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POWER FACTOR (P.F.) AND P.F. CORRECTION IN THE POWER SYSTEM INDUSTRY

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Abstract
An electric load operating under alternating current (AC) requires apparent power which consists of real power plus reactive power. Real power is the power actually consumed by the load, while reactive power is the power repeatedly demanded by the load but is returned to the power source and is the cyclic effect that occurs in the system networks. In this paper, power factor (P.F.) and its correction (PFC) are elaborately treated so that electricity consumers will know the consequences of using high or low P.Fs in their systems.

Keywords: Power factors (P.F), PFC, Real power, Apparent power, Reactive power, High P.F., Low P.F., Power utility companies, Electricity consumers.

1.0 Introduction

Power Factor (P.F.) is a very important tool in power system industry as they help to adjust the reactive power to control the system voltage. Power factor correction (P.F.C) can be defined as a way of counteracting the undesirable effects of electric load that create power factor less than unity.[2] As explained earlier, an electric load operating in alternating current, requires apparent power which is made up of real power plus the reactive power. While real power is the power consumed by the load, reactive power is the power repeatedly demanded by the load but is returned to the source, and is the cyclic effect that occurs when an alternating current (a.c) passes through a load containing reactive components. The presence of reactive power causes real power to be less than the apparent power so an electric load has a P.F. less than unity.[3]

Hence, $P.F. = \frac{real\ power}{apparent\ \ power}$ - - - - (1.1)

$= \frac{real\ power}{real\ power\ +reactive\ \ power}$ - - - - (1.2)

Reactive power also causes large flow of current between the source and the load, and this increases the power loss through transmission and distribution lines.[3] This results in huge operational and financial loss to the power utility companies. In addition, reactive powers require the use of wiring, switches, circuit breakers, transformers and transmission lines with higher current capacities.[3] This again increases the equipment cost.

A lot of research work has been going on in this area of power economy. In 1999, T.F. Wu, T.H. Yu and Y.C. Liu presented a paper on alternative approach to synthesizing a single-stage converter with P.F.C. features by selecting an eligible power factor correction (P.F.C) cell and inserting it in between input reactifier and d.c. link capacitors to yield a single-stage converter which can improve the input power factors significantly, although this has certain limitations such as voltage and current stress, output power limitations and problem of harmonic currents.

Again, Wu *et al* under the same year, published a work on design of an isolated single-stage converter, achieving power factor correction and fast regulation by integrating buck-boost and fly-back converters to form the above converter system. There are again limitations such as:

i. High voltage spike at the switching time due to leakage inductance of the power transformer.
ii. High component stress requiring components with high power rating hence, increasing the cost.

Further research[3] has shown that power factor correction can be carried out through various simple methods viz: switching in and out banks of capacitors or inductors which act to cancel the inductive or capacitive effects of the loads respectively. For example, the inductive effects of motorloads may be offset by locally connected capacitors. It is also possible to effect power factor correction with an unloaded synchronous motor connected across the supply. The power factor (P.F.) of the motor is varied by adjusting the field excitation and can be made to behave like a capacitor when over excited.

1.1 Nonlinear Loads

Nonlinear loads create harmonic current in addition to the original a.c. current. Therefore, the simple correction techniques described above do not cancel out the reactive power at harmonic frequency; and so more sophisticated techniques have to be employed.

Switched-mode power supplies (SMPS) for power factor correction (P.F.C.) on nonlinear loads was attempted,[6] where upon, a typical (SMPS) would first make a d.c. bus using a bridge rectifier or similar circuit and the output voltage was then derived from this bus. The problem with this is that the rectifier is a nonlinear device, so the input current is highly nonlinear. This means that the input current has energy at harmonics of the frequency of the voltage, and this presents a particular problem for power utility companies because they could not compensate for the harmonic current by adding capacitors or inductors as in the case of reactive power drawn by linear loads.

However, the simplest way to control the harmonic current is to use a filter designed to pass current only at line frequency (e.g. 50 or 60Hz).[7]

This filter kills the harmonic current, which means that the nonlinear device now behaves like a linear load. At this point, the power factor would have been brought to near unity using capacitors or inductors by researchers but this filter required large value, high current inductors that were bulky and expensive and so this method was found uneconomical and faulty. Nonlinear loads are loads that are dependent on voltage and current; examples are: transistors, thyristors, diodes, contactors and relays. Linear loads are loads that are independent of voltage and current; examples are: resistors, inductors and capacitors. They are constant R, L, C loads.

