the circuit is drawn, each angle can be measured and inferred directly off of the drawing. Also, the angle of the voltage across each of the loads is the same as the angle at which the load is drawn. This makes it easy to calculate the currents in each of the three loads, including both magnitude and phase angle. The nature of the load is really irrelevant, as long as it is known. It can be resistive, capacitive, inductive, or active. Whatever the nature and magnitude of the load, the current will be a complex number that can be expressed in either polar or rectangular form. Then, since Kirchoff's Current Law states that the sum of the currents entering a node is equal to the sum of the currents leaving a node, the three line currents can be easily found. This is shown below:

$\mathbf{I_1 = V/\underline{0^o}\ / Z_1}$ $\quad$ $\mathbf{I_2 = V/\underline{120^o}\ / Z_2}$ $\quad$ $\mathbf{I_3 = V/\underline{240^o}\ / Z_3}$, For the three phase currents.

Then, since the phase currents are known, the following is true:

$\mathbf{I_A = I_1 - I_2}$ $\quad$ $\mathbf{I_B = I_2 - I_3}$ $\quad$ $\mathbf{I_C = I_3 - I_1}$,

This approach helps the students actually see what the currents are in practice, and the $\sqrt{3}$ factor comes into play naturally. Thus, memorization of where the $\sqrt{3}$ is used is not required.

The Next Step, Wye Wye Circuits

Learning to analyze a wye wye circuit for unknown voltages and currents is even easier, if the neutral is connected. The neutral is the dotted line in the drawing below, figure # 2. Using the same idea of keeping the phase angles on the drawing the same as the actual phase angles helps the student to visualize the circuit. Then, when the impedances are drawn in at the same angle as the voltages, all the unknown currents can be found by a simple application of Ohm's Law. I_1, I_2

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and I_3 can be found by:

$$I_1 = V\underline{/\,90o}\ /\ Z_1 \qquad I_2 = V\ \underline{/\,-30o}\ /\ Z_2 \qquad I_3 = V\underline{/\,210o}\ /\ Z_3$$

As long as the rules of vector algebra are followed, this is a rather simple Ohm's Law problem. However, if the neutral wire doesn't exist the problem becomes a little more difficult. The problem is that the voltage at the connection point of the three loads is not known. Using Kirchoff's Current Law, one equation can be written for the V_N node. It would look like this:

$I_1 + I_2 + I_3 = 0$ And note that $I_1 = (V\underline{/\,90^o} - V_N) / Z_1$, $I_2 = (V\underline{/\,-30^o} - V_N) / Z_2$, and $I_3 = (V\underline{/\,210^o} - V_N) / Z_3$.

Notice that there is only one equation generated, and it has one unknown. Most of the time this is a fairly straightforward procedure. If all the components (angles and magnitudes and signs) are kept track of, accurate results are obtained. Once V_N is determined, the voltage across each of the loads can be found. When the voltage across a load is known the current can be found. This is shown below:

Using the neutral point as 0 volts, $I_1 = (V\underline{/\,90^o} - V_N) / Z_1$, $I_2 = (V\underline{/\,-30^o} - V_N) / Z_2$ and $I_3 = (V\underline{/\,210^o} - V_N) / Z_3$.

Note that for balanced three phase loads where the neutral is inaccessible, such as three phase motors, the neutral wire can be assumed to exist. Then the problem can be worked just as if the neutral did exist.

