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Research Paper

Power factor correction using capacitors & filters

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Abstract

Power factor is the ratio of the real current or voltage received by a load to the root mean square (rms) value of the current or voltage that was supposed to be acquired by the same load. The fact that the two become different is due to the presence of reactive power in the circuit which gets dissipated.

Improving the power factor means reducing the phase difference between voltage and current. Since majority of the loads are of inductive nature, they require some amount of reactive power for them to function. Therefore, for the better use of electrical appliances with minimum amount of electrical consumption, the power factor should necessarily be increased and should be brought near to 1. This can be easily done by the help of Automatic Power Factor Correction Capacitors and Active filters.

Keywords: *Power Factor; Linear Loads; Non-Linear Loads; Harmonic Analysis; Maximum Power Theorem.*

1. Introduction

In the current age, where all the industries are moving towards automation, attaining maximum capability of the machines in use becomes vital. The superiority of any machine is determined by the efficiency of the machine. This efficiency of the machine is given by the ratio of output received from the machine to the input of power given the machine.

The output power is always less than the input power due to the losses that occur in the machine resulting from various factors such as heating of appliances and leakage caused by charging and discharging of capacitors. Because of these, much of the power gets dissipated. Some of the dissipation is occurred due to the presence of reactive power in the circuit used, which hinders the machine from acquiring its maximum potential.

The presence of reactive power is because majority of the loads are of inductive nature, hence, they require some amount of reactive power for them to function. In such case, to improve efficiency, power factor also needs to be improved which will cause the reactive power to be considerably less.

Low power factor causes the following problems:

i) Poor Voltage Regulation
ii) To get the same real power, more apparent power is required.
iii) The increase in reactive power increases the current flowing through the network.
iv) The transmission cost increases as the transformer size increases.

This paper explains how power factor is related to efficiency of a machine and what are the methods available for the industries to make use of in order to improve their power factor.

2. Power theory

Power is the measure of energy per unit time. It basically gives the rate of energy consumption or energy production. Power Theory deals with the various types of powers which come into action when a machine works. These includes:

2.1. Active power

It is defined as the product of voltage and current values when both of these components are in the same phase. Active power comes into action mainly when the load is purely resistive. It is also known as real power or true power.

$$P = I^2R$$

Where, R= Resistance & I=Current.
Unit: Watts

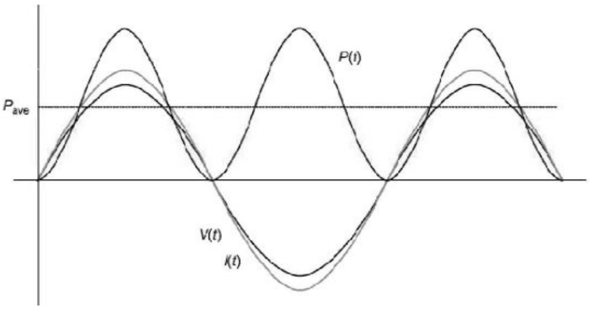


Fig. 1: Power as the Product of Voltage and Current, With Voltage and Current in Phase, Source.

2.2. Reactive power

If the load is completely reactive, then the phase difference between voltage and current is 90 degrees. The power calculated at this point of time is known as reactive power. The power here is positive for two quarters of each cycle of operation and is negative for 2 quarters. Reactive load includes either inductive load or capacitive load, which leads to the calculation of reactive power.

$$Q = I^2X$$

Where, X= Reactance & I=Current.
Unit: Volt-Amps-Reactive (VAR)
NOTE: During the flow of purely reactive power from both to and from the load, there occurs loss of energy in the line resistance.

2.3. Complex power

Practically, all loads contain reactive and active components. Due to this both active and reactive power will occur in the load. The power due to this is given by

$$S = VI\cos\varphi$$

Where, V= Voltage & I=Current & cos φ = Power Factor.
Unit: Volt-Amps-Reactive (VAR)
Here φ is the phase difference between the voltage and current. Its value depends on whether capacitance is greater or lesser than inductance and it is equal to the tangent inverse of the ratio of reactive power to real power.

