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17/ENG04/057
ELECTRICAL ELECTRONICS ENGINEERING
ELECTRICAL MACHINES

SECTION A: THEORETICAL FRAMEWORK

1. **Develop the theoretical framework required for the correction of the power factor for a multi - sectioned industrial complex from $Cos\ \emptyset_1$ to $Cos\ \emptyset_2$ where $\emptyset_1 > \emptyset_2$; $P_1 = P_2$; $Q_1 > Q_2$; and $S_1 > S_2$ to determine the kVAR rating of the capacitor(Q_{CAP}) and the magnitude of the capacitor (C) in farads required to correct the power factor of the complex. USE APPROPRIATE PHASOR DIAGRAMS.**

Solutions:

Multi-sectioned industrial complex operates on industrial loads (such as induction motors). From research, it can be deduced that industrial loads are inductive and operate at a low lagging power factor. Regardless of the fact that the inductive nature of the load cannot be changed, the power factor can still be corrected.
"The process of increasing the power factor without altering the voltage or current to the original load is known as power factor correction."

In a system with mostly inductive loads typically industrial power plants with many electric motors as shown in Fig.1a, the lagging voltage is compensated with capacitor banks. In other words, a load's power factor is improved or corrected by deliberately installing a capacitor in parallel with the load as shown in Fig.1b. The effect of adding the capacitor has be illustrated using both the phasor diagram and the power triangle of the currents involved as shown in Fig 1c & 1d respectively.

Furthermore, Fig.1c&d shows the latter, where it is assumed that the circuit in Fig. 1a has a power factor of $cos\,\emptyset_1$ ·while the one in Fig. 1b has a power factor of $cos\,\emptyset_2$. It is apparent from Fig.1c&d that adding the capacitor has caused the phase angle between the supplied voltage and current to reduce thereby increasing the power factor. Also, observing the magnitudes of the vectors in Fig.1c&d with the same supplied voltage, the circuit in Fig. 1a draws larger current I_L than the current I drawn by the circuit in Fig. 1b. Because, by minimizing current level it keeps the power factor as close to unity as possible.

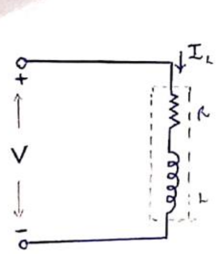


Fig. 1a : Inductive Load

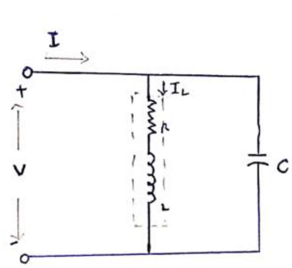


Fig. 1b : Inductive load with Improved Power Factor

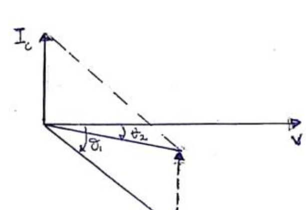


Fig 1c : Phasor Diagram Illustrating the effect of adding Capacitor in parallel with Inductive Load

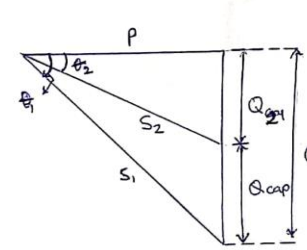


Fig 1d: Power Triangle Illustrating power factor correction.

By calculation:

Consider the power triangle in Fig. 1d. If the original inductive load has S_1 apparent power then

$$P = S_1 \cos \emptyset_1,$$
$$Q_1 = S_1 \sin \emptyset_1 = P \tan \emptyset_1$$

