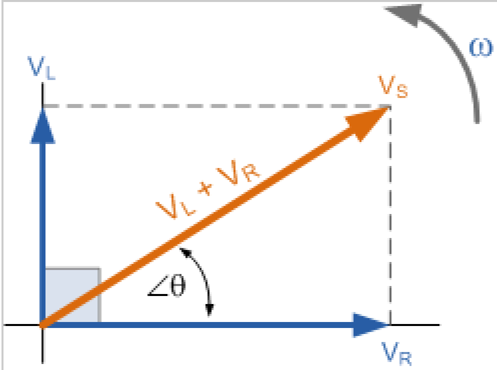


Power Factor Correction

Power Factor Correction uses parallel connected capacitors to oppose the effects of inductive elements and reduce the phase shift between the voltage and current

Power Factor Correction is a technique which uses capacitors to reduce the reactive power component of an AC circuit in order to improve its eficiency and reduce current.

When dealing with direct current (DC) circuits, the power dissipated by the connected load is simply calculated as the product of the DC voltage times the DC current, that is V*I, given in watts (W). For a fixed resistive load, current is poroportional to the applied voltage so the electrical power dissipated by the resistive load will be linear. But in an alternating current (AC) circuit the situation is slightly different as *reactance* affects the behaviour of the circuit.

For an AC circuit, the power dissipated in watts at any instant in time is equal to the product of the volts and amperes at that exact same instant, this is because an AC voltage (and current) is sinusoidal so changes continuously in both magnitude and direction with time at a rate determined by the source *frequency*.

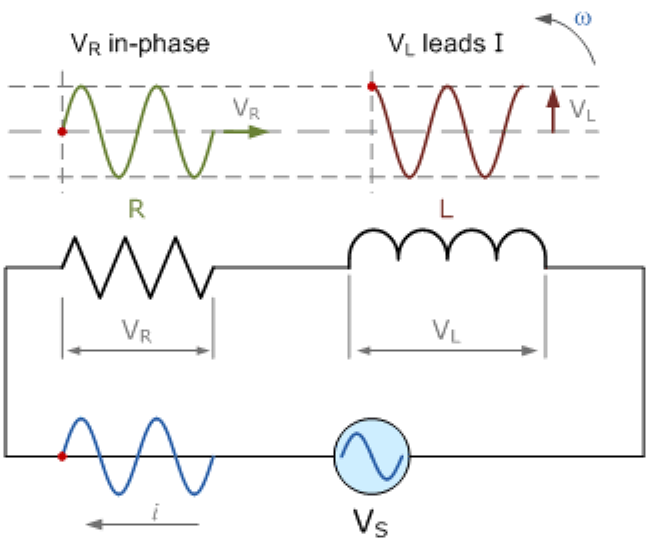
In a DC circuit the average power is simply V*I, but the average power of an AC circuit is not the same value as many AC loads have inductive elements, such as coils, windings, transformers, etc. where the current is out of phase with the voltage by some degrees resulting in the actual power dissipated in watts being less than the product of the voltage and current. This is because in circuits containing both resistance and reactance, the phase angle (Θ) between them must also be taken into account.

We saw in the tutorial about Sinusoidal Waveforms that the phase angle (∠Θ) is the angle in electrical degrees by which the current lags behind the voltage. For a purely resistive load, voltage and current are "in-phase" since there is no reactance.

However, for an AC circuit containing an inductor, coil, or solenoid or some other form of inductive load, its inductive reactance (X_L) creates a phase angle with the current lagging behind the voltage by 90^o. Therefore there is both resistance (R) and inductive reactance (X_L) both given in Ohms, with the combined effect called *Impedance*. Thus impedance, represented by the capital letter Z, is the resulting value given in Ohms due to the combined effect of a circuits resistance and reactance.

Consider the RL series circuit below.