$$\varphi = \tan^{-1}\left(\frac{Q}{P}\right)$$

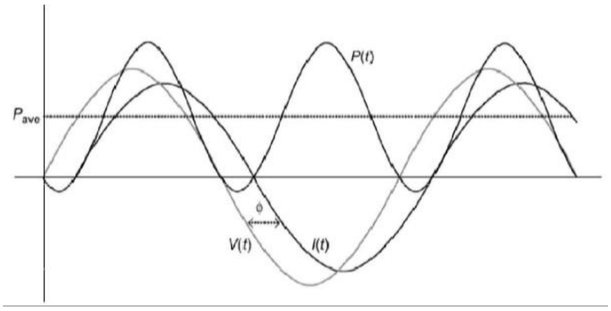


Fig. 2: Power as the Product of Voltage and Current, With Current Lagging Behind Voltage by A Phase Angle Φ.

2.4. Apparent power

It is defined as the magnitude of the complex power or the product of the rms values of voltage and current.

$$|S| = I^2Z$$

Where, S= Complex Power, I= Current & Z= Impedance.

$$Z = \sqrt{R^2 + X^2}$$

Unit: Volt- Amps- Reactive (VAR)
NOTE: Adding two or more apparent power of respective loads will not accurately give the total power unless voltage and current of both the loads are in the same phase.

2.5. Power triangle

It is defined as the relation between the active power, reactive power and the complex power where the complex power is the vector sum of active and reactive power [1]. Figure 3 depicts the graphical representation of the power triangle.

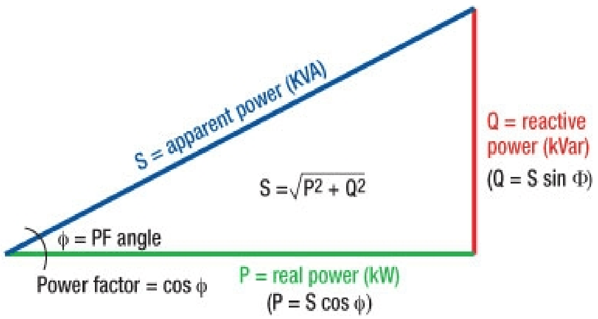


Fig. 3: Scalar Representation of Power Triangle.

3. Harmonic analysis

Harmonic voltages and currents in a system occur due to the presence of non-linear electric loads. These frequencies are a major cause of reducing the quality of power and thus affecting the power factor of a system [2].

3.1. Current & voltage harmonics

In an A.C. system, the current varies sinusoidally at a specific frequency. Whenever a linear load is connected to this system, the current drawn is of the same frequency as that of the voltage, which is not the case in non-linear loads. Whenever a non-linear load draws current from a system, it may or may not be sinusoidal. This leads to the formation of current harmonics, as the current waveform of non-linear loads is complex.

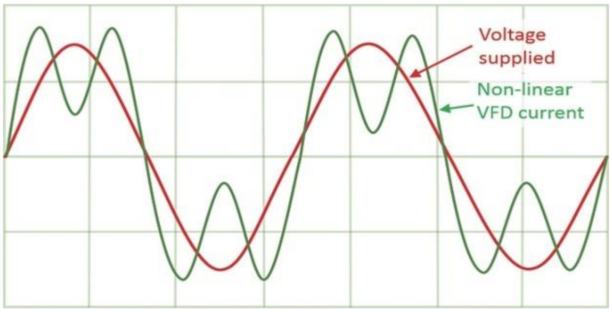


Fig. 4: Graphical Representation of Current & Voltage Harmonics.

Voltage Harmonics are a result of current harmonics. These are obtained because of the distortion of the voltage, provided by the voltage source due to source impedance.

3.2. Problems associated with harmonics

Harmonic distortion results in various problems which affect the quality of power in a system. These include:

i) Main Voltage Distortion.
ii) Losses of electrical energy.
iii) Increase in apparent power.
iv) Damage to capacitors.

In the above given context, points 3 and 4 result in the variation of power factor which results in loss of power and increases the cost of the system since more and more current is required by the system due to reduced power factor.

3.3. Solutions

In the real world, a number of solutions are available for limiting the harmonics:

i) Linear Reactors: Reduce all harmonics.
ii) Tuned Filters: Attenuate harmonics at a particular frequency.
iii) Transformers: Coupling, Star/Delta, etc formations can also reduce harmonics to an extent.
iv) Tuned filters with transformers: These are capable of reducing the total harmonic distortion to less than 5%.