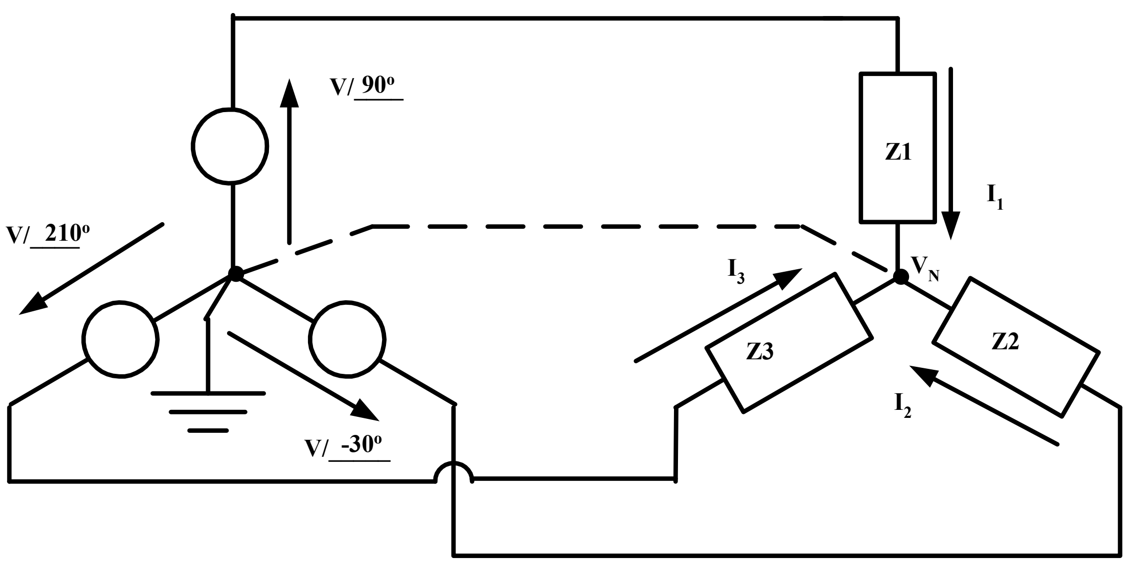

Figure # 2 Wye Wye Circuit

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Another Circuit, A Delta Source Driving a Wye Load

Now let's pretend that there is a three phase delta source driving a three phase wye load. An imaginary three phase wye source with an imaginary neutral can be placed inside the three phase delta source. This is shown in figure # 3. Notice that the voltages and phase displacements of the imaginary three phase wye source can be easily determined directly from the drawing. Then, let the imaginary neutral, which doesn't exist, be zero volts. Even though this wye source doesn't exist, it can be used to determine V_N, which does exist, but only has an imaginary reference. Then once V_N is known, the voltages and phase angles from the wye source that doesn't exist can be used to calculate the phase and line currents, which do exist. This is identical to the process used to determine phase and line currents for the wye-wye circuit. Note that the neutral that doesn't exist cannot be connected to V_N, which does exist. This process also makes it easy to determine the values of the voltages across the elements of the wye load.

