

Part 14: Three-Phase AC

14.1 Single And Three-Phase Supplies

Most domestic supplies are single-phase AC with a phase and neutral wire. However, most electricity is generated and transmitted as three-phase AC. Rather than having a single coil rotating in a magnetic field, three-phase generators have three coils fixed at 120° to each other; thus three voltages, that are 120° out of phase with each other, are produced in three separate circuits (figure 14.1). The phases are normally called red (R), yellow (Y) and blue (B) or line 1 (L_1), line 2 (L_2) and line 3 (L_3), or in the USA they are called A-phase, B-phase and C-phase.

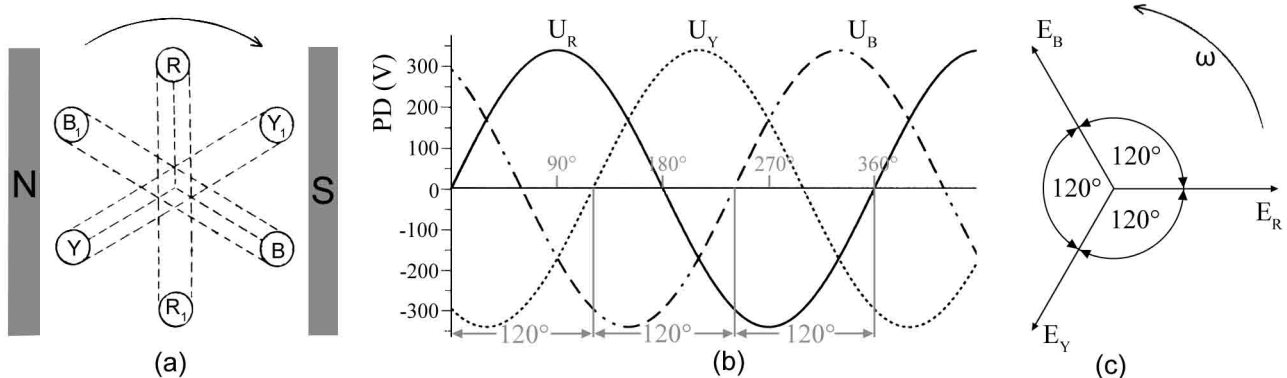


Figure 14.1: A three-phase AC supply with 240V RMS generated in each coil: (a) generation; (b) wave diagram; (c) phasor diagram.

The advantages of using three-phase AC for transmission and distribution of electricity are:

- less copper (or aluminium) is needed for the conductors of a three-phase system which transmits a given power at a given voltage over a given distance than for a simple single-phase system.
- three-phase motors have many advantages over single phase motors, including smaller size, steady torque output, and the ability to self-start.
- when connected in parallel, single-phase generators present difficulties which do not occur with three phase generators.

14.2 Three-Phase Voltages

If you look at the wave and phasor diagrams in figure 14.1 b and c it should be clear that if the three phases are added together the result is that the voltages cancel each other out and $V_R + V_Y + V_B = 0V$. Therefore, if one end of each coil (R_1 , Y_2 & B_3 from figure 14.1a) are connected together a common neutral line at zero potential is created and the result is called a *4-wire 3-phase supply*. Figure 14.2a shows how the generator (or transformer) coils can be connected to give a 4-wire supply, this configuration is called a *star*, *wye* or *Y* connection and the point x is called the *neutral point*, *star point* or *zero point*. Figure 14.2b shows an alternative connection for the generator coils, known as a *delta* or *mesh* connection, this configuration has no neutral wire and provides a *3-phase 3-wire supply*.

4-wire supplies are normally used to distribute domestic supplies since they can provide an earthed neutral. 3-wire systems are more commonly used for the transmission of high voltage supplies between substations because money is saved by not providing a neutral wire. If we consider a 4-wire supply we can see that there are 4 possible voltage supplies available, these are shown in figure 14.3.

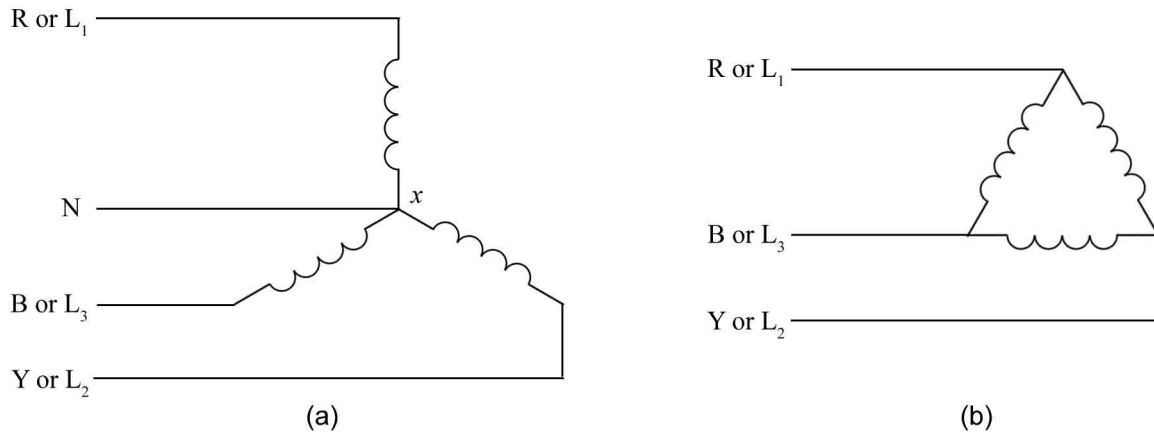


Figure 14.2: Three phase generator coils: (a) star, wye or Y connection ; (b) delta connection;

