**Power Circuits and Distribution**

There are many different types of electrical work. The word “electronics” generally means DC circuits that have a specific, practical function like a radio, television, or CD player. Power circuits are used to supply AC current to those devices. Often the phrases “line voltage” or “mains” are used to describe the supply of 120VAC power that electronic devices need in order to operate. Inside of a television is a power supply unit that converts the AC line voltage to a DC voltage that can be used by the electronics circuits. This chapter is concerned with the methods power circuits use to distribute electricity to a theatre, and within it.

The entertainment business uses very specialized equipment, in different ways than other industries. Cables are used to bring power and data to equipment. Because entertainment depends on rapidly changing from one show to another, special connectors are used to join cables together and to equipment.

**Electrical Service**

Most homes, and some theatre installations, use a 240v service. The conductors running into the house are a bare aluminum neutral and a twisted pair of black insulated wires that are the two hot legs.

The transformer steps down a higher voltage to 120 VAC using a center tapped secondary to create two hot legs and one neutral. The sine curves of the two hot legs are inversely proportional to one another, and as a result, voltage measurements taken show that a 120 volt potential exists between either of the two hot legs and the neutral, but 240 volts between the two hots. This occurs because when the sine curve of one of the hot voltages is at its positive peak, the other is at its negative peak, so the difference of the two is 240 volts.
Only one neutral is used for both hots. It might seem as if the neutral would be carrying twice the load as the hot wire, and thus should be physically larger in size than either of the two hot conductors to carry the load. In practice, the two voltages being opposite one another means that the loads on the two hot wires should cancel each other out on the neutral wire. If the loads on the two hots are unequal, the voltage applied to the ground wire is the amount of that inequality, but cannot be more than the full amount of one of the hots, so the wire gauge sizes can be equal without causing any overload.

**THREE PHASE POWER**

We have already studied the creation of AC in a theoretical power station generator. The movement of a coil of wire in a circle inside a magnetic field produces an alternating current that fluctuates from positive to negative in a regular pattern called the sine wave. A power station generator is a very large device, and operates more efficiently if more than one current is produced at the same time. *Three phase power* (3φ) is a very common result. The phi symbol (ϕ) is often used to denote phase. Remember that a standard 120v sine wave looks like this:

As the coil of wire in the generator makes its 360° circular journey around the generator’s magnetic field, the voltage induced rises to a peak after the first 90°, drops back to zero after 180°, reaches a peak reverse flow at 270°, and then returns to zero at the 360° mark. What would happen if there were more than one single coil of wire in the generator? If three electrically insulated coils are used instead, three separate and distinct currents will be formed. If the coils of wire are equally spaced inside the generator, then the sine waves of the other currents will be identical in shape but happen at different times or in different phases. The
generator will produce three times the electrical power, but use the same amount of mechanical energy to do it. The resulting 3 phase current is represented graphically like this:

On the graph, the x axis represents time, and since the time between the 0° position and the 360° position is 1/60th of a second (the total time of a normal 60Hz cycle) the beginning of the other two phases will fall at 1/180° and 1/90th of a second. This seems like a rather small time interval, but AC cycles in some electronic devices occur in Gigahertz, which would be billions of times a second. The alternation of power circuits is actually quite slow by comparison.

After the 3 phase power is generated, it must be distributed on different conductors, in order to maintain the separate phase arrangement. On a pole, the conductors might be arranged like this:

Notice that there are three hot legs, but only one neutral. Most of the time, only one neutral is required because the hot legs are arranged in different phases, and place demands on the neutral at different times. Theoretically speaking, if the loads on the phases are perfectly balanced, you will not receive an electrical shock from touching the neutral wire, although this doesn’t mean that you should personally test the theory. However, since the neutral is the “safe” conductor or terminal, it is often left more exposed than the hot.

Most larger lighting systems are meant to use 3 phase power rather than 240 single phase, but they split the hot legs up and use the power separately for different
groups of dimmers. There are two configurations of three phase power, \textit{wye}, and \textit{delta}. The delta configuration is used primarily in factories and is not often seen in theatres, where the wye configuration is much more common. Wye gets its name from the shape formed by the three secondary coils that form the outputs. These coils are contained within a transformer that is part of the building, probably in a vault in some inaccessible place. They will never be directly used by a stage electrician, but it is helpful to understand how they supply power to the dimming system.

For a wye connection, the voltage between any of the hot legs, and the neutral is 120 volts. In the rack, dimmers are arranged so that one third are connected to \textit{phase A}, one third to \textit{phase B}, and one third to \textit{phase C}. Each dimmer has an input of 120 volts. All phases use the same neutral connection, which works out okay because the different phases are using the neutral at different times. If the loading on each phase A, B, and C is the same, the neutral will not have too much current running through it, but if the phases have unequal loads, a dangerous imbalance may exist. Sometimes a double neutral wire is used to avoid any problems.