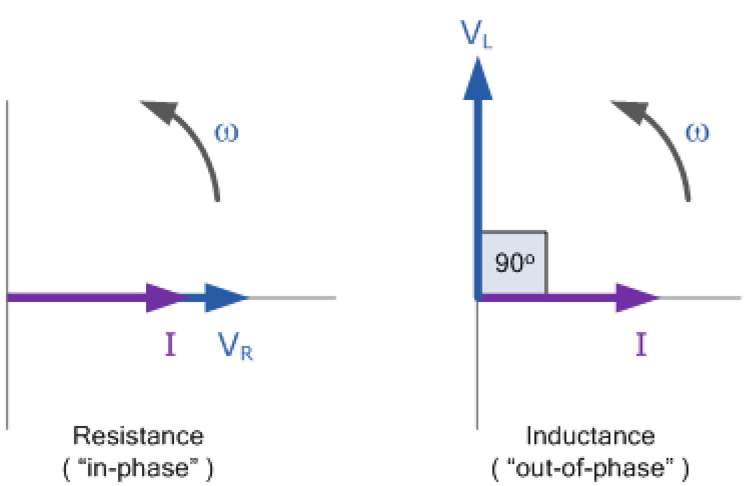
RL Series Circuit



Since it is a series circuit, the current must therefore be common to both the resistor and the inductor so the voltage dropped across the resistor, V_R is "in-phase" with the series current while the voltage drop across the inductor, V_L "leads" the current by 90^o (ELI). As a result the voltage dropped across the resistor is placed on the current vector because both vectors are in-phase, while the voltage developed across the inductor coil is drawn in a vertical direction due to the voltage leading the current by 90^o.

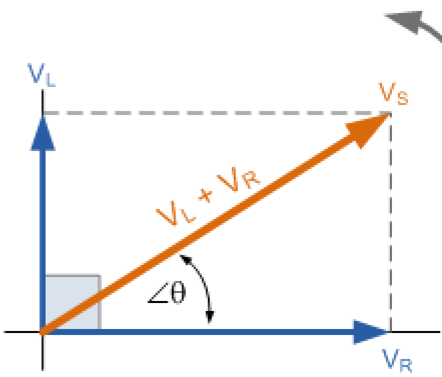
Thus the vector diagram drawn for each component will have the current vector as its reference with the two voltage vectors being plotted with respect to their position as shown.

R and L Vector Diagrams



The resistor voltage V_R is plotted along the horizontal or "real axis" and the inductor voltage V_L is plotted on the vertical or "imaginary axis". In order to find the resulting voltage V_S developed across the series connected circuit we must combine together the two individual vectors using the current as our reference. The resulting vectorial voltage can easily be found using Pythagoras' theorem as the combination of V_R and V_L forms a right angled triangle as shown below.

Phasor Diagram for the Series RL Circuit



The vector sum of V_R and V_L not only gives us the amplitude of V_S due to Pythagoras' equation of: $V_S^2 = V_R^2 + V_L^2$ but also the resulting phase angle (∠Θ) between V_S and i, so we can use any one of the standard Trigonometry functions of Sine, Cosine and Tangent to find it.

Power Factor Correction Example No1

An RL series circuit consists of a resistance of 15Ω and an inductor which has an inductive reactance of 26Ω. If a current of 5 amperes flows around the circuit, calulate:

1) the supply voltage.
2) the phase angle between the supply voltage and circuit current.
3) Draw the resulting phasor diagram.

1). The supply voltage V_S

$$V_R = I \times R = 5 \times 15 = 75V$$

$$V_L = I \times X_L = 5 \times 26 = 130V$$

$$V_S = \sqrt{V_R^2 + V_L^2} = \sqrt{75^2 + 130^2}$$

$$V_S = 150\,V_{RMS}$$

We can double check this answer of 150Vrms using the impedances of the circuit as follows:

$$Z = \sqrt{R^2 + X_L^2} = \sqrt{15^2 + 26^2} = 30\Omega$$

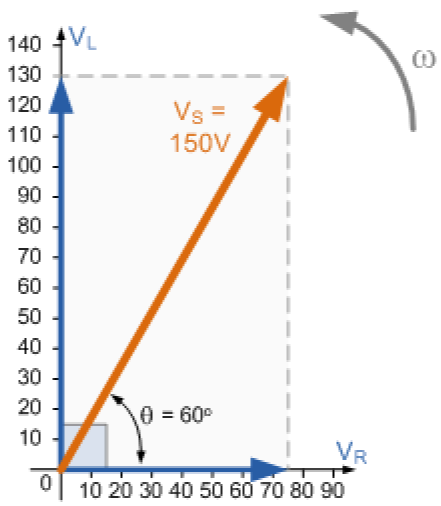
$$V_S = I_S \times Z = 5 \times 30 = 150\,V_{RMS}$$

2). The phase angle Θ using Triganometry functions is:

$$\cos\phi = \frac{V_R}{V_S}, \quad \sin\phi = \frac{V_L}{V_S}, \quad \tan\phi = \frac{V_L}{V_R}$$

$$\therefore \cos\phi = \frac{75}{150} = 0.5 \quad \text{therefore,} \quad \phi = 60^\circ$$

3). The resulting phasor diagram showing V_S



The calculated voltage dropped across the resistor (the real component) was 75 volts while the voltage generated across the inductor (the imaginary component) was 130 volts. Clearly the sum of 75 volts plus 130 volts equals 205 volts which is far greater than the calculated 150 volts. This is due to the fact that the value of 150V represents the phasor sum. Knowing the individual voltage drops and impedances we can convert these values into values that represent the power consumed, either real or imaginary in the circuit.

Power in a RL Series Circuit

In a circuit containing reactance, the current, i will either lead or lag the voltage by some amount depending on whether the reactance is capacitive or inductive. The power consumed by the resistor in watts is called the "real power" so is given the symbol "**P**" (or **W**). Watts can also be calculated as I^2R, where R is the total resistance of the circuit. However, to calculate the value of the real power in terms of the rms voltage and rms current ($V_{rms}*I_{rms}$), we must also multiply these values by the cosine of the phase angle, cosΘ giving:

$$\text{Real Power, } P = V*I\cos(\Theta)$$

Since, as we have seen above, the voltage and current are "in-phase" for a resistance, the phase angle is therefore zero (0), thus giving us cos(Θ) = 1. Multiplying V*I*1 will therefore give us the same real power value as does using I^2R. Then using our coil example above, the power dissipated by the 15Ω resistor is:

$$P_R = I^2R = 5^2 \text{ x } 15 = 375 \text{ watts}$$

which is the same as saying:

$$P_R = V_R*I\cos(\Theta) = 75 \text{ x } 5 \text{ x } \cos(\Theta) = 375 \text{ watts}$$

When the voltage and current are "out-of-phase" with each other because the circuit contains reactance, the product of V*I is called the "apparent power", given the units of volt-amperes (VA) instead of watts. Volt-amperes has the symbol "**S**". For a purely inductive circuit the current lags the voltage by 90^o so the reative power for an inductive load is given as: V*I cos(+90^o) which becomes: V*I*0. Clearly then there is no power consumed by an inductance so there is no power loss, thus P_L = 0 watts. However to show that this wattless power exists in an AC circuit, it is called volt-amperes reactive (VAR) and is given the symbol "**Q**". So the volt-amperes reactive, or simply "reactive power" for an inductive circuit uses the symbol $\mathbf{Q_L}$.

Similary, for a purely capacitive circuit the current leads the voltage by 90^o, the reative power for a capacitive load is given as: V*I cos(-90^o) which again becomes: V*I*0. Clearly then and as before, there is no power consumed by a capacitance so there is no power loss as P_C = 0 watts. So to show that this wattless power exists in a capacitive circuit, it is called volt-amperes reactive capacitive and is given the symbol $\mathbf{Q_C}$. Note here that the reactive power of a capacitance is defined as being negative, resulting in $\mathbf{-Q_C}$.