Given that $P_1 = P_2$ and $S_1 > S_2$

Therefore, increasing the power factor from $Cos\ \emptyset_1$ to $Cos\ \emptyset_2$ without alternating the real power ($P = S_2 \cos \emptyset_2$), then

$$Q_2 = P \tan \emptyset_2$$

From Fig.1d, the original reactive power Q_1 has been reduced by the capacitor to obtain Q_2 & Q_{cap}, therefore;

$$Q_{cap} = Q_1 - Q_2 = P(\tan \emptyset_1 - \tan \emptyset_2).$$

Whereby; $Q_1 > Q_2$

Note: *The amount of capacitance to be installed for a given power factor correction is a function of the amount of reactive power taken by the system. Reactive power which is measured in VAR or KVAR; the capacitors used for power factor correction are rated in KVAR.*

Therefore,

Recall that; $Q_{cap} = \frac{V_{rms}^2}{x_c}$

Where; $x_C = \frac{1}{2\pi f C}$

$$Q_{cap} = V_{rms}^2 * 2\pi f C \text{ VAR}$$

Conclusively, **the KVAR Rating of the capacitor** is the product of the inverse reactive capacitance (x_c^{-1}) at a rated frequency and the rated voltage divided by 1000, hence:

$$\text{KVAR} = \frac{V_{rms}^2 * 2\pi f C}{1000}.$$

The magnitude of the capacitor can be calculated as:

Recall: $Q_{cap} = V_{rms}^2 * 2\pi f C$

$$C = \frac{Q_C}{V_{rms}^2 * 2\pi f}$$

$$C = \frac{P(\tan \emptyset_I - \tan \emptyset_2)}{\omega V_{rmS}^2} \text{ in farad}$$

TO PROVE THIS USING EXAMPLE 7:

An industrial load absorbs 5 MVA at a pf of 40% capacitive at 6kV. To improve the pf up to 85% capacitive, determine Q and C of the required capacitor.

Solution:

Preamble:

Apparent power (S) = 5MVA

Voltage = 6KV

Initial power factor= 40%=0.4 lagging

Improved power factor=85%=8.5 lagging

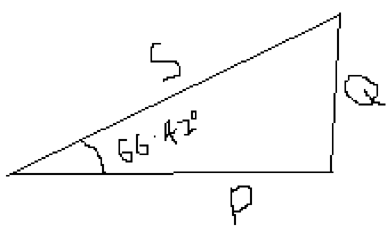
Where; power factor=$cos\,\emptyset_1$

$$cos\,\emptyset_1 = 0.4$$

$$\emptyset_1 = cos^{-1} * 0.4$$

$$\emptyset_1 = 66.42^{\circ}$$

Diagrammatic representation:



Where, S= 5Mva

$$cos\,\emptyset_1 = \frac{P}{5 * 10^6}$$

P=$0 \cdot 4 * 5 \times 10^6$

$$P = 2MW$$

$$sin\,\emptyset_1 = \frac{Q}{5 * 10^6}$$

Q=$0 \cdot 916 * 5 \times 10^6$

$$Q = 4.6MVAR.$$

$NOTE$: when improving the power factor,

$\emptyset_1 > \emptyset_2$, $P_1 = P_{2,}$ $Q_1 > Q_2$, $S_1 > S_2$

Therefore; where $P_1 = P_2$

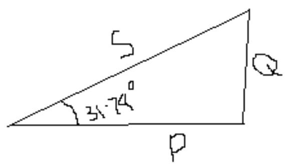
Power factor=$cos\,\emptyset_2$

$$cos\, \emptyset_2 = 0.85$$

$$\emptyset_2 = cos^{-1} * 0.85$$

$$\emptyset_2 = 31.788^{\circ}$$

Diagrammatic representation



$$cos\, \emptyset_2 = \frac{P}{S_2}$$

S_2=$0 \cdot 85 * 2 \times 10^6$ $\quad\quad$ $S_2 = 2.35MVA$

$$tan\, \emptyset_2 = \frac{Q_2}{P}$$

Q_2=$\tan 0.85 * 2 * 10^6$

$$Q_2 \; = 1.24MVAR.$$

Where, $\quad Q_1 = \; Q_{cap} + \; Q_2$

, $\quad\quad Q_{cap} = \; Q_1 - \; Q_2$

$$Q_{cap} = 4.6 - 1.239$$

$$Q_{cap} = 3.26MVAR$$

Obtaining the value for C;