You may notice that the dimmers in a rack seem to have a very odd numbering system, that the numbers skip around something like this:

\begin{align*}
1,2 & \quad 7,8 & \quad 13,14 & \quad 19,20 \\
3,4 & \quad 9,10 & \quad 15,16 & \quad 20,21 \\
5,6 & \quad 11,12 & \quad 17,18 & \quad 23,24
\end{align*}

This doesn’t make all that much sense when read from left to right, but top to bottom a clear pattern emerges. When dimmers are inserted into a rack, connectors on the back meet up with a \textit{bus bar}, the end of the phase connection. The bus bar is one solid piece, and one third of the dimmers in the rack must mate with each of the bus bars. The dimmers are in groups of two, so the numbers 1,2,7,8,13,14,19,20 fall together in order on the first bus bar; 3,4,9,10,15,16,20,21 on the second; and 5,6,11,12,17,18,23,24 on the third.
Engineers would like to spread the load of all the dimmers evenly between the three phases of the power supply so that the load on the neutral is balanced. If the dimmer numbers of all circuits on the first electric are 1 – 24, and all of the lights hung on it are on at the same time, the load should be evenly balanced on the neutral. Although it is impossible to predict in advance how a lighting designer may choose to divide up which lights are on at any particular moment, lighting systems engineers feel that this is their best attempt at doing so.

In a large permanent theatre installation the feeder cable to the dimmer racks is most likely in a conduit that runs directly into the dimmer racks, and will not need to be changed from show to show. Portable equipment on the other hand must be supplied with power by means of a disconnect box. This set up is by its very nature temporary, and is the type used by touring shows that travel with their own dimming equipment. The disconnect could be either a smaller 240 single phase type, or it could be three phase as in a professional theatre. The type of disconnect can be determined by the number of fuses in the panel. 240 single phase has two fuses inside, one for each of the hot legs. Three phase power has three fuses. Voltages in either case should be 120 volts from any hot to the neutral, 120 volts from any hot to the ground wire, and 0 volts from the ground to the neutral. If the panel contains 240 single phase the potential from one hot to another should be 240 volts, and for three phase 208 volts.

In stagehand terminology, 240 volt single phase is often called three wire service, while three phase is known as four wire service. Three wire has two hots and a neutral, while four wire has three hots and one neutral. These are the current carrying conductors, but each type of service must also have a ground wire to make it safer. Inside the panel, the ground wire is often connected to the neutral bus bar, or it may be connected only to the metal housing. In either case, a wire is run from the terminal inside to a grounding source for the building.

Typically, a disconnect box has a handle on the right-hand side that must be pulled down before the box will open. The
handle disengages the power to the connections inside making them safer to handle. Large cartridge fuses denote the current carrying capacity of the system. There should be a fuse for each hot leg, but none for the neutral. The total amperage available from the panel is the total of the amounts stamped on the fuses. If 200 amp fuses are in use, the total available current would be 600amps, which is enough for 30, 20 amp dimmers working at full capacity. The neutral and ground are generally not connected together in 3 phase. At the bottom of the box, directly under each of the fuses, is a set of terminal lugs. When a disconnect is used for a permanent installation, the dimmers are hard wired to the box, which is then may be used more or less as a giant off-on switch for repair purposes.

On a touring set up, the disconnect box is used to supply power to portable dimmer racks. Very special wiring is used for this purpose, most often #0000 (four ought) entertainment cable with a heavy SO rubber sheathing on the outside that provides insulation. Each conductor is run separately, and each has its own connector for just the one wire. Cam lock connectors are used for that purpose. Cam locks come in male and female versions just like other connectors, with the female being the source of current, and the male pointing toward the power. Obviously, if the male connector with its exposed brass fitting were energized, the risk of electrical shock would be huge.

*Tails* are used to make the connection with the disconnect box. These are short sections of cable that have a female connector on one end, and bare wire on the other. The bare wire is wrenched down to one of the lugs in the disconnect box. It feeds out through an appropriate opening and is given a strain relief, which may simply be tying all the conductors up with line, so that pulling on the extensions will not place a mechanical strain on the terminal lug. It is common practice when working with #0000 feeder cable that one should make the ground connection first, then the neutral, and then the three hots. If there is some misadventure, this procedure will ensure that the ground is in place before any current can reach the equipment.

The most common theatrical connector for power circuits is the *pin connector*, but
a second type, the *twist lock*, is also popular. The pin connector has been around for many decades and is extremely durable. The quarter inch diameter brass pins are almost impossible to break off. As a safety feature, the ground pin in the center is slightly longer than the other pins, so that the ground connection makes up first. The neutral is located closest to the ground, and the hot is on the far side. Early versions were not grounded, and have no center pin.

Twist locks have the obvious advantage of a positive method of making sure that the connection stays together. The stagehand must twist them together slightly causing the two halves to lock. If not tied or taped together, pin connectors can come apart when someone accidentally pulls on the cable. However, twist lock connectors are not as sturdy as the pin connector, the blades tend to bend easily, and it is sometimes difficult to line them up with the proper holes without looking closely. There are many brands and types of twist locks, for different ampacities. Pin connectors come only in 20 amp (most common) and 60 amp (very rare) versions.