4. Power factor correction

As mentioned previously, low power factor is a consequence of the presence of high reactive power due to the presence of inductive components in the load. Hence, the phase difference between current and voltage increases. This causes the ratio of real power to apparent power or power factor to be reduced.

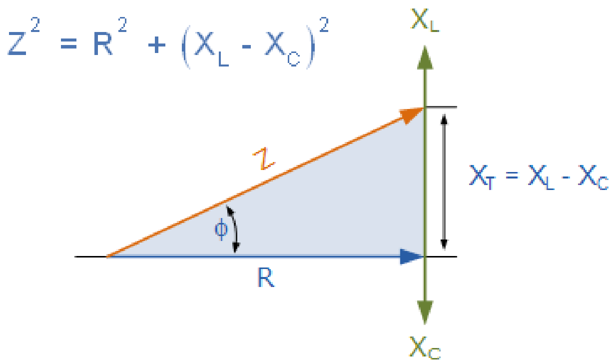


Fig. 5: Impedance Triangle.

According to the fact that both the capacitive and inductive reactance have a phase difference of 180 degree. Therefore, in order to compensate for the reactance caused by the inductive component, capacitors need to be added to the circuit. This concept can be explained by the following calculation. For a power factor of 1 in the real world, following can be given

$$\cos\varphi = 1$$

Now,

$$\cos\varphi = \frac{P}{S}$$

Where, P is Real Power and S is Apparent Power

Then,

$$\frac{P}{S} = 1$$

Therefore,

$$\frac{I^2R}{I^2Z} = 1$$

$$Z = R \tag{1}$$

Where Z is the total impedance of the load and R is the resistive value of the load.
Now,

$$Z = \sqrt{R^2 + (X_l - X_c)^2} \tag{2}$$

Where, X_l is the inductive reactance and X_c is the capacitive reactance.
From Eq. 1 and Eq. 2, it can be hence deduced that

$$X_l - X_c = 0$$

Or,

$$X_l = X_c \tag{3}$$

Hence, can state that in order to get a high-power factor, capacitive reactance is required to compensate for the inductive reactance and hence reduce the impedance making it almost equal to the purely resistive component in the circuit.
Now,

$$X_l = \omega L \tag{4}$$

And,

$$X_c = \frac{1}{\omega C} \tag{5}$$

Where, ω is angular frequency, L is inductance and C is capacitance. Therefore, from Eq. 3, Eq. 4 and Eq. 5, we can say

$$\omega L = \frac{1}{\omega C}$$

Or,

$$\omega = \frac{1}{\sqrt{LC}}$$

Or,

$$LC = \frac{1}{\omega^2} \tag{6}$$

Now, ω is given by

$$\omega = 2\pi f \tag{7}$$

where, f is the frequency of the sinusoidal wave of voltage and current provided to the loads. In India, the value of f is 50Hz. Taking this into account, we can say

$$\omega = 2\pi \cdot 50 \tag{8}$$

Therefore,

$$LC = \frac{1}{(2\pi \cdot 50)^2} \tag{9}$$

Or,

$$|LC| = 1.013 \cdot 10^{-5} \tag{10}$$

From the Eq. 10 it can be deduced that for a quality factor of 1 the product of inductance and capacitance should be in the order of $1.013 \cdot 10^{-5}$. This creates an ideal table of combination of capacitance and inductance values that can be used to achieve a quality factor of 1.

Table 1: Tabular Relation between Inductance and Capacitance for Equation 10

S. No.	Inductance (µH)	Capacitance (F)
1.	1.0	10.13
2.	9.1	1.11
3.	100	0.1013
4.	910	0.0111
5.	1000	0.01013
6.	9100	0.00111
7.	10000	0.001013

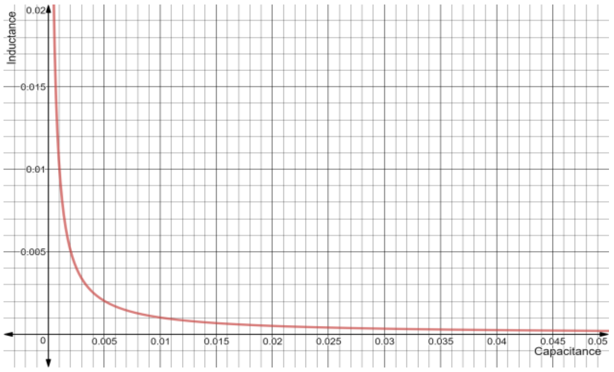


Fig. 6: Graphic Representation of Relationship between Inductance and Capacitance Required for A Power Factor Equal To 1.

