PDHonline Course E219 (2 PDH)

Single to Three Phase Conversion Circuit

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Course Content

Initially, electrical power transmission (or distribution) was accomplished using a simple two wire system. As power loads became greater, heavier loads were placed on conductors distributing the amperage and voltage. Generation of power was improved using greater technology in design and construction of large Alternating Current (AC) power machinery. The machinery used to produce AC is commonly referred to as Alternators, while Direct Current (DC) electricity is produced by Generators.

Basically, Alternators rotate a magnetic rotor in a static field. The nature of the electrical waveform produced is sinusoidal and completes one waveform in one full 360° rotation of the magnetic rotor. Because of this feature and the compatibility of trigonometry with angular computation, an AC waveform is often measured in degrees, with 360° representing one complete cycle. As development progressed, alternators were designed to employ three magnetic fields in the rotor and stator, producing three evenly distributed waveforms. Thus, one complete 360° rotation of the rotor produces three waveforms (phases) separated by 120° rotation. This now affords the power to be distributed on three separate conductors using only one conductor for the return (commonly known as ground). Actually, if the electrical load on the three distribution conductors is about the same (balanced), very little current is returned to ground.

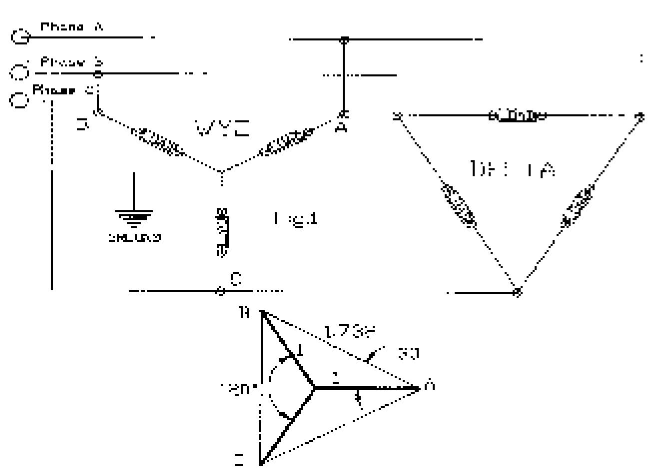

Figure 1

The three phase distribution system consists of two basic configurations, "wye" and "delta". **Figure 1** illustrates the differences in circuit configuration. The phases are generally labeled "A", "B" and "C". Terminology defines the sequence of phases in relation to time as A, then B, then C. The return shown for the Wye is shown as "ground" or can also be termed "common". The three phases are connected to the common through the loads, thus forming a "Y" configuration. The Delta configuration does not employ a common, but connects each phase to each other through their respective loads. This configuration is not recommended for power distribution circuits with unbalanced loads because the unbalances will affect the power source and conductor loads adversely. Because the Wye configuration has a separate return, it can more effectively handle unbalanced loads. In describing the circuit for conversion of single to three phase, it will also be shown that the voltages between each Delta phase are 1.732 times the voltages between the Wye phases and ground.

Because the AC waveform is related to the rotation of the rotor in the Alternator, the sinusoidal wave is cycled in relation to the angular velocity (or rotational speed) of the rotor. Thus the number of cycles related to time (cycles per second) becomes the frequency (f) of the waveform. As we know, power frequencies commonly provided vary within various countries, but we are most familiar with a frequency of 60 cycles per second (60 cps). This means that one cycle will take approximately 0.01666 seconds or 16.66 milliseconds (16.66 ms.) More intricate AC waveform calculations also employ a different measure of angles called radians (RAD) rather than degrees. This notation is related to the mathematical formula for the circumference of a circle and uses the Greek letter π (Pi). It designates one full rotation, or 360 degrees, as 2π radians. We are most familiar with AC voltage and amperage being expressed with a single value, but it is obvious that the value of the wave is constantly changing with time. In reality, the value we are most familiar with is the RMS (root mean square) of the peak value the voltage normally achieves and reflects the effective power of the wave. This is calculated to be 0.707 of the peak value. Classic AC waveforms are expressed in terms of the peak value (E or V), the frequency, and the time elapsed in reference to the first zero crossing of the waveform in a positive direction. Angular position is also a part of the expression. Frequency and angular position are generally combined and expressed using the Greek letter ω (omega) to represent $2\pi f$. Combinations of phases, time, angles, etc. can become confusing. It must be recognized that we must reference all of these variables to one in order to analyze the conditions we are examining. Thus, we shall use one waveform as our reference (Phase A).