So again using our example above, the reactive power flowing in and out of the inductor at a rate determined by the frequency is given as:

$$Q_L = I^2X_L = 5^2 \text{ x } 26 = 650 \text{ VAR}$$

As there is a 90^o phase difference between the voltage and the current waveforms in a pure reactance (either inductive or capacitive) we multiply V*I by sin(Θ) to give the vertical component that is 90^o out-of-phase. However, the sine of the angle (sin 90^o) gives the result as "1" so we can find the reactive power by simply multiplying the rms voltage and current values as shown.

$$Q_L = I^2X_L = V*I*\sin(\Theta) = 130*5*\sin(90^o) = 130*5*1 = 650 \text{ VAR}$$

Then we can see that the *volts-amperes reactive* or VAR part has a magnitude (the same as for the real power) but no phase angle associated with it. That is **reactive power** is always on the 90^o vertical axis. So if we know that:

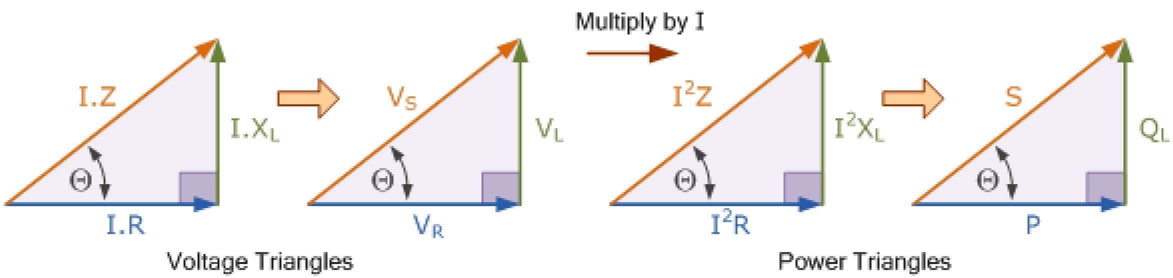
$$P_R = I^2R = 375 \text{ Watts}$$

and

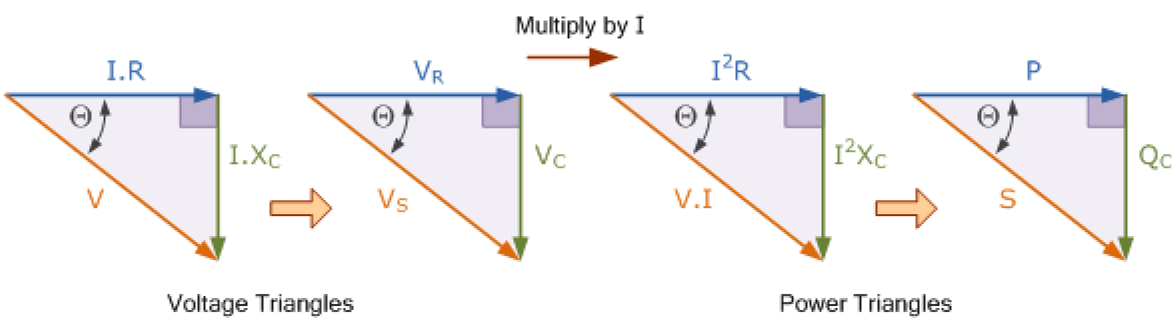
$$Q_L = I^2X_L = 650 \text{ VAR (ind.)}$$

we can construct a power triangle to show the relationship between P, Q, and S as shown.

Inductive Power Triangle



Capacitive Power Triangle



Again we can use the previous Pythagoras' Theorem and the Trigonometry functions of Sine, Cosine and Tangent to define a power triangle.

