Power Factor Primer

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Abstract This paper is written so that an individual with an elementary understanding of technology can gain insight into the concept of Power Factor, and how it relates to their everyday lives. It starts with an explanation of Direct Current circuits and how they utilize electrical power. It then goes on to explain Alternating Current, how it is utilized, and why Power Factor Correction is needed. Implementation of Power Factor Correction is then explained. Then, a practical example is given of the real reason for using Power Factor Correction, namely energy and cost savings. In our energy conscious world, every opportunity to save energy usage should be implemented.

First, Direct Current

To understand the concept and need for power factor correction, we need to look at basic DC electrical principles. First, we have something called 'voltage', which is electrical pressure. Then, we need something for this pressure to push, and we call it 'current'. And finally, we need somewhere for this current to flow through, and we call that 'resistance'. Figure # 1 shows the relationship of these three items voltage (E), current (I) and resistance (R).

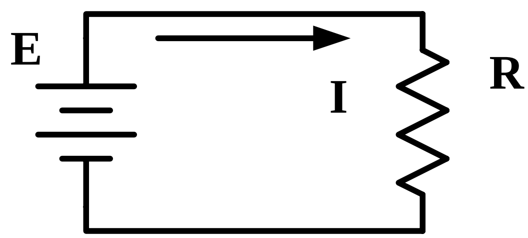

Figure # 1, Basic DC Circuit

Now, when current (I) flows through resistance (R) it heats up and dissipates power (P). So electrical energy existing or being generated by the voltage source becomes heat energy in the resistor. At the time that current is flowing power is being dissipated. The two important relationships that we need to know to determine what is happening in the circuit are E = I * R and P = E * I.

Now the voltage supply (E) and the resistance load (R) might be separated by some distance. In real circuits this is usually so. And if this is so, an extra resistance, called 'R_{line}', is added between the supply and the load, as shown in figure # 2.

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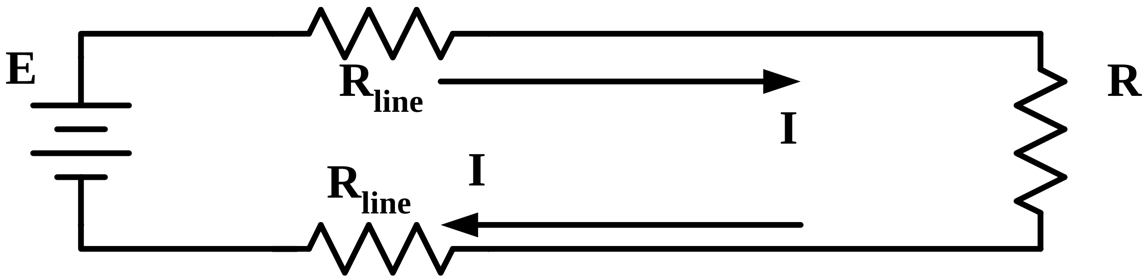

Figure # 2, DC Circuit Showing Line Resistance

The extra resistances (R_{line}) are the resistances of the wires connecting the load to the source. There is no way to avoid this. Now, we need to look at power again and what we will call 'line losses'. Since the current flows in the wires and the wires have resistance, there is a power loss in the wires and a voltage drop across the line. There is also no way to avoid this. From the two previous relationships (E = I*R and P = E * I), two more power relationships can be derived. They are $P = I^2 * R$ and E^2 / R. As we look at figure # 2, we can see that there is a power loss in the lines equal to $2 * (I^2 * R_{line})$. The factor 2 occurs because the current flows through both lines and thus both line resistances. There is also a voltage drop across the lines equal to $2 * (I * R_{line})$. Both of these effects are undesirable and unavoidable. The first effect is energy that comes from the voltage source and is used to heat the wires. This does the load no good at all and causes the source to work harder to deliver a certain amount of power to the load. The second effect is a voltage drop across the lines which subtracts from the voltage across the load. This causes the voltage across the load to be less and thus less power is delivered to the load. To compensate for this the voltage of the voltage source can be raised. This allows the load to operate at the proper voltage but does nothing about the power losses in the lines. These ideas are important to understand as we look at alternating current and what power factor is and how it has undesirable effects on our electrical power system.