Recall; C=$\frac{Q_C}{V_{rms}^2 * 2\pi f}$

Note: standard frequency in Nigeria = 50Hz

C=$\frac{3.26*10^6}{6000^2*2\pi*50}$

C=295*10^{-6} Farads $\approx \; 295\mu F$

From the example used, it has been proven that when correcting a power factor, the following conditions must be met:

$$\emptyset_1 > \emptyset_2 \; , \; P_1 = P_{2,} \quad Q_1 > Q_2, \; S_1 > S_2$$

2) What determines the power factor of the Dangote Cement Factory at Abajana, Kogi State?

The power factor of Dangotes Cement Factory at Abajana, Kogi State is determined by both the Apparent power (S) in KVA and the Working power (P) in KW, in other words by Dividing the working power by the apparent power.

For a more practical and effective method; it is known that the power factor of dangotes cement factory varies along the time. So, only typical values are obtained, potentially, the highest and lowest values of these parameters (Apparent and Working power). To acquire information about the power factor, connect an energy analyzer with the recording capacity. Then, analyzing the obtained data in typical days of the factory; should give the potential values needed to obtain the power factor.

3) **The power factor (pf) of Eleme Petrochemical Industry Port Harcourt is given as $\mathbf{Cos}(\boldsymbol{\alpha} \pm \boldsymbol{\beta})$; what is the state of the pf of the complex when $\boldsymbol{\alpha} > \boldsymbol{\beta}$; $\boldsymbol{\beta} > \boldsymbol{\alpha}$ and $\boldsymbol{\alpha} = \boldsymbol{\beta}$. Draw the respective Phasor diagrams.**

Solution:

Recall that, the power factor is the cosine of the phase difference between voltage and current. It is also the cosine of the angle of the load impedance.

$$\text{Power factor} = \frac{P\ (real\ power)}{s(\ apparent\ power)} = \cos\emptyset$$

From the question, it can be deduced that, $\emptyset = \alpha \pm \beta$

Where, the power factor angle is equal to the angle of the load impedance if V is the voltage across the load and I is the current through it.

Evidently;

$$z = \frac{v}{I} = \frac{v_m < \alpha}{Im < \beta} = \frac{v_m}{Im} < \alpha - \beta$$