2.0 Power Factor Models

Power factor can be modeled in any of the following ways[1]:

i. Cosine of angle of lead or lag.

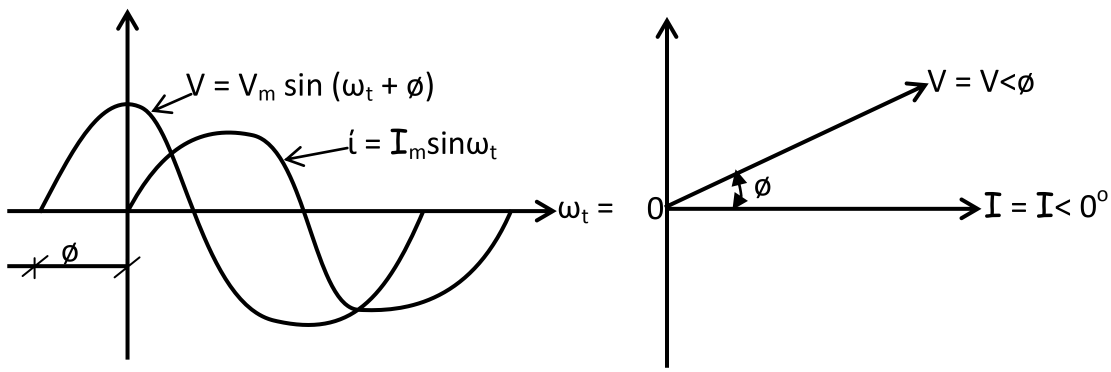
ii. The ratio of $\frac{True\ power}{Apparent\ \ power} = \frac{watts}{volt\ amperes} = \frac{W}{VA}$

iii. The ratio of $\frac{Resistance}{Impedance} = \frac{R}{Z}$

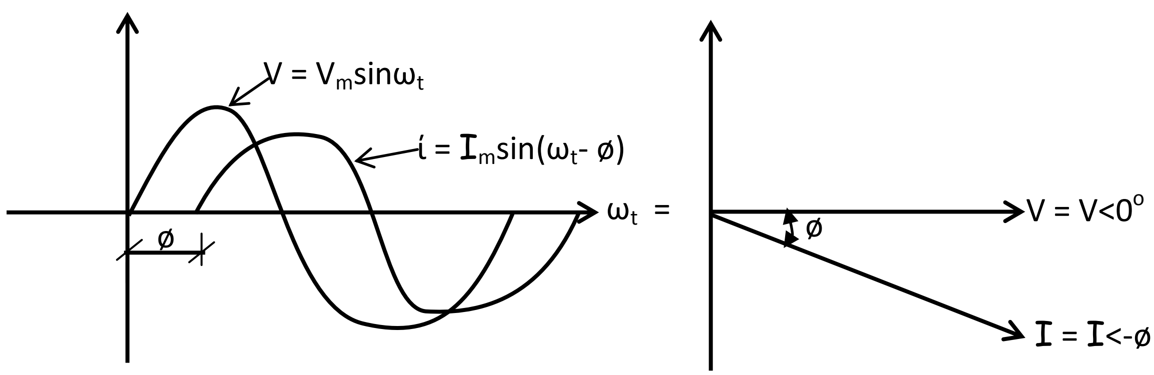
iv. Ratio of $\frac{KW}{KVA}$

i. Angle of Lead or lag

A leading alternating quantity as shown in fig. 2.1(a) is one which reaches its maximum or zero value earlier than other quantity. Similarly, a lagging alternating quantity fig. 2.1(b) is one which reaches its maximum or zero values later than the other quantity. Again, a plus sign (+) when used in connection with phase difference, denotes "lead" whereas a minus (-) sign denotes "lag." Therefore, the cosine of angle of lead or lag is the power factor (P.F.).



(a)



(b)

Fig. 2.1: (a) Voltage leads the current by ø

(b) Current lags the voltage by ø or voltage leads the current by ø.

ii. **The Ratio of True Power to the Apparent Power**:

The mean or true power consumed in a circuit is given by the product of the voltage V and the component of the current Iwhich is in phase with the voltage.

Hence, Pi = V x I cos ø - - - - - - (2.1)

Where Pi = average input or true power

V = r.m.s value of the input voltage

I = r.m.s value of the input current.