Power Triangle Equations

$$VA^2 = W^2 + VAR^2 \Rightarrow S^2 = P^2 + Q^2$$

$$VA = \sqrt{W^2 + VAR^2} \Rightarrow S = \sqrt{P^2 + Q^2}$$

$$\text{power factor, pf} = \cos(\Phi) = \frac{\text{Real Power}}{\text{Apparent Power}}$$

$$pf = \cos(\Phi) = \frac{W}{VA} = \frac{P}{S}$$

$$pf = \sin(\Phi) = \frac{VAR}{VA} = \frac{Q}{S}$$

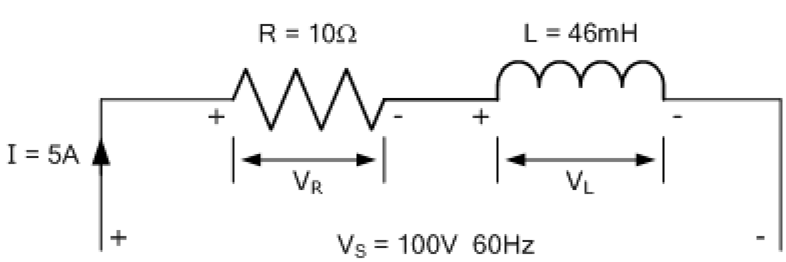
$$pf = \tan(\Phi) = \frac{VAR}{W} = \frac{Q}{P}$$

$$P = VA\cos(\Phi) \qquad Q = VA\sin(\Phi)$$

Power Factor Correction Example No2

A coil has a resistance of 10Ω and an inductance of 46mH. If it draws a current of 5 Amperes when connected to a 100Vrms, 60Hz supply, calculate:

1) the voltages across the components.
2) the phase angle of the circuit.
3) the different powers consumed by the series RL circuit.



First find the impedances

$$X_L = 2\pi f L = 2\pi \times 60 \times 46 \times 10^{-3} = 17.34\Omega$$

$$R = 10\Omega$$

$$Z = \sqrt{R^2 + X_L^2} = \sqrt{10^2 + 17.34^2} = 20\Omega$$

1). The voltages across the resistor, V_R and inductor, V_L

$$V_R = I \times R = 5 \times 10 = 50V$$

$$V_L = I \times X_L = 5 \times 17.34 = 86.7V$$

$$V_S = \sqrt{V_R^2 + V_L^2} = \sqrt{50^2 + 86.7^2} = 100V$$

2). The phase angle of the circuit

$$\cos\phi = \frac{V_R}{V_S}, \quad \sin\phi = \frac{V_L}{V_S}, \quad \tan\phi = \frac{V_L}{V_R}$$

$$\cos\phi = \frac{50}{100} = 0.5 \quad \text{therefore,} \quad \phi = 60^\circ$$

3). The circuit power

$$\text{Real Power, (P)} = VI\cos(\phi) = 100 \times 5 \times \cos(60^\circ) = 250\,W$$

$$\text{Reactive Power, (Q)} = VI\sin(\phi) = 100 \times 5 \times \sin(60^\circ) = 433\,VAR$$

$$\text{Apparant Power, (S)} = VI = 100 \times 5 = 500\,VA$$

We can confirm that the circuit draws 500VA of complex power from the supply as $S = I^2Z$, so 5^2 x 20 = 500VA and the construction of a *power triangle* would also confirm this as being correct.

However, this complex or *apparent power* being consumed by the series RL circuit is large because the phase angle (Θ) by which the voltage leads the current (ELI) is also large resulting in a poor power factor of 0.5 ($\cos60^\circ$) lagging. So we need to cancel some of this inductive reactive power being consumed (433 VAR) by the coil used to sustain the coils magnetic field by adding some more reactance to it but of the opposite type to the circuit.

Should we be concerned about the coils low power factor. Well yes as power factor is the ratio of the coils real power to its apparent power (Watts/Volt-Amperes), it gives an indication of how effectively the electrical power being supplied is being used. Thus a low power factor means that the electrical power being supplied is not fully utilised as in our example coil above, at 50% power factor (W/VA = 250/500) it takes 500VA to produce just 250W of real power.

If the coil has inductive reactance which is positive, then we must add some capacitive reactance which is negative to cancel it out and improve the coils overall power factor value. Adding capacitors to reduce a circuits phase angle and reactive power consumption is referred to as **power factor correction** which allows us to reduce a circuits power factor to nearer 1, unity.