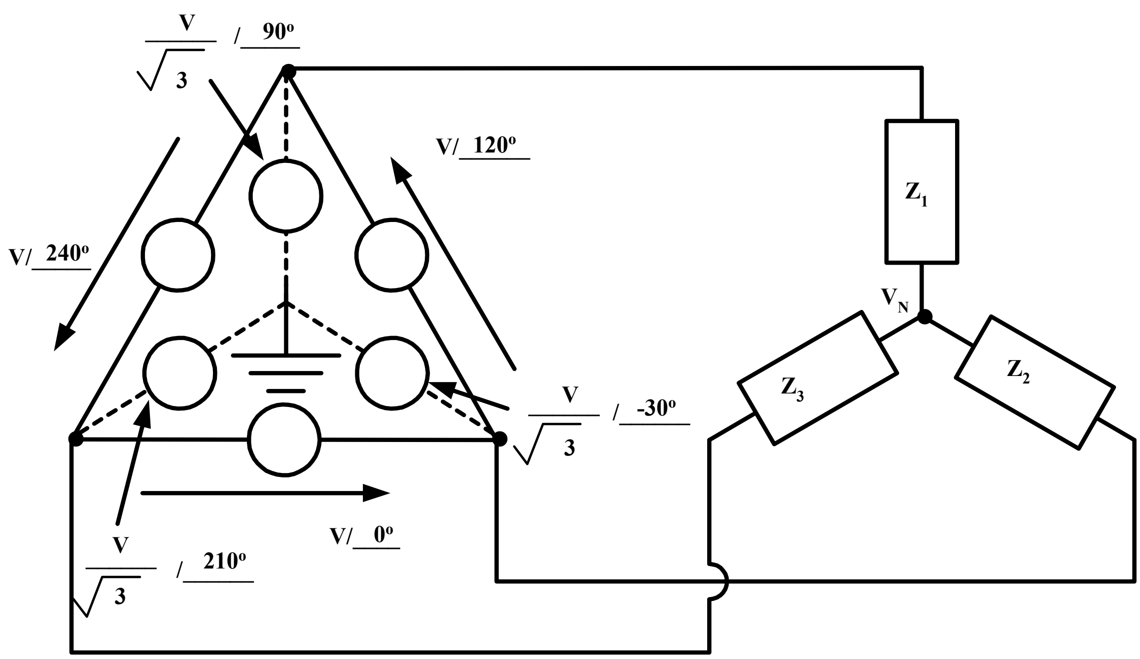

Figure # 3 Three phase Delta Source Driving a Wye Load

A Wye Source Driving a Delta Load

Another common source load found in three phase circuits is shown below in figure # 4. It is a wye source driving a delta load. In the industrial and commercial world this is relatively common. The reason is that many, if not most, industrial three phase sources are wye connected. This is for safety reasons. The source has a definite point that can be connected to earth ground. This prevents static charges from causing the source to be floating at a high voltage above ground. Also, if a short occurs anywhere in the system, a fuse will blow and the short circuit will

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have to be repaired. In a floating delta system two shorts will have to occur before a problem surfaces. The existence of two short circuits in a system make trouble shooting much more difficult. This is one of the more difficult problems that can occur in three phase delta systems. Methods exist to detect when the first short occurs. At that stage, only the existence of the short circuit is known, not it's location. Finding it's location can be very difficult.

To analyze a wye source driving a delta load, it is necessary to generate a make believe delta source from the real wye source. Just by looking at the drawing, it can be seen that the phase to phase voltage is √ 3 times the phase to neutral voltage. The phase angles for the make believe delta can be calculated, or inferred from the angles on the drawing. This problem then works just like the delta-delta problem worked previously. As long as the analysis is consistent and all the vector math kept track of, accurate results are obtained.

One last detail that might exist is the phase sequence. If the phase sequence needs to be reversed, the easiest thing to do is to change the connections on the load. With the loads moved, this then becomes just another problem using the same techniques as previously employed.