$$v_{rms} < \alpha \ , \ I_{rms} < \beta$$

At, $\alpha = \beta$

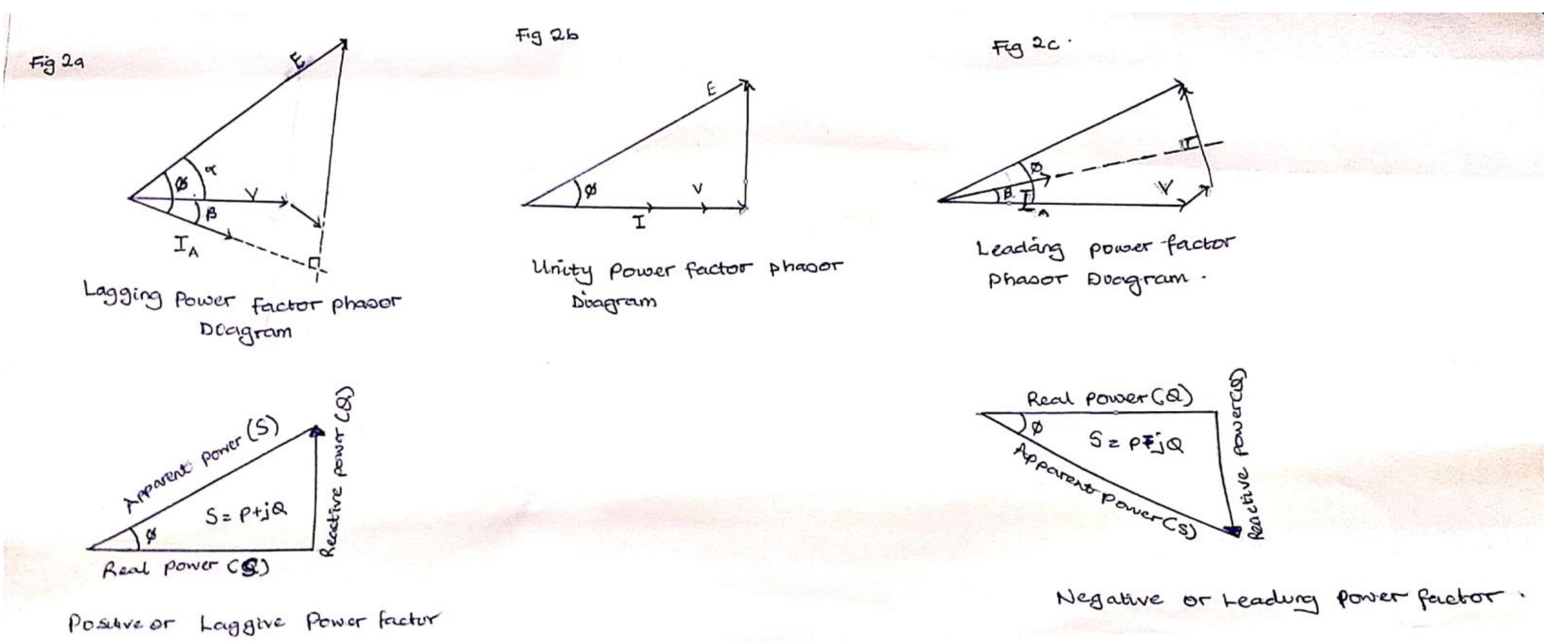
It is a purely resistive load; the voltage and current are in phase, so that $\alpha - \beta = 0$ and the state of the power factor is **unity.** Fig. 2b

At, $\alpha > \beta$

It is an inductive load; the current lags the voltage so it is a **Lagging power factor**. Fig. 2a

At, $\beta > \alpha$

It is a capacitive load; the current leads the voltage so it is a **Leading power factor.** Fig. 2



4) **For $\alpha > \beta$; Write an expression for P and Q respectively with units in W and VAR. What does P and Q represent.**

Solution:

At, $\alpha > \beta$

It is an inductive load; the current lags the voltage so it is a **Lagging power factor**. From Fig.2a it can be deduced that:

Using the formula for a right-angle triangle;

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

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

Expressing it in complex form:

$$S = \sqrt{P^2 + jQ^2}$$

VA =$\sqrt{W^2 + jVAR^2}$

Also:

tan Ø = $\frac{Q}{P}$

$$P = tan\, Ø^{-1} Q = arctan\, Ø * Q$$

$$W = arctan\, Ø * VAR$$

$$Q = p\, tan\, Ø$$

$$VAR = W tan\, Ø$$

Where; P= Real power measured in Watt(W).

Q= Reactive power measured in Volt-Amperes reactive (VAr).

5) **Justify the need for power factor correction to ABUAD and PHCN or an IPP**.

Energy saving has always been an issue of great concern in the electrical power system, especially in electrical power supply stations. Reducing the losses of electrical energy constitutes a great part of this concern. Power factor correction of a power system, is a very important and vital method to achieve savings, both of energy and cost. If there is low power factor, the system will draw more current and the excessive heat generated will damage/ shorten the equipment's life.

Considering ABUAD'S College of Engineering; having various well-equipped laboratories, if the power factor is low, this will shorten the life-span of equipment's, leading to excessive cost for replacing/ repairing. ABUAD as a school having numerous individuals, from the non-academic staff- academic staff and also the students, the rate of power consumption is very high. The higher the portion of reactive power, the lower the power factor; Note, if the reactive power component is reduced and phase angle through compensation; the apparent power vector reduces in length, resulting in lower electricity consumption and energy charges. In other words, saving cost and consumption.