Although achieving quality factor of 1 is not possible as achieving purely resistive circuit is not ideal as there is always a little amount of reactive component left in the circuit due to losses in other forms. Hence, it becomes more practical to achieve high quality factors that are near 1 like 0.98 and 0.99.

This is possible by using high capacitance value for low inductance values and vice versa as shown in Table 1.

Now that is has been deduced that capacitive reactance is required to compensate for the inductive reactance in order to increase the power factor, it is necessary to demonstrate how the capacitance should be adjusted as required by the load.

For a low inductance at the load, the capacitance required is high. Now, for a set capacitive value of 6μF (say), in order to increase the capacitance to achieve the required power factor, the capacitors that will be added need to be added using parallel connections. This is because, when two capacitors are placed parallel to each other, their resultant is given by

$$C_{eq} = C_1 + C_2$$

Similarly, for a high inductance at the load, the capacitance required is low. For the same set capacitive value of 6μF, in order to decrease the capacitance, the capacitors that will be added need to be added using series connections. This is because, when two capacitors are placed in series, their resultant is given by

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2}$$

Hence, these combinations are to be used for increasing or decreasing the capacitive reactance in order to compensate for the inductive reactance and reduce the losses cost by it and improving the power factor.

5. Power factor correction methodology

There are a few methods presently used to improve the power factor and compensate for the reactive power produces due to the inductive reactance. The methods used vary according to requirement of the system.

5.1. Types of compensation

Power factor correction is done by using two techniques.

i) Individual compensation

This technique is used when the compensation is done near the load itself. It allows the capacitive value to be set as required by the load. The power lost here is less and it can be easily manipulated as required. Although this technique has a few drawbacks. The requirement of correction panels will be more as the number of load increases which increases the cost. Hence, when there are a large number of loads, this technique becomes ineffective.

ii) Central compensation

This technique is used when the compensation is done at the source of power. Hence, this method requires less number of capacitors. Although this technique also has its demerits. Here, the capacitance cannot be adjusted according to different kinds of loads, i.e. when the source supplies power to different loads with two different inductances, the capacitive reactance used for compensation will not be able to produce the same amount of power factor at both the loads.

5.2. Correction methods used

The compensation of reactive inductance done using the compensation techniques mentioned above are done by using the following methods.

i) Automatic Power Factor Correction (APFC) Units

This method is used for power factor correction in linear loads. These units consist of a number of number of capacitors connected to each other in series and parallel combinations according to the requirements forming capacitor banks. These capacitor banks then get automatically switched on depending on the inductive reactance produces. These capacitor banks are switched on and off according to the output given by a regulator [3].

ii) Static VAR Compensator (SVC)

SVCs are devices that are used to quickly and reliably control line voltages by providing reactive power as required. The SVCs are able to provide capacitive and inductive reactance as required depending on the load. Hence SVCs are made of at least two of the following elements:

a) Thyristor controlled reactor (TCR)
b) Thyristor switched capacitor (TSC)
c) Harmonic filters
d) Mechanically switched capacitors or reactors

In order to compensate for the capacitive reactance, the TCR are used to consume the reactive power due to the capacitance and in order to compensate for the inductive reactance, capacitor bank is automatically switched in [4].

Using SVC helps to improve the capability of the transmission cables, improves stability, helps avoid overvoltage of the system and improve the power factor. It is also a cheaper and faster system which is also more reliable.