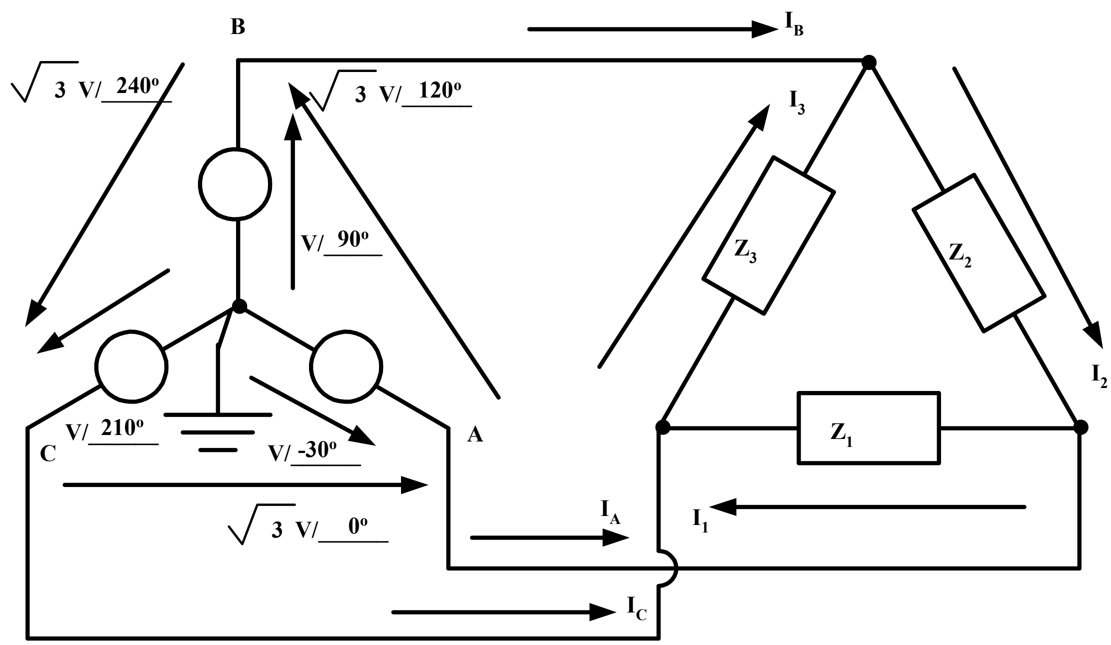

Figure # 4 Wye Delta Circuit

In Conclusion

As you might have noticed by now, this method of looking at three phase circuits was developed without the use of any computer software. As a matter of fact, all of the work can be done with a TI-36 or similar scientific calculator. Once the student graduates, he or she will find the appropriate software and computer tools to use in whatever line of work he or she chooses to go

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into. Oftentimes, the choosing is done for them. If they have a good basic understanding of how things really work they will, on their own, quickly learn how to apply whatever software is used in their particular organization. However, if they don't understand the basics of how circuits really work they will have a great deal of difficulty applying computer software to whatever they're doing. To acquire a real understanding of how things really work requires actually doing the work. The doing of the work by hand and the use of a simple calculator impresses on their minds the real feel of basic circuits. There is no substitute for this.

Attached is a set of 6 templates of the most common three phase circuits used in the United States today. These are by no means the only three phase circuits in use. It is my desire that these templates will be picked up by colleges and universities around the country so that students can gain a basic understanding of power circuits. Some of them might even become electrical power engineers.