Power Factor Correction

Power Factor Correction improves the phase angle between the supply voltage and current while the real power consumption in watts remains the same, because as we have seen a pure reactance does not consume any real power. Adding an impedance in the form of capacitve reactance in parallel with the coil above will decrease Θ and thus increases the power factor which in turn reduces the circuits rms current drawn from the supply.

The power factor of an AC circuit can vary from between 0 and 1 depending on the strength of the inductive load but in reality it can never be less than about 0.2 for the heaviest of inductive loads. As we have seen above, a power factor of less than 1 means that there is reactive power consumption which increases the closer it gets to 0 (fully inductive). Clearly then a power factor of exactly “1” means the circuit consumes zero reactive power (fully resistive) resulting in a power factor angle of 0^{o}. This is referred to as “unity power factor”.

Adding a capacitor in parallel with the coil will not only reduce this unwanted reactive power, but will also reduce the total amount of current taken from the source supply. In theory capacitors could provide 100% of compensated reactive power required in a circuit, but in practice a power factor correction of between 95% and 98% (0.95 to 0.98) is usually sufficient. So using our coil from example no2 above, what value of capacitor is required to improve the power factor from 0.5 to 0.95.

A power factor of 0.95 is equal to a phase angle of: cos(0.95) = 18.2^{o} thus the amount of VAR required is:

$$\mathrm{Tan}(18.2^{o}) = \frac{Q}{P} = \frac{VAR}{W} = 0.329$$

$$0.329 = \frac{VAR}{250} \quad \therefore VAR = 250 \times 0.329 = 82.2\,VAR$$

Therefore for a phase angle of 18.2^{o} we need a reactive power value of 82.2VAR. If the original uncorrected VAR value was 433VAR and the new calculated value is 82.2VAR, we need a reduction of 433 – 82.2 = 350.8 VAR(capacitive). Therefore:

$$VAR_{(capacitive)} = Q_C = 350.8$$

$$Q_C = 350.8 = \frac{V_S^2}{X_L} = \frac{100^2}{X_L}$$

$$\therefore X_L = \frac{100^2}{350.8} = 28.5\Omega$$

The capacitor required to reduce the reactive power to 82.2VAR must have a capacitive reactance of 28.5Ω at the rated supply frequency. Therefore the capacitance of the capacitor is calculated as:

$$X_C = 28.5\Omega = \frac{1}{2\pi f C}$$

$$\therefore C = \frac{1}{2\pi \times 60 \times 28.5} = 93uF$$

So to improve the power factor of the coil in example no2 from 0.5 to 0.95 requires a parallel connected capacitor of 93uF. Using the values from above we can now calculate the amount of real power supplied by the source after the power factor correction has been applied.

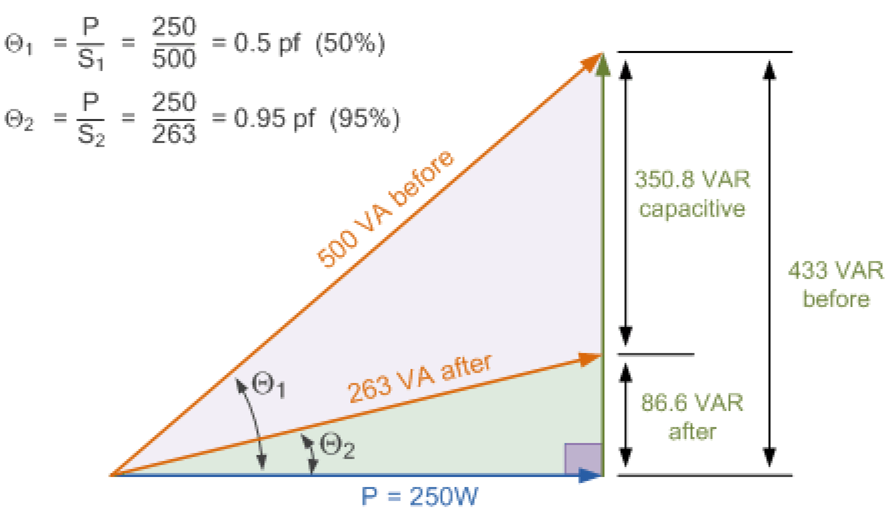
New Volt-Amperes Value

$$VA = \sqrt{W^2 + VAR^2} = S = \sqrt{P^2 + Q^2}$$

$$S = \sqrt{250^2 + 82.2^2} = 263VA$$

We can also construct a power triangle to show the before and after values for VA (S) and VAR (Q) as shown.