Now, Let's Look at Alternating Current

Now that we've looked at DC sources, let's consider an alternating current (AC) source. Figure # 3 shows an AC source connected to a load with the associated line resistances.

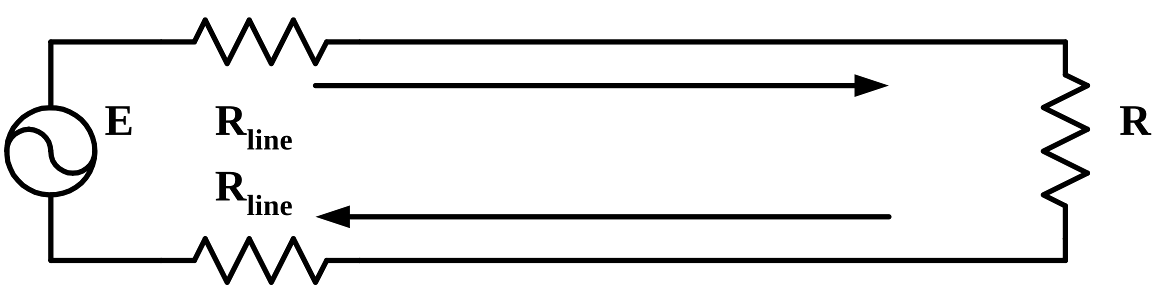

Figure # 3, AC Circuit With a Resistive Load and Line Resistances

The alternating current is usually a sin wave or close to it as shown in figure # 4.

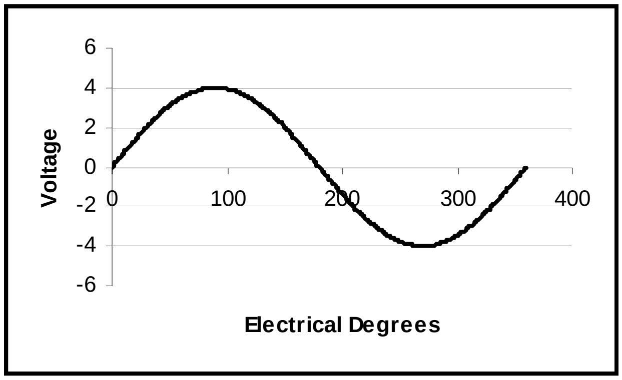

Figure # 4, Waveform for a Typical AC Source

Notice that the steady DC voltage has been replaced by an AC voltage that goes positive and negative. This causes the current to flow first in one direction and then the other. If the load is a resistance, this AC source works just like a DC source with a resistive load. Figure # 5 shows the voltage, current, and power relationships for a resistive circuit. It is important to notice here that the voltage and current occur at the same time and are in phase. Also notice that the power (P = E * I) being dissipated at any instant is always above zero or positive. The line resistance has no effect on this phase relationship, a condition which is very important in power factor studies. The line resistance does cause a power loss and a voltage drop. But regardless of anything else, the voltage is always in phase with the current at all points in this circuit.

A Non Ideal World

If this were an ideal world, which it isn't, there would be no need for power factor correction. The pure resistive circuits would have some line losses associated with them, and we would just live with it. However, it's not an ideal world, and a pure resistive load is not very common. What usually happens is that our load now looks like a resistor in series with an inductor. To give an idea of what an inductor does to current flow, let's look at an AC circuit with an inductor as the only load in place of the resistor. Figure # 6 shows this connection.

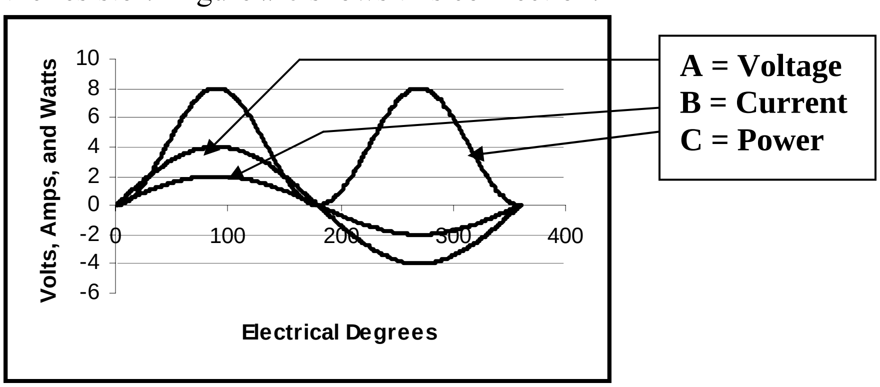

Figure # 5, Relationship Between Voltage, Current, and Power in an AC Resistive Circuit