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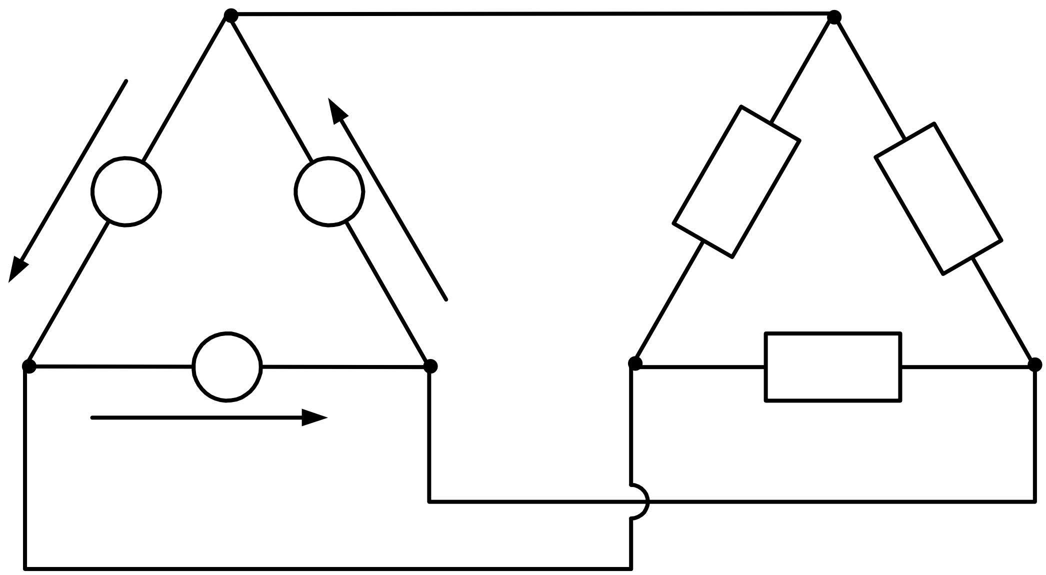
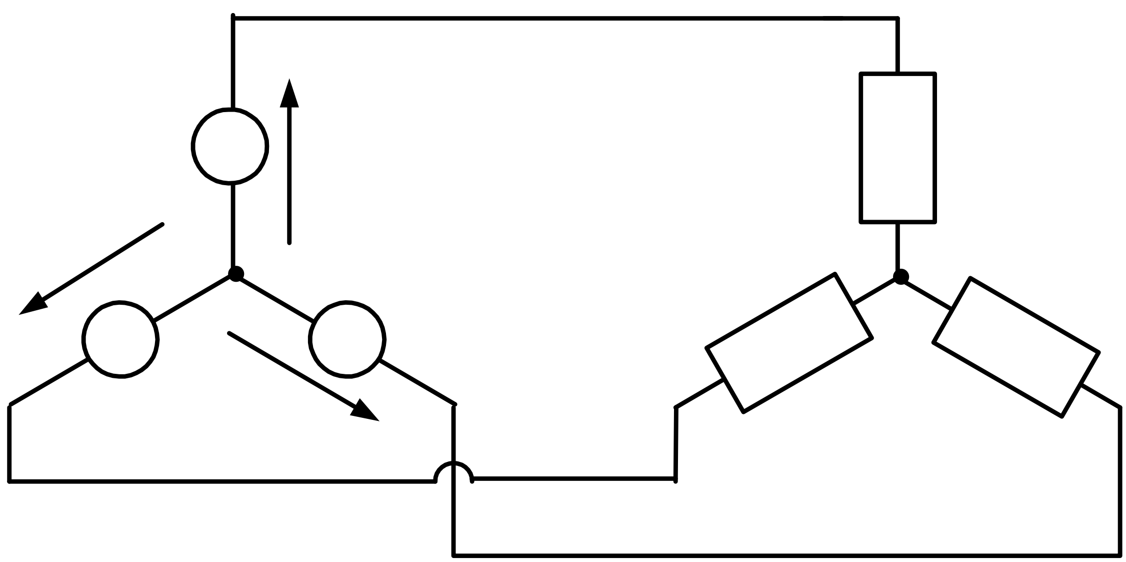