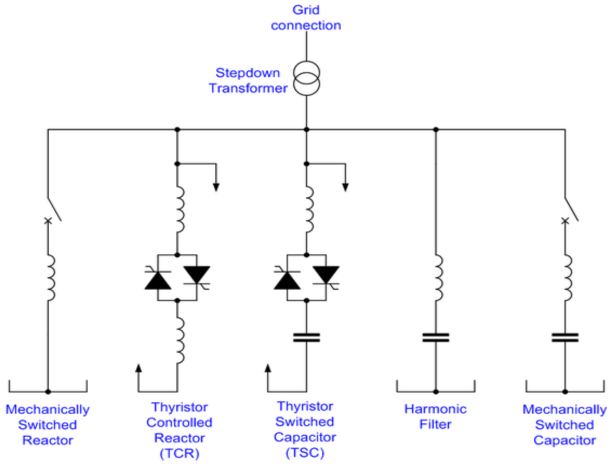


Fig. 7: Various SVC Configurations.

iii) Active PFC

It is the use of power electronics circuits such as buck, boost, buck-boost and synchronous condensers to improve the power factor of the circuit by manipulating the current waveform drawn from the load.

iv) Passive PFC

Power Factor correction in non-linear loads can be carried out using Passive Power Factor Correctors (Passive PFC). It is possible to design a filter which allows a frequency of 50Hz to pass and thus controlling the harmonic currents. Reducing the harmonic currents result in transformation of a non-linear load into a linear load. Now, power factor can be brought near to unity by using high current inductors and capacitors. The cost of these inductors is very high but Passive PFC are better than Active PFC.

v) Dynamic PFC

Dynamic PFC is also referred as real-time power factor correctors because they are used in stabilization of loads that have rapid changing impedance. DPFC uses switches and thyristors to connect and disconnect inductances and capacitances to improve the power factor of the circuit [5]. The main features of DPFC are:

a) Optimized thermal design
b) Low loss
c) Choked design
d) Minimal mains feedback

6. Proposal

The power factor of the system can be controlled by adding capacitor and inductors of higher value and/or by filtering the output values.
According to maximum power theorem, in order to obtain maximum power output, the impedance that is to be applied to the load should be complementary to that of the load. This means that for an inductive load, capacitive impedance should be applied. Also, this impedance must contain some resistance and this should be equal to the resistance that is provided by the load.
In figure 8, it can be seen that in order to obtain a power factor of 1, the impedances of the two must be complementary. This is so that the reactance due to the inductor can be rectified by that of the capacitor. But this is not achievable in ideal case due to real world errors. Hence in figure 9, an example of how to obtain a power factor value close to 1 is shown.
It must be noted that on increasing the capacitance value, the power factor is improved, after a certain value, on increasing the capacitance, the power factor will get reduced. This is because the capacitive reactance will exceed the inductive reactance and hence the impedance will now contain a reactive component. Due to this, the reactive power will again increase, but in the opposite direction, and hence the power factor will decrease. Although, this decrease in power factor will be less and almost negligible.

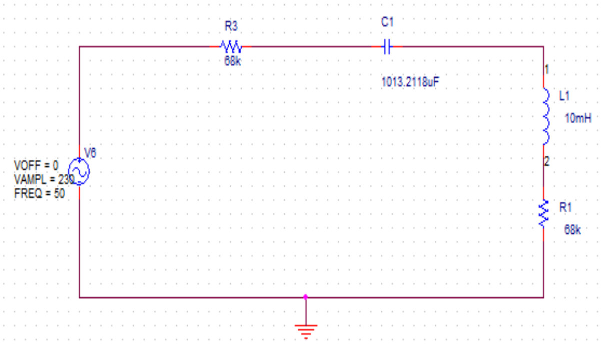
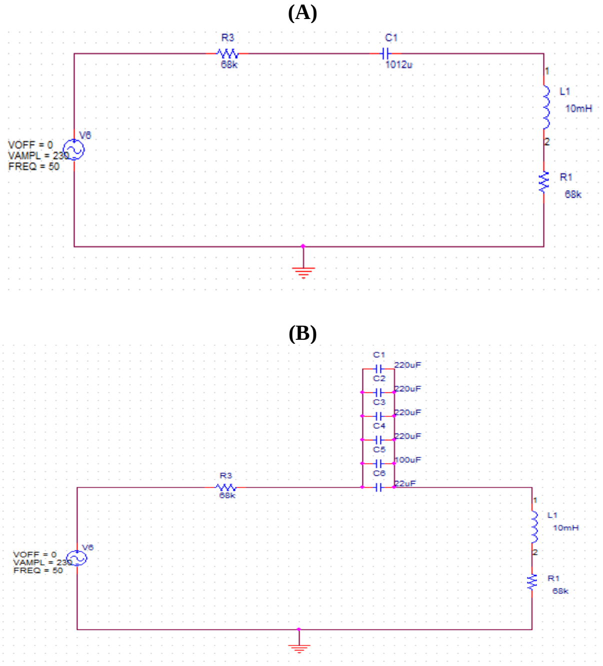


Fig. 8: Maximum Power Output Circuit Using Thevenin Theorem to Get Power Factor = 1.