We shall express a 60 cps AC voltage of 0.707(rms) volts. With this expression we can calculate the amplitude of the wave at any point in the cycle.

E = sin wt where sin = sine (trigonometric value); t = time; $\omega = 2\pi f = 2\pi$RAD X 60 cps

NOTE: 0.707E(rms)/0.707 = **1 x <u>E(peak)</u>**

When simplified, to express the amplitude for the precise location in the cycle we can use:

E = sin q where θ = value of an angle in degrees.

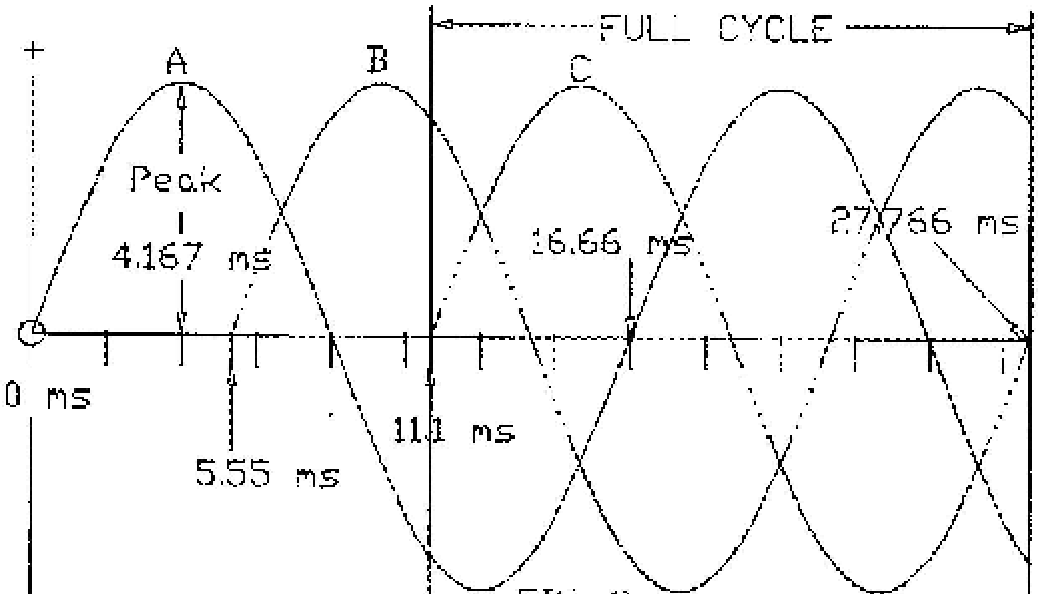

FIG. 2

Figure 2 shows a simplified illustration of three waveforms typical of a three phase circuit. The waveform labeled "A" is our reference wave and begins at the zero time point. Note that Phase B and Phase C zeros occur at a later time. Also, note that the peak positive wave for Phase A occurs at t = 4.167 ms (0.004167 sec.). We can use the above classic notation to prove this. Be aware that the waveforms continue after completing their cycle.

E= sinωt; E = sin 2π x 60 x 0.004167; E = sin (2π RAD) x 0.25; E = Sin $\pi/2$ RAD

2π RAD = 360°; ∴ E = sin ∠90; Sin ∠90 = 1; **<u>E = 1 (peak)</u>**

Phase B cycle begins 5.55 ms (0.00555 sec.) later than Phase A. We calculate the angular lag with the formula: $\omega t = 2\pi ft = 2\pi$ RAD x 60 x 0.00555 = 0.333 x 360° = **<u>120°</u>**

Phase C cycle begins 11.1 ms lagging Phase A. We calculate the angular lag with the formula: $\omega t = 2\pi ft = 2\pi$ RAD x 60 x 0.0111 = 0.666 x 360° = **<u>240° and lagging Phase B by 120°</u>**.