Delta Delta Circuit



Wye Wye Circuit

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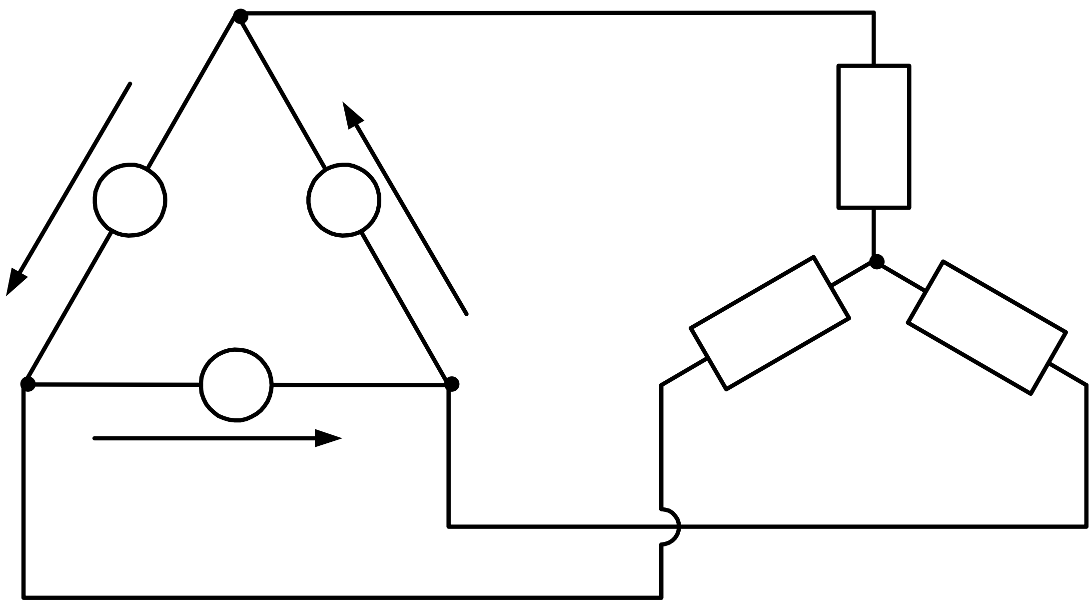
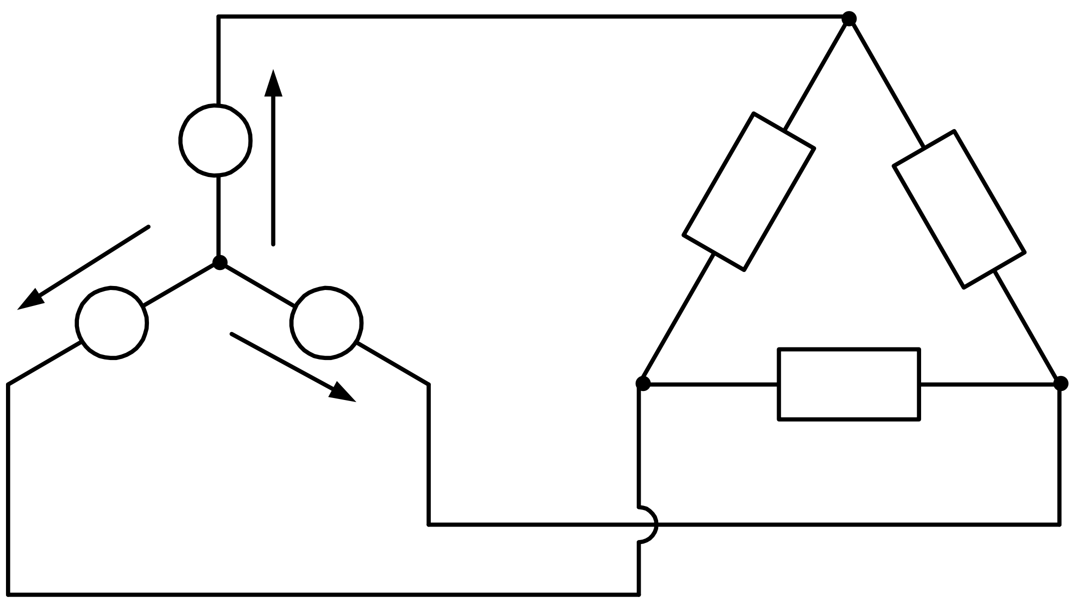