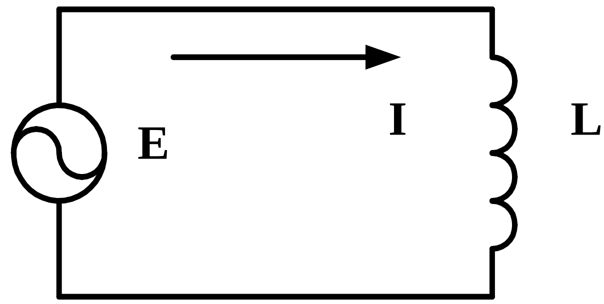

Figure # 6 AC Circuit With an Inductive Load.

An inductor is any coil of wire, and many, if not most, practical devices in the world are inductors. Now this ideal inductor has a property called reactance, which is similar to resistance in that it opposes or limits current flow. One big difference is that when AC current flows through an inductor, no power is dissipated. At first glance you might wonder, "How Can That Be?" There's a voltage drop and a current flow but zero power. And P = E * I. To understand this, we need to look at the inductance as having this property called 'reactance' which opposes current flow. Let's call this reactance an imaginary resistance and denote it by $+jX_L$. In figure # 6 the current would then be equal to $E / +jX_L$. This is the same equation as before except R is replaced by $+jX_L$. Then $I = E / +jX_L = -jE / X_L =$
$(E / X_L)\ \underline{/-90^o}$. This means that the current lags the voltage by 90 degrees. If we plot E, I, and power versus time on the same graph we get the results shown in figure # 7.

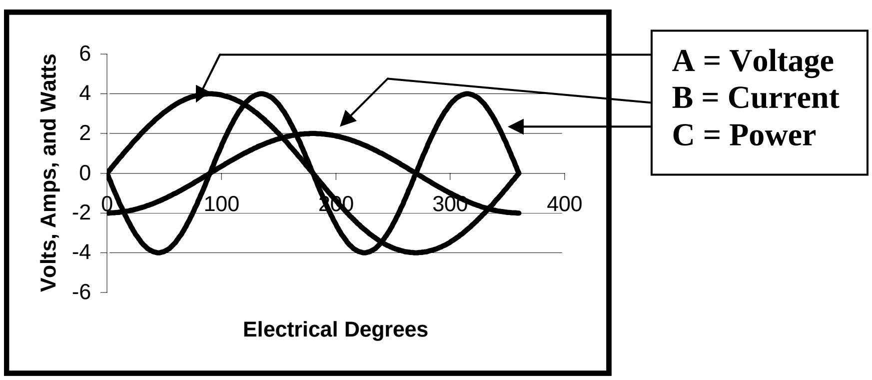

Figure # 7, Graph of Voltage, Current, and Power for an Inductive Circuit

A Look at Capacitors

Notice that voltage exists, current flows, and the average power is zero. The average power is seen to be zero by noting that the power curve has an area above the horizontal axis equal to the area below the horizontal axis. This means that our voltage source is producing voltage and current but no useful work is being done. The inductor does not get hot, and the generator, even though it is producing current, does not use any energy to produce current. However, the wires between the source and the load still have resistance. The $I^2 * R$ power losses and the I * R voltage drops still occur. This means that the source is producing work, but the load is not absorbing work. Clearly the person running the source doesn't like this condition. It's producing work to let an inductor to sit energized at the end of a line and do nothing. Fortunately there is a way to correct this condition at the load. This is done by using another electrical element, called a 'capacitor', which also uses no power but has a negative imaginary reactance instead of a positive imaginary reactance. Let's look at figure # 8 and see how a capacitor works.