Examine the waveforms in total, concentrating on the time between 11.1 ms and 27.766 ms, which constitutes a full 360° phase cycle. There are three positive and three negative waveforms in one cycle of power. When powering the same load, three phase power is considerably smoother than single phase which produces only one positive and one negative wave per cycle. While an important advantage of three phase power is in distribution and transmission of power, the waveforms also become an attractive feature. The power pulses provided for motors is three times more than single phase and lends itself to smoother running three phase motors.

This is particularly useful for three phase motors because they generally impose very balanced electrical loads. Additionally, the greater number of power pulses per cycle and the fact that the total voltage variation never reaches zero in any point of the total cycle produces smooth Direct Current power when used with rectifier circuits. This allows very steady DC voltages and less variation (ripple). However, this comparably low power application is not often used because the appropriate equipment is normally supplied only with single phase power.

Because we are dealing with waveforms that are sinusoidal in nature and cycle every 360 degrees, we can sum different voltages together that are not in phase (not at the same angle) using vector analysis providing they are cycling at the same frequency. This is quite the same as using vectors for aircraft navigation and in calculating mechanical loads at various angles. A voltage is simply expressed with the maximum amplitude and reference angle. In Figure 1, earlier, we used Phase A as our reference, labeled **E sin wt**. Phase B would then be labeled **E sin wt - 120°**. Phase C would then be labeled as **E sin wt - 240°**. The minus sign designates that the waveform is considered to be lagging the reference voltage (Phase A). Of course, because the waveforms are continually cycling there is no "race" being held, but we have established that the waveforms are separated by 120 °. This description of a voltage is often called a "phasor".

The most uncomplicated way to convert single phase power to three phase is to power a single phase motor which in turn mechanically drives a three phase alternator. However, if heavy power is not required, two phases can be "built" which lag the single phase by 120° and 240°. This is accomplished using two electrical tools. We can employ transformers which convert voltages and polarities using the original single phase power. Then we can use capacitors to provide a lagging angle of 90° to the converted voltages and polarities. With judicious use of Trigonometry our three phase circuit can be constructed.

To refresh the reader, transformers use the electromagnetic fields produced by varying voltages and currents to couple conductor windings. We call the initial power source the "line" and it is connected to the Primary winding of the transformer. Through magnetic material (i.e. iron) the magnetic fields are coupled to Secondary windings. The number of windings in the primary and secondary of the transformer dictate the voltages that are converted to the secondary. The voltages are directly proportional to the ratio of the primary to secondary windings. Thus, we can vary voltages on the secondary of the transformer by varying the windings. Also, the direction (polarity) of the secondary waveform is determined by the direction of the windings around the magnetic core relative to the primary and secondary. One connection on the secondary winding will provide a voltage of the same polarity (phase) to the primary, the other end of the winding will provide a voltage of opposite polarity (180° out of phase). It is important to recognize that this also can represent a lagging angle of 180°.

The second tool we will use is the capacitor. Reviewing again, a capacitor simply consists of two closely separated and insulated conductive plates each having an electrical connection. When the connections are made to an AC circuit, the capacitor will shift the voltage waveform to **lag** the supplied voltage by 90° (π/2 RAD).