For the PHCN, improved power factor will not only increase the distribution system's efficiency but also reduce the energy cost associated with low power factor penalties. A circuit with low power factor will use greater amount of current to transfer a given quantity of real power than a high power factor thus causing increased losses due to resistive heating in the power lines and requiring the use of higher rated conductors and transformers. Consider the whole power generation, transmission and distribution process; if the power been generated is transmitted at a higher current than voltage, there would be losses in the transmission lines. In other words, before the power gets to the distribution company and then to the local transformers, reasonable amount of power would have been lost. This is one of the major problems most under-developed countries are facing.

6) Why is Q needed in an industrial complex with numerous induction motors?

The reactive power is needed because it is related to the energy needed to maintain the motors internal magnetic field. In an induction motor, the rotor field always lags behind the stators field, so the induction motor always consumes reactive power due to the magnetization current.

SECTION B: APPLICATION OF THEORETICAL FRAMEWORK

7) An industrial load absorbs 5 MVA at a pf of 40% capacitive at 6kV. To improve the pf up to 85% capacitive, determine Q and C of the required capacitor. State how the correcting equipment will be integrated into the industrial power network for this load.

Solution:

a) Preamble:

Apparent power (S) = 5MVA
Voltage = 6KV
Initial power factor= 40%=0.4 leading
Improved power factor=85%=8.5 leading

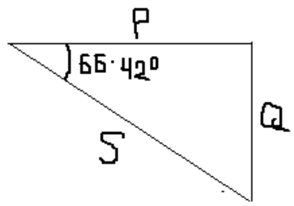
Where; power factor=$cos\,\emptyset_1$

$$cos\,\emptyset_1 = 0.4$$

$$\emptyset_1 = cos^{-1} * 0.4$$

$$\emptyset_1 = 66.42^{\circ}$$

Diagrammatic representation:



Where , S= 5Mva

$$cos\,\emptyset_1 = \frac{P}{5*10^6}$$

P=$0\cdot 4 * 5\times 10^6$

$P = 2MW$

$$sin\,\emptyset_1 = \frac{-Q}{5*10^6}$$

-Q=$0\cdot 916 * 5\times 10^6$

$Q = -4.6MVAR.$

$NOTE$: when improving the power factor,

$\emptyset_1 > \emptyset_2$, $P_1 = P_{2,}$ $Q_1 > Q_2,$ $S_1 > S_2$

Therefore; where $P_1 = P_2$

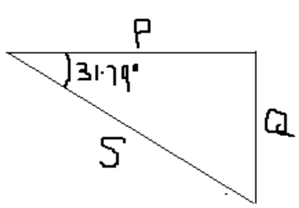
Power factor=$cos\,\emptyset_2$

$cos\,\emptyset_2 = 0.85$

$\emptyset_2 = cos^{-1} * 0.85$

$\emptyset_2 = 31.788^{\circ}$

Diagrammatic representation



$$cos\,\emptyset_2 = \frac{P}{S_2}$$

S_2=$0\cdot 85 * 2\times 10^6$ $S_2 = 2.35MVA$

$$tan\,\emptyset_2 = \frac{-Q_2}{P}$$

$$-Q_2 = \tan 0.85 * 2 * 10^6$$

$$Q_2 \ = -1.24MVAR.$$

Where, $Q_1 = \ Q_{cap} + \ Q_2$

, $Q_{cap} = \ Q_1 - \ Q_2$

$$Q_{cap} = -4.6 * 10^6 - 1.239 * 10^6$$

$$Q_{cap} = -5.8393MVAR$$

Obtaining the value for C;

Recall; $C = \frac{Q_C}{V_{rms}^2 * 2\pi f}$

Note: standard frequency in Nigeria = 50Hz

$$C = \frac{-5.83*10^6}{6000^2*2\pi*50}$$

C= - 515.4*10^{-6} Farads $\approx -515.4\mu F$

7b) State how the correcting equipment will be integrated into the industrial power network for this load.