Power Triangle

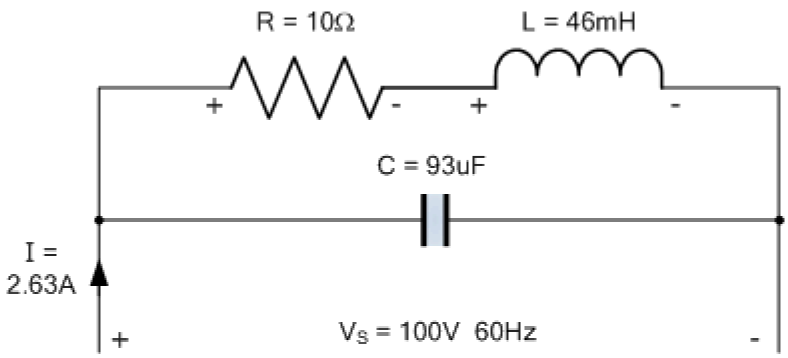


If the circuits apparent power has been reduced from 500VA to just 263VA, we can calculate the rms current supplied as:

S = V*I, therefore: I = S/V = 263/100 = 2.63 Amperes

So just by connecting a capacitor across the coil not only improves its overall power factor from 0.5 to 0.95, but reduces the supply current from 5 amperes to 2.63 amperes, a reduction of some 47%. The final circuit will look like this.

Final Power Factor Correction Circuit



You could if so wished, increase the capacitor value from the calculated value above of 93uF for our simple example, to the maximum value of 114.8uF improving the power factor further from the required 0.95 to 1.0 (unity). In reality a single standard 100uF non-polarised capacitor would be sufficient for this example.

We have seen in this tutorial that a lagging power factor due to an inductive load increases the power losses in an AC circuit. Adding a suitable capacitive reactive component in the form of a capacitor in parallel with an inductive load, we can reduce the phase difference between the voltage and current.

This has the effect of reducing the circuits power factor, that is the ratio of active power to the apparent power, as well as improving the power quality of the circuit and reduces the amount of source current required. This technique is called "Power Factor Correction".

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- *Sirelkhatim*

  This is a useful article I am interested in power factor correction because I work in water pumps and need to get pump energy efficient.
  Thanks for your appreciated effort.

  Posted on December 31st 2023 | 8:22 am
  Reply
- *Y I Vansia*

  Can the Electricity bill be reduced by using power factor correcter unit sold online ?

  Posted on December 21st 2023 | 6:59 am
  Reply
  - *Bubakrry manneh*

    Power factor Can reduce the consumption electricity

    Posted on December 26th 2023 | 11:12 am
    Reply
  - *Wayne Storr*

    No, most domestic consumption is resistive. Inductive loads such as fridge motors or air-con motors are already corrected by the manufacturer

    Posted on December 21st 2023 | 10:12 am
    Reply
- *Bubakrry manneh*

  I learn a on this page I will like to be part of the family

  Posted on November 23rd 2023 | 3:38 pm
  Reply
- *Emmanuel c Ambrose*

  Please if there’s anything incorrect when commenting tag the incorrect with an answer to help aspiring mind just coming in to get in touch thanks

  Posted on October 14th 2023 | 3:07 pm
  Reply

- *Sirelkhatim Nugud*

  I was confused about pf correction, after reading your explanation I understood it
  Thanks a lot

  Posted on May 29th 2023 | 10:01 am
  Reply
- *Venus Siddons*

  To the electronics-tutorials.ws webmaster, You always provide useful information.