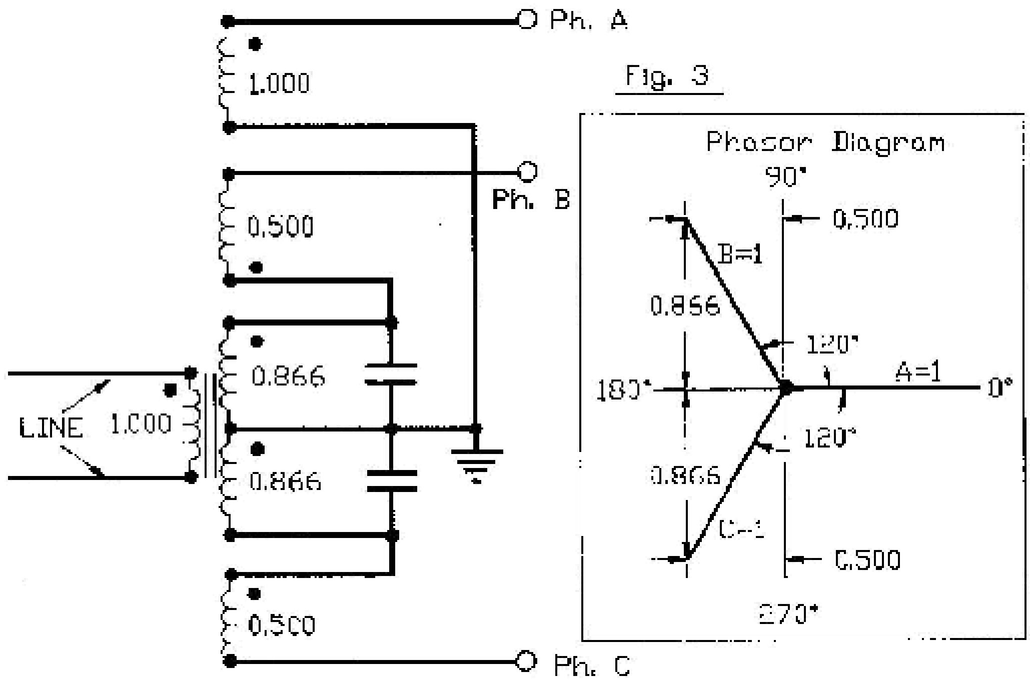

Figure 3

As mentioned above, the transformer and capacitor are used in conjunction with prescribed voltages and angles to produce "phasors". Please refer to Figure 3.

Figure 3 describes the basic circuit and phasor representation of the three phase circuit. The joined semicircles represent transformer windings and the heavy dots on the ends are connections. The winding connected to the conductors marked "LINE" is connected to the incoming single phase power and is called the Primary winding. The vertical lines between the windings represent the magnetic coupling between the Primary winding and the coupled windings which are called Secondary windings. Note that all six secondary windings are magnetically coupled with the Primary winding. The dots adjacent to the windings indicate the polarity of each winding relative to the incoming power. The capacitors are shown as two parallel lines in close proximity and connected to the circuit. They are not polarized and both plates (sides) can accept positive and negative voltages. The series of parallel lines drawn in a triangular form represent ground or common and are connected to the circuit..

Note that the dot on the Primary winding is at the top of the winding. Referring now to the uppermost Secondary winding, the dot is also at the top. This indicates that the voltage of the incoming line is exactly in phase with the voltage on the top winding of the Secondary winding. If we are to observe the voltage from the bottom connection to the top, we will observe a voltage exactly 180° out of phase with the incoming line. Also note the numbers (1.000; 0.500; 0.866) placed adjacent to each winding. These represent the ratio of the number of coils in the windings relative to the Primary. The Primary winding normally is labeled as "1.000" for reference, but in construction the actual number of windings vary depending on the specific design.

Now note that the uppermost Secondary winding also is labeled "1.000". This means that the voltage ratio between the Primary and Secondary is 1:1, or the voltages are equal. This winding will be our reference phase (Phase A) and is connected to the Ground. It is equal to the incoming voltage and exactly in phase or 0°. We depict this phase on our phasor diagram as "A" and place it on the zero angle of the horizontal line (or "X" axis) which originates from the origin.

Now let us trace the circuit for Phase B to Ground. Starting at the circle marked Ph. B, the circuit connects to a secondary winding with 0.500 turns ratio. This indicates that the voltage produced is ½ of the line voltage. Also, the course of the circuit is traced from the end of the winding <u>opposite</u> the dot, thus the voltage is 180° out of phase with Phase A. Refer again to the phasor diagram. This voltage is represented by extending the equivalent of 0.500 volts along the "X" axis in the direction of 180°. Continuing, the circuit is now connected to a capacitor which is connected across another winding producing 0.866 times the voltage of the line voltage. However, our circuit connects to the winding at the dot. This means that the capacitor will create a lag of 90° to an in phase voltage. Referring to the phasor diagram, this voltage is represented by extending the equivalent of 0.866 volts along the positive (90°) "Y" axis. The circuit then is directed to Ground which completes this power phase. Note the phasor drawn on the phasor diagram labeled "B=1". This represents the sum of the 0.500 at an angle of -180° plus the phasor of 0.866 at an angle of -90°. These phasors can be represented as $0.500\angle{-180}$ plus $0.866\angle{-90}$. Trigonometry confirms that the summation of these two phasors result in the hypotenuse of a right triangle with sides of 0.5 and 0.866. Using the Pythagorean theorem and the Laws of Sines and Cosines, we discover the hypotenuse to be a voltage of 1 and the angle of the hypotenuse to the "Y" axis to be 30°. Thus, Phase B is equal in voltage to Phase A and lagging it by - 120°.