The power supplies shown in figure 14.3 are:

- The three phase wires together give a 3-phase 3-wire supply suitable for heavy machinery such as 3-phase motors. With a 240V supply in each line the 3-phase supply has an RMS voltage of $240\sqrt{3} = 415V$. (The mathematical derivation of why $\sqrt{3}$ is used is too complex for this text)
- Three single-phase 240V supplies are available between each phase line and the neutral wire.
- The three phase single-phase 415V supplies are available between any of the three phases. The wave diagram for the potential difference between two 240V lines, 120° out of phase is shown in figure 13.11b. (Note that the PD when a load is connected between phase lines is one voltage minus the other voltage, the resultant voltage when two phase lines are connected together is the line voltages added together (figure 14.4a).)
- The three phase lines and the neutral together give a 3-phase 4-wire supply with a RMS voltage of $240\sqrt{3} = 415V$.

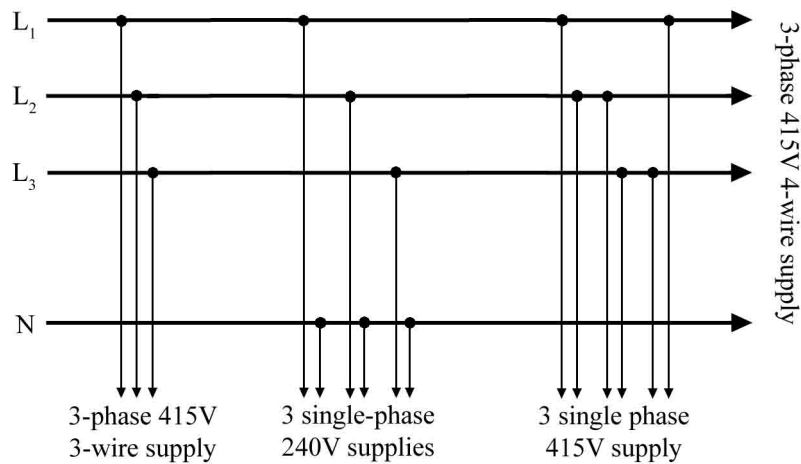


Figure 14.3: A 3-phase 4-wire supply carrying 240V in each wire.

Loads can be connected to a 3-phase supplies using the same two methods used for generator coils; that is star and delta. Figure 14.5 shows these connections. The current that flows in the lines is called the *line current* (I_L) and the PD between any two phase lines is called the *line voltage* (U_L). The current in each load is called the *phase current* (I_P) and the PD across each load is called the *phase voltage* (U_P).

For a *balanced system*:

- each load has the same magnitude of impedance;
- each load impedance has the same phase angle;

- each phase voltage (and current) is equal in magnitude;
- each phase voltage is displaced by 120° from each other

The example in section 2.5 shows an analogous system for a DC supply where the branch containing R_3 is the equivalent to the neutral wire. When the system is balanced no current flows through R_3 , only when the system becomes unbalanced does any current flow through this resistor.

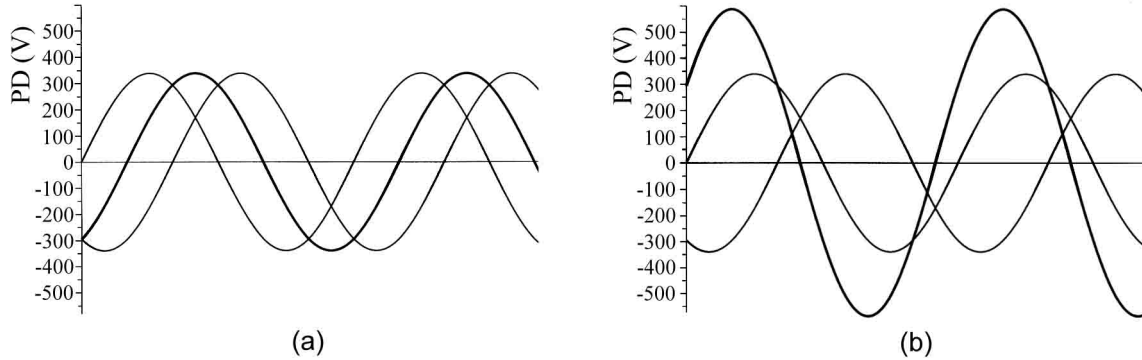


Figure 14.4: The wave diagrams for: (a) adding together two 240V lines that are 120° out of phase to find the voltage supply when two lines are connected to the same point; (b) subtracting two 240V lines that are 120° out of phase to find the PD between the lines. The resultant is shown as a bolder line. It is interesting to note that the potential difference between any two phase lines at U volts is $\sqrt{3}U$ volts whereas the same two phases added together result in a voltage of U volts.