(A)

(B)

Fig. 9: Maximum Power Output Circuit Using Thevenin Theorem to Get Power Factor Close to 1 Shown By A) the Capacitance Value Required Using Single Capacitance Bank And B) the Capacitance Value Required Using Multiple Capacitance Bank in Parallel Connection.

In figure 10, a capacitance vs power factor graph is shown, which clearly shows how for a 10mH and 1kΩ load, the power factor achieved from the network increases with the increase in capacitance. Although, after a certain value of capacitance, approximately 1000µF, the power factor decreases gradually but at a negligible rate.
An alternative method to maintain a high-power factor is by introducing a load that is much higher than the resultant of the reactance of the circuit. Due to this, this resultant becomes almost negligible and the power factor becomes almost equal to 1.

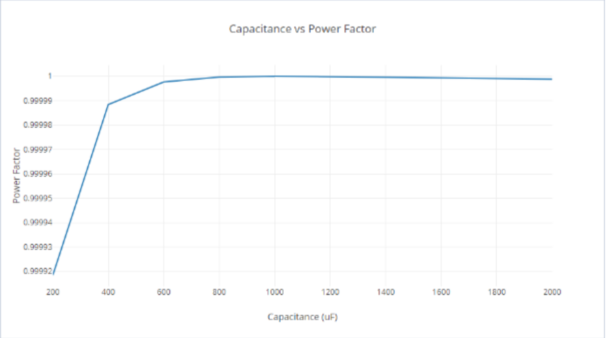


Fig. 10: Power Factor vs. Capacitance for an Inductance of 10mh and Total Resistance of the Circuit of 1kΩ.

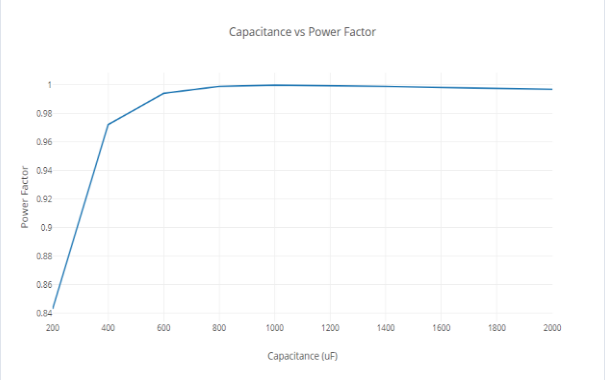


Fig. 11: Power Factor vs. Capacitance for an Inductance of 10mh and Total Resistance of the Circuit of 20Ω.

In figure 11, the capacitance vs power factor graph for 10mH and 20Ω load is shown. In this graph, the power factor increases with increase in capacitance for a value of approximately 1000µF. After this value, the power factor again depletes at a gradual but negligible rate similar to the graph in figure 10. However, due to the presence of resistance which has a value comparable to the value of reactance in the circuit, it can be seen that the range of power factor achieved is higher than the range of power factor achieved when the value of resistance is much higher than the value of reactance of the circuit.
Hence, it can be concluded that by applying resistance of value much higher than the value of reactance of the circuit, the power factor can be improved to a value close to 1 even with the use of low capacitance in the circuit.

7. Conclusion

It can hence be concluded that in order to improve the power factor of a system, the reactive power or the angle φ of the power triangle shown in figure 3 should be reduced. This is done by either increasing the real power of the system to a value much higher than the reactive power of the system or by decreasing the value of reactive power to a value much lower than that of the real power. In order to increase the real power, the real component or the resistance of the system needs to be
increased. This will produce a high power factor even for a low capacitive reactance value in the total reactance of the circuit. Due to this the range of power factors that can be achieved will be les while its value will be high (between 0.99 to 1). To decrease the value of reactive power, the inductive reactance produced by the load needs

to be neutralized. This is done by introducing capacitive reactance which will hence decrease the reactive power and improve the power factor of the system. In order to achieve a power factor of 1, the relationship between the inductance and capacitance of the system should be.

$$|LC| = 1.013 \cdot 10^{-5}$$

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