Now let us trace the circuit for Phase C to Ground. Starting at the circle marked Ph. C, the circuit connects to a secondary winding with 0.500 turns ratio. This indicates that the voltage produced is ½ of the line voltage. Also, the course of the circuit is traced from the end of the winding <u>opposite</u> the dot, thus the voltage is 180° out of phase with Phase A. Refer again to the phasor diagram. This voltage is represented by extending the equivalent of 0.500 volts along the "X" axis in the direction of 180°. Continuing, the circuit is now connected to a capacitor which is connected across another winding producing 0.866 times the voltage of the line voltage. However, our circuit also connects to the winding <u>opposite</u> the dot. This means that the capacitor will create a lag of 90° to a 180°out of phase voltage.

Referring to the phasor diagram, this voltage is represented by extending the equivalent of 0.866 volts along the negative (270°) "Y" axis. The circuit then is directed to Ground which completes this power phase. Note the phasor drawn on the phasor diagram labeled "C=1". These phasors can be represented as $0.500\angle{-180}$ plus $0.866\angle{-270}$. Trigonometry confirms that the summation of these two phasors result in the hypotenuse of a right triangle with sides of 0.5 and 0.866. Using the Pythagorean theorem and the Laws of Sines and Cosines, we discover the hypotenuse to be a voltage of 1 and the angle of the hypotenuse to the "Y" axis to be 30°. Thus, Phase C is equal in voltage to Phase A and lagging it by -360° + 120° or -240°.

While the circuit seems quite simple, it will require a great deal of effort to create a workable tool. The circuitry shown is a very simple illustration to demonstrate the theory. Depending on the circuit parameters (voltages, resistances, reactive loads, component specifications, etc.) use of capacitors can create high amperage loads. Also, the transformer winding ratios required are not commonly available. Additionally, transformer losses (inefficiencies) vary depending on their intended use. Another important consideration is the "reflected" loads that transformers impose. All of the power and energy that is provided by the three phases in the Secondary will be imposed on the single phase of the Primary, thus increasing the amperage flow considerably on the supply line. A workable and efficient design of this circuit requires the attention of an experienced electrical circuit designer and careful attention to the intended loads and apparatus to be serviced. Judicious use of current limiting devices without undue effect on the impedances must be exercised. Also, careful attention to the loads and their effect on phase angles must be observed to minimize variations in phase angle separations.

Earlier, reference was made to the difference in voltage between the Delta and Wye phases. Now, refer to Figure 1 again. We have reviewed phasors and the use of trigonometry in adding them. Observe the triangular figure at the lower part of Figure 1. The triangle represents the resulting Delta phases and within the triangle is located three phases for the Wye configuration. As we have learned, the Wye phases are separated by 120°. As described, the Delta phases connect the voltages to each other (through loads). The phasor diagram adds each phase connection. The phasors are represented by an isosceles triangle with equal sides of "1", an included angle 120° and equal angles of 30°. Again, using Trigonometry, we find that the resultant Delta phases are truly 1.732 times the equal sides, or the respective Delta voltages are 1.732 times the respective Wye voltages. If we calculate the angle on the Delta phases, we shall discover that they too are separated by 120°. Using Phase A (Wye configuration) as a reference, from A to B the phasor is $1.732\angle 150°$, from B to C is $1.732\angle 270°$ and from C to A is $1.732\angle 30°$.

A value of "1" has been assigned to our reference voltage. It is obvious that this value can be any voltage the design requires providing the ratios are observed. The ratio between the primary and all secondary windings can also be varied, providing the ratios between the secondary windings are kept as described in the circuit (i.e. 1.000:0.866:0.500).