The product VI is called the volt-amperes denoted by Pa, and this is not a true power.

$$\therefore P.F. = \frac{true\ \ power}{apparent\ \ power} = \frac{Pi}{Pa} \quad - \quad - \quad - \quad - \quad - \qquad (2.2)$$

$$= \frac{VI\cos ø}{VI}$$

$$= \cos ø \quad - \quad - \quad - \quad - \quad - \quad - \quad - \qquad (2.3)$$

The true power (VI cos ø) consumed in a circuit is due to ohmic resistance only because pure inductance does not consume any power.

iii. **The Ratio of Resistance to the Impedance (R/Ƶ)**:

If we refer to equation 2.1, it should be noted that the power consumed is due to ohmic resistance only because pure inductance does not consume any power. With the reference to the impedance triangle in fig. 2.2, now:

P = VI cos ø - - - - - (2.4)

= VI x (R/Ƶ) - - - - - (2.5)

Where (R/Ƶ) = cos ø (from the impedance triangle)

P = V/Ƶ .IR ⇒I.I.R

$\therefore P = I^2R$ watts - - - - - - - (2.6)

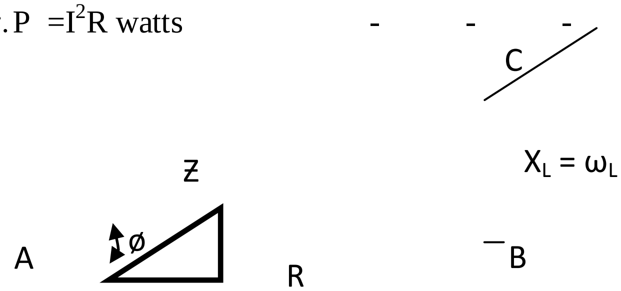


Fig. 2.2: The impedance triangle

Equation 2.6 is the power consumed, and below is the graphical representation.

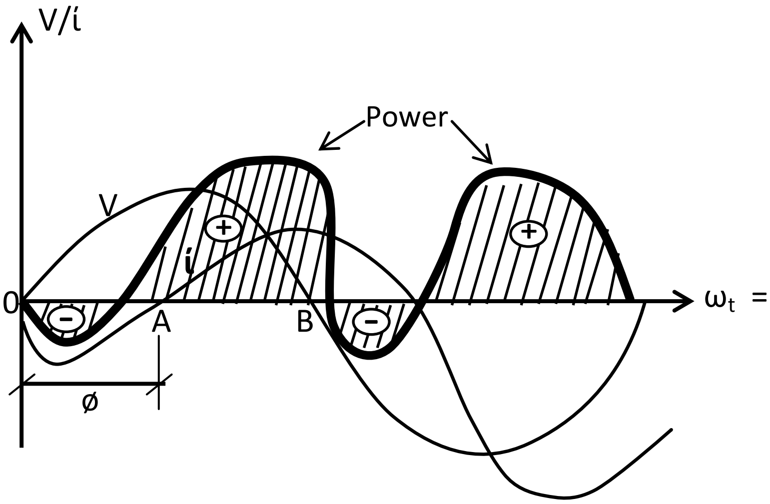


Fig. 2.3: Graphical representation of power consumed when current lags behind the voltage[9].

It should be noted that the positive shaded area represent the energy supplied from the alternator to the circuit while the negative shaded portion represent the energy returned from the circuit to the alternator.

2.1 Active and Reactive Components of Circuit Current

To obtain the 4th model of the P.F., the active and reactive components of circuit current were examined. Simply put, P.F. is that which takes into account the fact that not all the currents being carried by cables in an a.c. circuit deliver power to the load. The total current is made up of two components.[9]

a. The power component, otherwise called the active or wattful component, I cos ø. This is in phase with the applied voltage.
b. The reactive component, otherwise called idle or wattless component, I sin ø. This is in quadrature with the applied voltage (see figure 2.4).

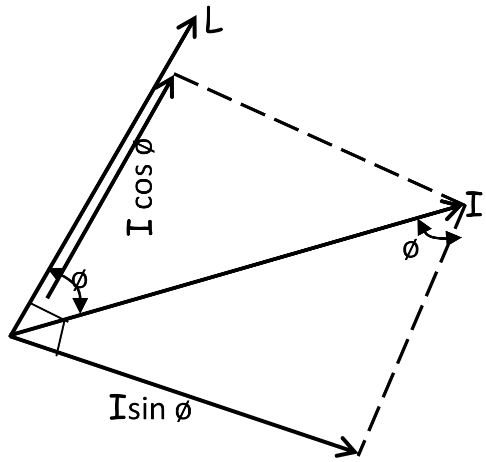


Fig. 2.4: Vector form of voltage and current

From figure 2.4, I has been resolved into two mutually perpendicular components, I cos ø along the applied voltage V and I sin ø along the quadrature.