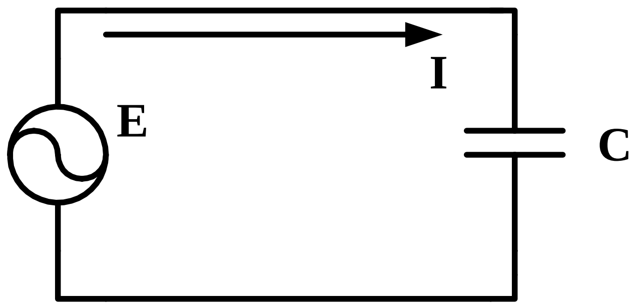

Figure # 8, Capacitive Circuit

The first thing that we need to look at is the equation for current: $I = E / -jX_C = +jE / X_C$. Notice that the current leads the voltage by 90^o. If we refer back to the inductor circuit, we can see that the current lags the voltage by 90o ($I = -jE / X_L$). A graph of voltage, current, and power versus time for a capacitor is shown in figure 9.

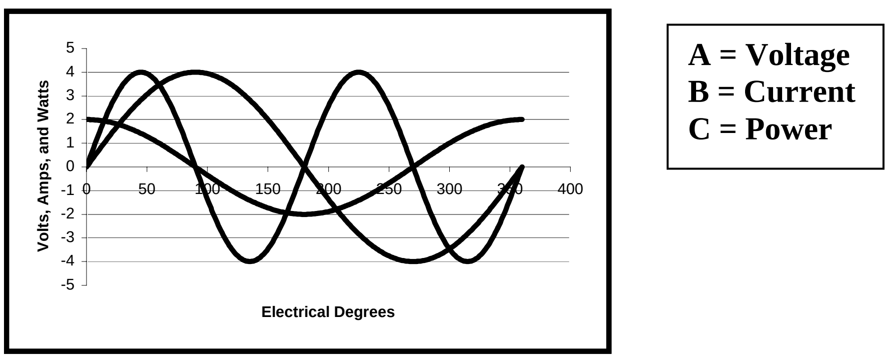

Figure # 9, Graph of Voltage, Current, and Power Versus Time for a Capacitive Circuit

Notice that the average power is again zero. However, when the power for the capacitor is going positive (just as the voltage waveform goes through zero), the power for the inductor is going negative. Refer to figure # 7 to see this. The same thing can be shown to be true for the capacitive and inductive currents. When the current for one is going positive, the current for the other is going negative. Refer to figure numbers 7 and 9 to see that.

Now, knowing that and using something called Kirchoff's Current Law, which states that the sum of the currents entering any junction equals the sum of the currents leaving that junction, it can be shown that the capacitive current can cancel the inductive current and make the total current equal to zero in a parallel capacitive inductive circuit. Refer to Figure # 10.

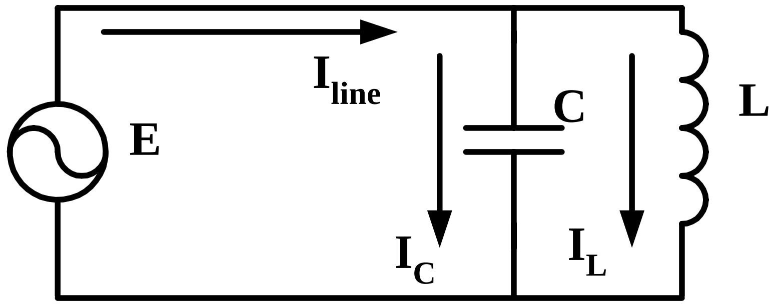

Figure # 10, Inductive Capacitive Circuit Showing Kirchoff's Current Law

Now remember that I_C can be denoted by $+jI_C$ and that I_L can be denoted by $–jI_L$. If we let $I_C = I_L$ (and this can be done by properly choosing L and C), $I_{line} = +jI_C –jI_L = 0$. So all of a sudden, line current can be 0 even though the capacitive and inductive currents are not zero.