From the question, it is stated that the industrial power network is operating on a capacitive load, it can be concluded that it will have a leading (capacitive) power factor; which means that the correcting equipment (capacitor of the minimal size (-515.4 μF)) which will be integrated in parallel to the industrial power network. This industrial power requires a minimal capacitor because it already deficient with leading VARs (it operates at a lagging PF) and thus this deficient power network will absorb the leading VARs and tend to improve its lagging PF to unity.

8) An industrial load absorbs 5 MVA at a pf of 40% inductive at 6kV. To improve the pf. Up to 85% inductive, determine Q and C of the required and necessary capacitor. State how the correcting equipment will be integrated into the industrial power network for this load. How different are the values of Q7 and Q8 in terms of magnitude and type of pf correction?

Preamble:

Apparent power (S) = 5MVA

Voltage = 6KV

Initial power factor= 40%=0.4 lagging

Improved power factor=85%=8.5 lagging

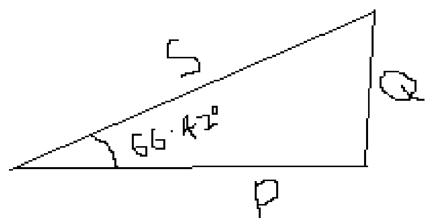
Where; power factor=$cos\, \emptyset_1$

$$cos\, \emptyset_1 = 0.4$$

$$\emptyset_1 = cos^{-1} * 0.4$$

$$\emptyset_1 = 66.42^{\circ}$$

Diagrammatic representation:



Where, S= 5Mva

$$cos\, \emptyset_1 = \frac{P}{5 * 10^6}$$

P=$0 \cdot 4 * 5 \times 10^6$

$$P = 2MW$$

$$sin\, \emptyset_1 = \frac{Q}{5 * 10^6}$$

Q=$0 \cdot 916 * 5 \times 10^6$

$$Q = 4.6MVAR.$$

$NOTE$: when improving the power factor,

$\emptyset_1 > \emptyset_2$, $P_1 = P_{2,}$ $Q_1 > Q_2,$ $S_1 > S_2$

Therefore; where $P_1 = P_2$

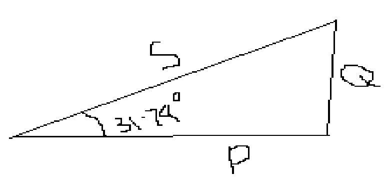
Power factor=$cos\, \emptyset_2$

$$cos\, \emptyset_2 = 0.85$$

$$\emptyset_2 = cos^{-1} * 0.85$$

$$\emptyset_2 = 31.788^{\circ}$$

Diagrammatic representation



Where :

$$cos\,\emptyset_2 = \frac{P}{S_2}$$

S_2=$0 \cdot 85 * 2 \times 10^6$ $\quad\quad S_2 = 2.35MVA$

$$tan\,\emptyset_2 = \frac{Q_2}{P}$$

Q_2=$\tan 0.85 * 2 * 10^6$

$Q_2 \;= 1.24MVAR.$

Where, $\quad Q_1 = \; Q_{cap} + \; Q_2$

, $\quad\quad Q_{cap} = \; Q_1 - \; Q_2$

$Q_{cap} = 4.6 - 1.239$

$Q_{cap} = 3.26MVAR$

Obtaining the value for C;

Recall; C=$\frac{Q_C}{V_{rms}^2 * 2\pi f}$

Note: standard frequency in Nigeria = 50Hz

C=$\frac{3.26*10^6}{6000^2*2\pi*50}$

C=295*10^{-6} Farads $\approx\; 295\mu F$

From the example used, it has been proven that when correcting a power factor, the following conditions must be met:

$$\emptyset_1 > \emptyset_2 \;,\; P_1 = P_{2,} \quad Q_1 > Q_2,\; S_1 > S_2$$

8b) State how the correcting equipment will be integrated into the industrial power network for this load.