  Posted on April 16th 2023 | 8:31 am
  Reply
- *CG PORWAL*

  SSR ?

  Posted on January 19th 2023 | 3:52 pm
  Reply
- *Mahesh Mehta*

  Update

  Posted on November 13th 2022 | 4:25 pm
  Reply
- *Waqar Ali*

  Suppose supply frequency is raised to 60Hz, the voltage remaining same at 100V as shown in below figure 06 (b). Select the value of the capacitor C1 to be connected across the above series so that current drawn from supply is minimum. Also, conclude the analyzed results

  Posted on October 27th 2022 | 1:08 pm
  Reply
- *Saurabh*

  wanted to calculate Power Loss in the electrical instrument (Voltage relay : Din rail based)

  Anybody , knowing how to put required data to a tabular format explaining the power loss during the functioning of the instrument ??

  Posted on August 26th 2022 | 3:24 am
  Reply
- *Bijoxavier*

  I want to improve powerfactor.9 to 1,if added more capacitor parallel whypowerfactor not improving?

  Posted on June 19th 2022 | 8:40 am
  Reply
- *Kashif S. Malik*

  I am an enthusiast with under-grad level of electronics knowledge (that is, I know what Kirchhoff's Rule does, but can't apply it now, after having left the University two decades ago) . Anyway, found this article to be a good refresher. It was rather easy to follow, with just enough maths to make it palatable.

  Posted on May 19th 2022 | 11:06 pm
  Reply
- *Asaf Atias*

Great article. Though I didn’t understand why at the end XL =XC = 28.5ohm
And Xc =93uF isn’t it supposed to be C?

Posted on September 26th 2021 | 11:15 am
Reply

- *AVIOMOH GILBERT*

  An engineer in making

  Posted on August 11th 2021 | 9:02 pm
  Reply
- *Dreuge*

  Many good things here but also many incorrect statements and concepts. For example, “takes 500VA to produce just 250W of real power” is meaningless. Apparent power is not supplied power. This same issue appears in the statement “Adding a capacitor in parallel with the coil will not only reduce this unwanted reactive power, but will also reduce the total amount of current taken from the source supply.” False! Adding a capacitor reduces the impedance Z and thus increases the supply current: I_supply = V_supply/Z. Improving the Power Factor to unity is the same has making the circuit resonant (i.e. X_total = 0) which allows the circuit to consume/deliver more power. This is of course what one wants for electric motors.

  Posted on June 14th 2021 | 8:50 pm
  Reply
- *Marcos Venster*

  I will have to go trough this lessons several times until it “sits”.
  But good, I’m a hobbist who never went to university, and this will give me a background, so I’ll blow up fewer things.

  Posted on June 10th 2021 | 1:09 pm
  Reply
- *Andersh Pahtrejn*

  Thank you for this article. I am in industrial electro-technician and this was a very good review for what a power factor, rlc circuit and voltage/current calculations are.

  Regards.

  Posted on June 08th 2021 | 6:58 pm
  Reply
- *Said Suleiman Hamad*

  I’m Mechanical engineer but I prefer Electrical engineering also.

  Posted on May 16th 2021 | 9:39 am
  Reply
- *Clement Belo*

  Very helpful information to learn about.

  Posted on March 29th 2021 | 9:59 pm
  Reply
- *Kurt Becker*

  While the explanation is 100% correct… text like this is practically useless.
  Anybody who understands electronics will never read it (they now it already) while those who want to know what it is all about are overwhelmed by jargon and other basic electronic knowledge they do not have.
  Sorry, I hate tutorials like that.
  many practical questions have not been answered at all… like

Why do larger switching power supplies have additional circuitry called PFC.
In simple words, how is it done in practice.
I am an EE myself and all my life, I have seen promising youngsters giving up on the wonderful world of electronics because documents like this one.
The simple RLC circuit in the end with a capacitor of 93uF and an inductor of 46mH speaks volumes… I bet the author does not know on which end a solder iron is hot… lol.
Posted on March 09th 2021 | 6:07 pm
Reply

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