Delta Wye Circuit



Wye Delta Circuit

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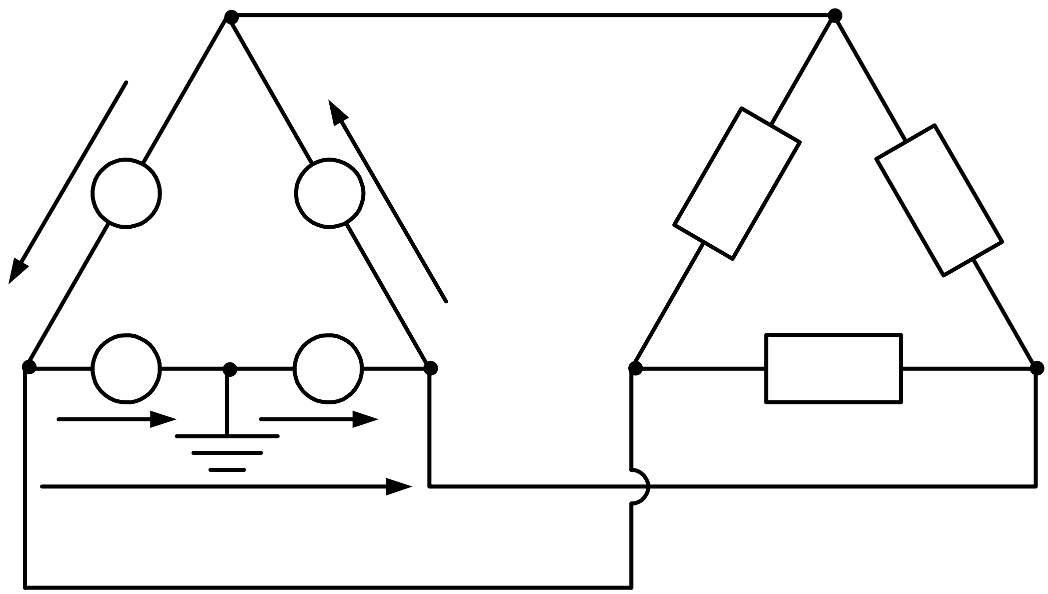
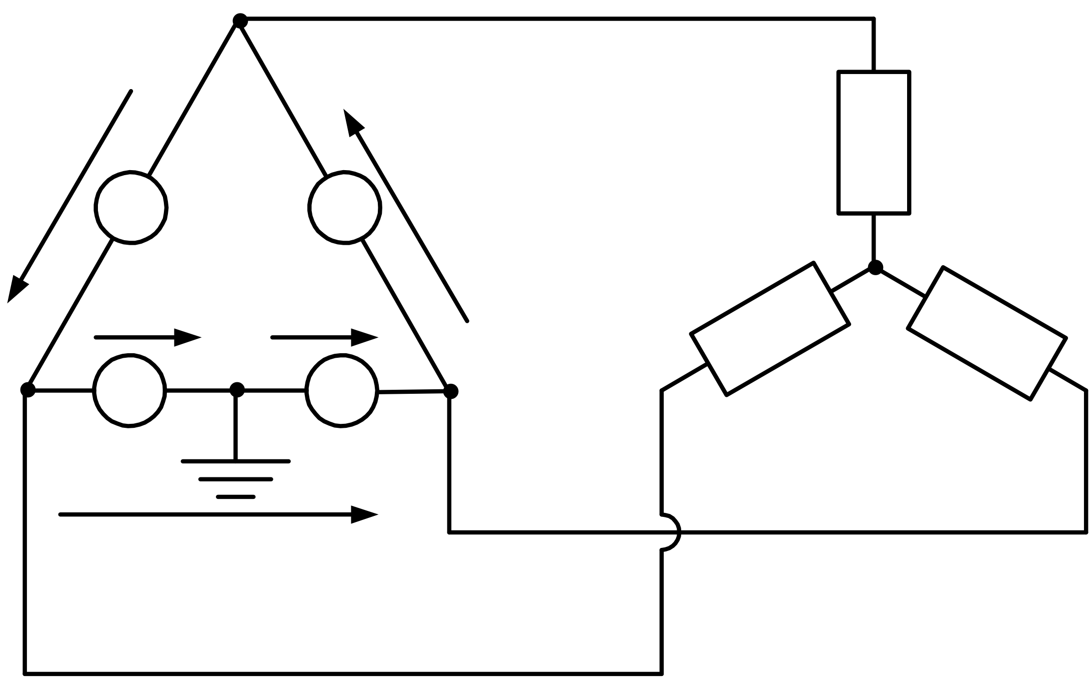


Three phase Delta Source With Delta Load And Single Phase Leg Usually Set Up For 120/240 VAC



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