When a lighting fixture in a theatre is hung too far away from a circuit box for its own tail to reach the receptacle, a *jumper* is used to bridge the gap. They are like extension cords for lighting. Most theatres have ready made jumpers in specific lengths on hand at all times. If a theatre has lots of circuits in all the right places, it may not need many jumpers. If the circuits are in inconvenient places, it may need many jumpers.

Socapex® makes a multi-connector with 19 pins for cables that have that many conductors. They are often used when a large number of wires must be run, perhaps in a touring rig. A six circuit multicable is much easier to manipulate than six separate runs of 12/3 SO. They can carry power to a number of lights all at one time. A 19 pin Socapex connector can be used to make up a multi that services 6 lighting circuits, each having a separate hot/neutral/ground, with one pin left spare. A *breakout* is used at the end of the cable, to separate it into individual circuits.
A breakout has one male Socapex connector, and multiple individual female connectors. Multicables and breakouts are most often used to distribute power from a touring dimmer rack.

Modern lighting systems also use XLR connectors for control functions between the board and dimmer racks, moving fixture lights, and other peripheral equipment that requires a digital signal to operate. These cables are not expected to carry large amounts of current, and as a result they are much smaller. Three pin XLRs of the sort very commonly used for microphones, are also used for moving fixture lights. Four pin XLRs are often used for color changers, while the five pin version is meant for DMX transmission from the light board. DMX 512A is the computer program protocol used in the entertainment industry. It calls for special cable to be used in carrying data to digital equipment. The standard specifically states that the type of 3 pin XLR jumpers regularly used in audio work should not be used for digital transmissions because the conductors inside are not twisted around one another, and as a result they may be subject to interference that may distort the square wave signal. This is especially problematic when induction around lighting cables causes a strong magnetic field. Even so, audio cables are often used with no ill effects.

The size of a wire used to conduct electricity is determined by its AWG (American Wire Gauge) number. For the most part, the larger the gauge number, the smaller the wire is. So #20 wire is actually much smaller than #10 wire, just the opposite of what might seem intuitive. The largest wire used in the entertainment industry is #0000 (four ought) feeder cable, which is larger in diameter than #00. #0000 cable is about as big in diameter as a roll of pennies.

Wire can be made solid, or stranded. Stranded electrical cable is much easier to bend, so it only makes sense that portable cables such as those used in theatres should be of the stranded variety. Solid copper wire is used in permanent installations where the cable never needs to be moved about. Solid wire mistakenly used in a situation requiring mobility will soon develop metal fatigue and become dangerous.

Larger gauge wires are able to carry more current than small ones, while the voltage capability depends on the insulation surrounding the conductor. The insulation can be plastic or rubber. Rubber insulation is preferred for theatre cabling, and the code for that is generally type SO or SJ. SJ is somewhat lighter and smaller than SO.

### Approximate Ampacities of Gauges

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Ampacity</th>
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<tbody>
<tr>
<td>#0000</td>
<td>225 amps</td>
</tr>
<tr>
<td>#0</td>
<td>175 amps</td>
</tr>
<tr>
<td>#4</td>
<td>80 amps</td>
</tr>
<tr>
<td>#8</td>
<td>46 amps</td>
</tr>
<tr>
<td>#12</td>
<td>20 amps</td>
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</tbody>
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The exact ampacity of any conductor is affected by a large number of factors like the metal alloy used, the size and number of the strands, the frequency of the sine wave, temperature, and all sorts of other peculiar details. Most portable lighting cables are made from #12, because it can easily handle a 20 amp load, which is the most common dimmer rating. This cable may be referred to as “12/3 SO” which indicates that it is 12 gauge, 3 conductors (hot/neutral/ground) with type SO rubber insulation on the outside.

The various conductors inside a jumper are each sheathed in their own insulation to keep them separated from one another. Although the outside insulation is black, a standard color coding is used to tell the individual conductors apart. This color code is not just for theatres, but is used in all different types of electrical work.

**Insulation Color Code**

<table>
<thead>
<tr>
<th>Color</th>
<th>Purpose</th>
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<tbody>
<tr>
<td>Black</td>
<td>Hot</td>
</tr>
<tr>
<td>Red</td>
<td>Hot (220)</td>
</tr>
<tr>
<td>Blue</td>
<td>Hot (three phase)</td>
</tr>
<tr>
<td>White</td>
<td>Neutral</td>
</tr>
<tr>
<td>Green</td>
<td>Ground</td>
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**TERMS USED IN THIS CHAPTER**

- #0000 or four ought
- 240 volt service
- American wire gauge
- Breakout
- Bus bar
- Cam lock
- Cartridge fuse
- Category 5
- Color code
- Connector
- Delta connection
- Disconnect box
- Ethernet
- Four wire service
- Ground wire
- Jumper
- Line voltage
- Mains
- Phase
- Phase A
- Phase B
- Phase C
- Pin connector
- Power circuit
- Power supply unit
- SJ rubber insulation
- SO rubber insulation
- Strain relief
- Tails
- Terminal lugs
- Three phase power
Three wire service
Twist lock connector
Wire/solid
Wire/stranded
Wye connection
XLR connector