Power Factor Correction

In its simplest form, this is 'power factor correction'. In the world of real devices that do real work, it is never quite that simple. The inductor is never a pure inductor but always has a series resistor associated with it. What this effectively does is give a current with a real component that cannot be cancelled and an imaginary component that can be cancelled. This is illustrated in figure # 11. One more idea that should be introduced here is that power factor is defined as the cosine of the angle between the voltage and the current.

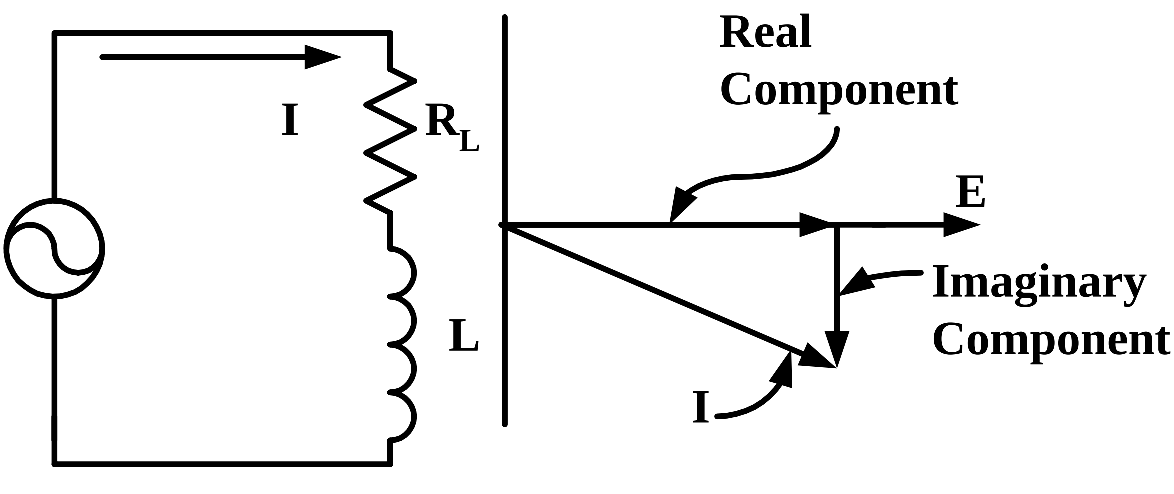

Figure # 11, Practical Inductive Circuit Showing Current and Its Real and Imaginary Components

Since only the imaginary component can be cancelled (the resistor is after all getting hot since $P = I^2 * R$), it is impossible to make the line current 0. It is, however, possible to minimize it by canceling the imaginary component of the current. This is done by placing a capacitor in parallel with the resistive inductive circuit. If the capacitor is chosen to cancel the imaginary component of the current, the power factor is said to be corrected to unity. Under this condition the line current is in phase with the voltage. Note that the phase angle between the voltage and current is zero degrees. Also note that the cosine of zero degrees is 1 or unity. Thus , the expression, 'Unity Power Factor', takes on a real meaning. It thus takes minimum current to deliver a certain amount of power to the load. Refer to figure # 12 to see a circuit with the power factor corrected to unity. This minimizes the line voltage drop ($E = I * R_{line}$) and line power loss ($P = I_2 * R_{line}$). Thus, the voltage generator, doesn't have to produce as much power to get a certain amount of power to the load and the voltage generated can be lower for a certain load. Refer to figure # 13 to see the effects of line resistance on a power factor corrected circuit**.**

This is very important because the power company has to deliver a certain voltage and current capability to a customer. They charge for this. The way that they charge is that the current to a load is monitored continuously. The real thing that is recorded is actually volts times amps or volt-amps. Since volts is close to a constant and current varies with load, we can think of this as monitoring current.