Figure 14.5a shows that for a star connected loads the PD across any load is the PD between the phase line connected to it and the neutral, however the line voltage will be greater than this because it is the PD between two phase lines. The current through the load will be the same as the line current. Thus for balanced star connected loads:

$$U_L = \sqrt{3}U_P$$

$$I_L = I_P$$

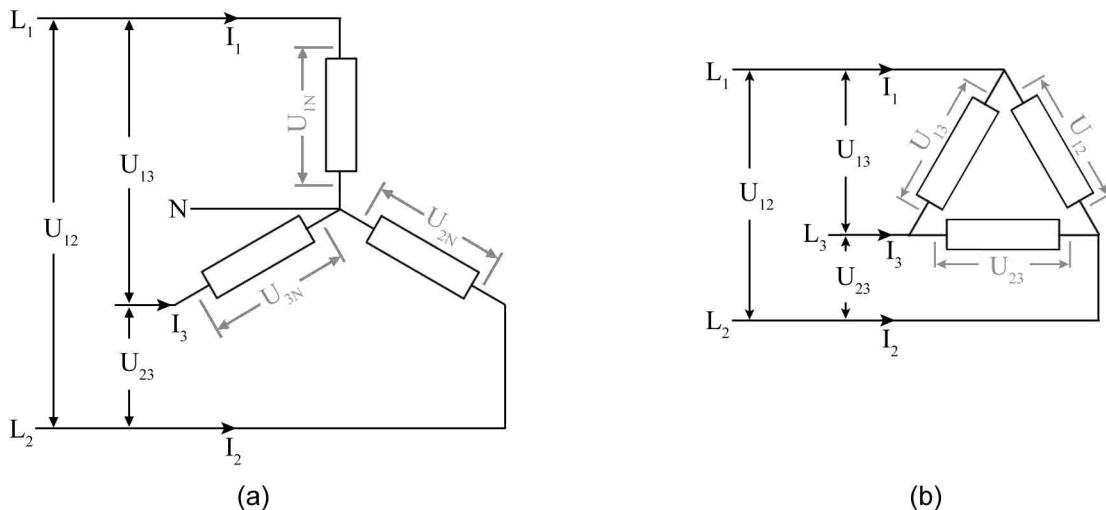


Figure 14.5: 3-phase load connections: (a) a 4-wire star connection (note that a 3-phase wire connection is also possible when the neutral wire is left out); (b) a 3-wire delta connection. The line voltages are shown in black and the phase voltages are shown in grey.

Thus for a balanced system with 240V lines $U_L = 415V$, and $U_P = 240V$. For a balanced system no neutral wire is needed and even in a star supply the neutral wire can be left out. Only when the star connected loads are unbalanced will any current flow down the neutral, in a balanced system one of the other lines will always be at a lower potential than the neutral and the current will 'return' down

this. This type of load connection is usually used for domestic distributions, where houses connect to one phase line and the neutral. If more houses are connected to one line than the others the loads become unbalanced and the neutral wire carries current.

Figure 14.5b shows that for delta connected systems of loads the phase voltage is equal to the difference between two lines. The phase current for each load is coming from two lines (because each load is connected to two lines) and will be more than the line current. Thus for delta connected loads:

$$U_L = U_P$$

$$I_L = \sqrt{3}I_P$$

Thus for a balanced system with 240V lines $U_L = U_P = 415V$. This method of load connection is usually only used for machines with windings such as 3-phase motors which have three identical windings, since the absence of a neutral can mean that unbalanced loads can cause problems.

14.3 Three-Phase Transformers

The primary windings of a transformer need not be connected in a same configuration as the secondary windings. For example a transformer with a star connected primary can have either a star or delta connected secondary (called *star-star* and *star-delta* respectively), also a transformer with a delta connected primary can have a star or delta connected secondary (called *delta-star* and *delta-delta* respectively). Due to the effects of unbalanced loading the star-star transformers are not often used for distribution, and delta-star are favoured. Three-phase transformers are covered in more detail in part 15.

14.4 Three-Phase Power

Both star and delta connections contain three separately connected loads. The total power dissipated in all these loads is thus the sum of the powers dissipated in its three phases or for a balanced load, three times the power dissipated in each phase. For a balanced star connection load:

$$P = 3U_P I_P \cos \phi$$

But $I_P = I_L$ and $U_P = \frac{U_L}{\sqrt{3}}$

Therefore: $P = 3 \frac{U_L}{\sqrt{3}} I_L \cos \phi = \sqrt{3} U_L I_L \cos \phi$

For a balanced delta connected load: $P = 3U_P I_P \cos \phi$

But $U_P = U_L$ and $I_P = \frac{I_L}{\sqrt{3}}$

Therefore: $P = 3U_L I_L \cos \phi = \sqrt{3} U_L I_L \cos \phi$