An active component is obtained by multiplying KVA by cos ø and this gives power in KW. The reactive component is also obtained by multiplying KVA by sin ø and this gives power in KVAR (kilovar). Since the phase angle difference between the two is 90^o:- total KVA =

$$\sqrt{(KW)^2 + (KVAR)^2} \qquad - \quad - \quad - \quad - \quad - \quad - \qquad (2.7)$$

Where KVA = kilo volt-amperes.

The above relationship is driven home further by putting it in KVA triangle in figure 2.5.

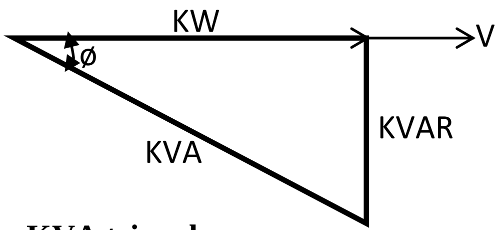


Fig. 2.5: The KVA triangle

Hence, $\cos ø = \frac{KW}{KVA}$ - - - - - - (2.8)

or $P.F. = \frac{KW}{KVA}$ - - - - - - - (2.9)

Therefore, power factor (P.F) can be defined as the ratio of power in (KW) to the product of voltage and current (KVA) in a circuit.

The power in a single-phase (S.P.N) circuit:

$P = V_L I_L \cos ø$ (watts)

$\therefore I_L = = \frac{P}{V_L \cos ø} A$ - - - - - - (2.10)

Power in a 3-phase (T.P.N) circuit:

$P = \sqrt{3} V_L I_L \cos ø$ (watts)

$\therefore I_L = = \frac{P}{\sqrt{3} V_L \cos ø} A$ - - - - - (2.11)

Where

P = Power in watts

V_L = line voltage

I_L = line current

Cos ø = P.F. of the circuit being supplied.

3.0 Types of Power Factor Correction (PFC) in Electricity Industry

i. **Passive PFC**:

This is the simplest way of correcting the nonlinear of an electric load, using capacitor banks. The method is not as effective as the active PFC. Switching the capacitors into or out of circuit causes harmonics and for this reason active PFC or synchronous motor is preferred.

ii. **Active PFC**:

An active PFC is a power electronic system that controls the amount of power drawn by a load in order to obtain a power factor as close as possible to unity. In most applications, the active PFC controls the input current of the load so that the current waveform is proportional to the mains voltage waveforms (sine waves).[3]

Some types of active PFC are: boost converters, buck converters and buck-boost converters. Active PFC can be single-stage or multi-stage and is the most effective, producing a PFC of about 0.99 (99%).

iii. **Synchronous Motors**:

Synchronous motors can also be used for PFC. In the past, shaftless motors were made to which no load could be connected and which ran free on the line at capacitive (leading) power factor for the purpose of power factor correction (PFC).[3]

3.1 Economic Importance of Power Factors and Its Correction to Electricity Consumers/ Utility Companies

(i) Power factors and hence, PFC is important because it attempts to adjust the reactive power to control the system voltage in a transmission network.

(ii) It is applied by power utility to improve the stability and efficiency of the transmission network or could be installed by individual customers to reduce the costs charged to them by electricity suppliers.[3]

(iii) It is intended to inform all the electricity consumers especially those operating on high electric loads to limit their P.Fs between 0.9 and above to avoid being surcharged by power utility companies.[3]

(iv) Operating at low P.Fs (0.6 and below) produce poor power quality leading to poor output powers and losses.

(v) Power utility companies have to operate at low P.Fs (0.6 and below) because this causes large flow of current between the source and the load leading to power loss between transmission and distribution lines. This brings huge operational and financial loss to the power utility companies.

(vi) It is possible for an existing plant of a given KVA rating to increase its earning capacity (which is directly proportional to power supplied in KW) if the overall P.F. is improved or raised.

4.0 Conclusion

Power factor is a very important tool in power system industry as high P.F. (0.9 and above) improves the overall power quality, efficiency and system stability while low P.Fs (0.6 and below) produce poor output powers and hence losses.

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