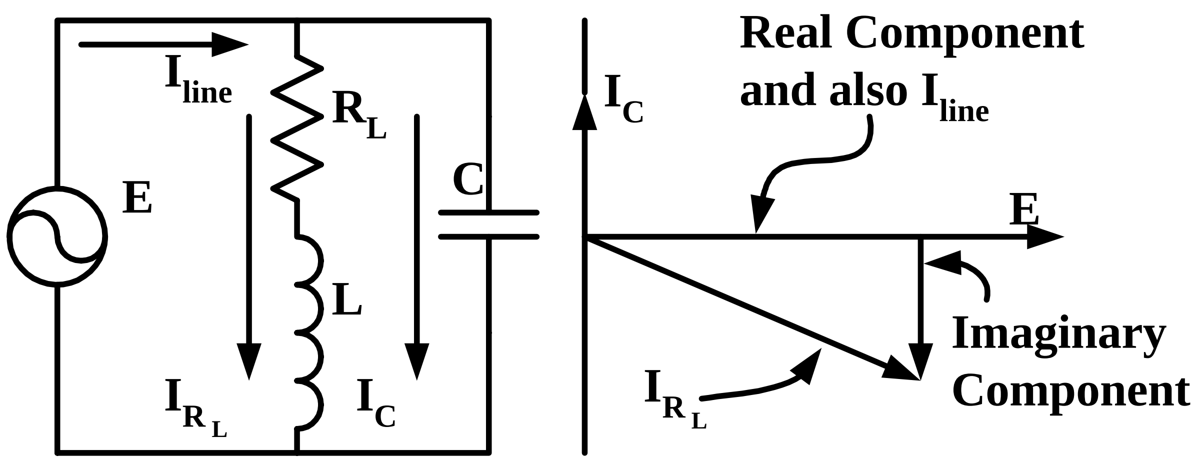

Figure # 12, Resistive Inductive Load Corrected to Unity Power Factor by the Addition of a Parallel Capacitor

One more thing that we can look at is the graph of voltage, current and power versus time for a RL series circuit. I chose an example where the current lags the voltage by 45^o . This is shown in Figure # 14. The thing to notice about this graph is that the power goes positive and negative, but the positive area is greater than the negative area. This means that the circuit is absorbing power and returning power to the source. However it is taking more than it is giving.

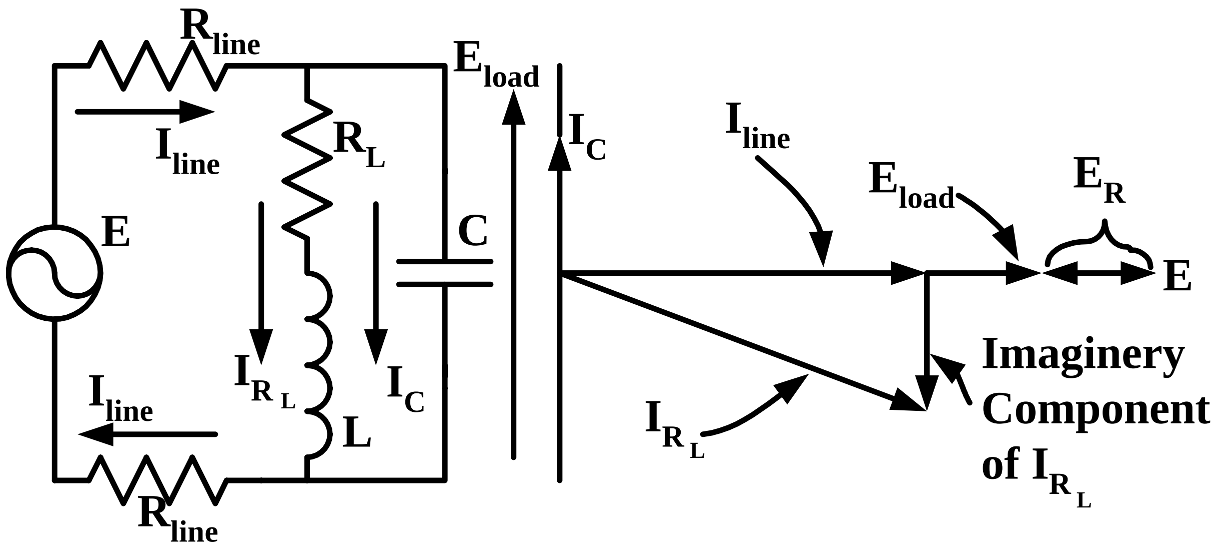

Figure # 13, Power Factor Corrected Load With Effect of Line Resistances on Source Voltage Taken Into Account

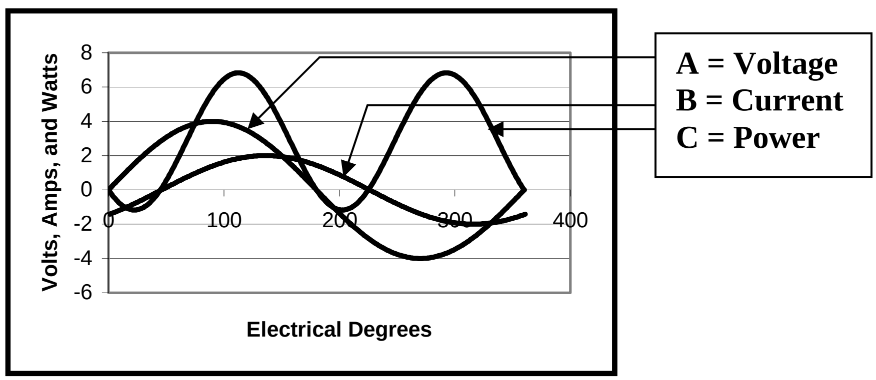

Figure # 14, Graph of Voltage, Current and Power Versus Time For a RL Series Circuit

How This Helps the Customer and the Supplier

The power company then looks at a month's usage and picks out the ½ hour during the month when the usage was the highest and adds a charge to the bill that depends on that maximum and calls it a 'demand charge'. The reason for this demand charge is that the power company needs to be able to supply the customer with whatever current the customer demands. If the customer demands more current, the power company must have bigger equipment to supply the current. This is how the electric suppliers pay for the equipment that is needed to get electrical power to the consumers. The charge is between $10 and $20 per KVA of demand per month. One KVA is simply 1000 VA's. In Memphis the charge is about $10 per KVA of demand, among the lowest in the country. The demand charge is typically ½ of an electric bill for industrial customers. It can be much more than ½ of the bill if the customer runs a big load for ½ hour sometime during the month and then has a 29 day vacation where almost nothing runs.

As seen in figure # 13 the line current and thus the Volt Amps is less when the parallel capacitor is added to the circuit. If I_C is equal to the imaginary part of I_{RL} , there is no imaginary line current and the only current that flows is the real current and that cannot be eliminated if any real work is being done. The load, then, actually looks like a resistor. At this time, the line current is in phase with the voltage and the power factor is unity. Remember our definition of power factor as being the cosine of the angle between the voltage and current? The cosine of 0^o is 1. Real power (P) is also defined as $P = E * I * \cos (\varphi)$ where φ is the angle between the voltage and the current.

An Example

In summary, the power factor is corrected when any load can be corrected so that it looks like a purely resistive load. I will now give data on a circumstance to give an idea of the savings that can be realized by power factor correcting a typical small industrial or commercial location.

First we have to assume a maximum KVA of demand of 1000 KVA of demand at .707 lagging power factor. This is a typical inductive load and represents about 800 to 1000 horsepower running at some time during the month for at least ½ hour. Then, we can say that this load ran for approximately 100 hours during the month for an energy use of 70,000 KW-hours. We haven't mentioned KW-hours yet, but it is simply the total energy use during the month. If a load of 1 KW ran for 1 hour the energy use would be 1 KW-hour. For costing purposes, let's say that the demand charge is $10 per KVA of demand. Then, assume the energy cost is $.03 per KW-hour of energy. Then the demand charge would be:

1000 KVA * $10 / KVA = $10000

The energy charge would be:

70000KW-hours * $.03 / KW-hour = $2100

The total bill would then be: $12100.

If corrected to unity, the demand would be lowered to 707 KVA of demand, the real part of the 1000 KVA of demand. The new demand charge would be:

707 KVA * $10 / KVA = $7070

The energy charge would stay the same so the lowered, power factor corrected , bill would be $9170. The saving would be $2930 or almost $3000 per month.

The above example would be typical for a processing plant that needs to operate under full load for about ½ month and does very little for the rest of the month. A barge loading or unloading facility could meet this condition. Notice in this example that the demand charge is much higher then the actual energy usage.