From the question, it is stated that the industrial power network is operating on an inductive load, it can be concluded that it will have a lagging (inductive) power factor; which means that the correcting equipment (capacitor of the appropriate size (295 μF)) which will be integrated in parallel to the industrial power network as demonstrated in Fig 1b.

8c) How different are the values of Q7 and Q8 in terms of magnitude and type of pf correction?

- Observing values in terms of magnitudes; with the same supplied voltage, the capacitor needed in Q7 is minimal ($-\ 515.4\mu F$) and is less required compared to that of Q8 having a high capacitive value of ($295\mu F$). Also, the Q_{cap} of the capacitive load is more reactive tending towards the negative ($-5.8393MVAR$) than that of inductive load which is tending towards positive ($3.26MVAR$).
- The type of power factor correction used is AUTOMATIC POWER FACTOR CORRECTION.

9) The National Universities Commission (NUC) Complex in Abuja has a total load of 100kW. It is powered by a 415 V, three phase, 4 wire power supply. The power factor is 0.85lagging and NUC desires to avoid the payment of penalties for this poor power factor. What Should the facility manager advise NUC management to do? If an improved pf of 0.95 lagging is desired, determine the magnitude of the required Q and C.

Solution:

a) The facility manager should advice the NUC management to improve the power factor of the installations. If this is optimized, the payment penalties for low power factor will be reduced and at least 20% of the monthly electricity bill will be saved. Not only will that be saved, the rate of electricity consumption will also be lowered.

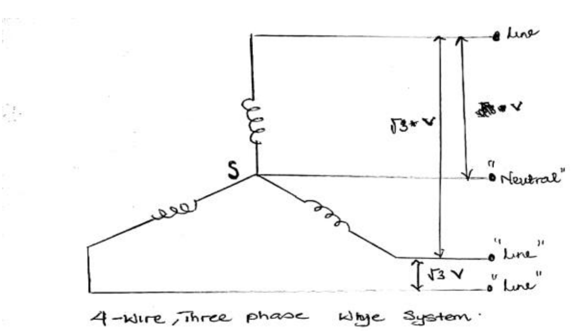
b) *Preamble:*

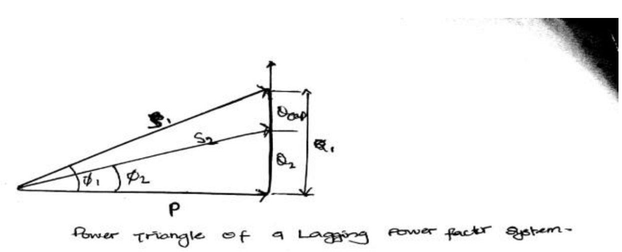
Real power (P) = 100kW
Voltage phase = 415V
Initial power factor=0.85 lagging
Improved power factor=0.95 lagging

Where; power factor=$cos\ \emptyset_1$

$$cos\ \emptyset_1 = 0.85$$
$$\emptyset_1 = cos^{-1} * 0.85$$
$$\emptyset_1 = 31.788^{\circ}$$

Diagrammatic representation





Where, P= 100KW

$$cos\,\emptyset_1 = \frac{100K}{S}$$

S=$0 \cdot 85 * 100 \times 10^3$

$S = 85KVA$

$$tan\,\emptyset_1 = \frac{Q}{P}$$

Q=$0.6197 * 100 \times 10^3$

$Q = 62KVAR.$

$NOTE$: when improving the power factor,

$\emptyset_1 > \emptyset_2$, $P_1 = P_{2,}$ $Q_1 > Q_2,$ $S_1 > S_2$

Therefore; where $P_1 = P_2$

Power factor=$cos\,\emptyset_2$

$$cos\,\emptyset_2 = 0.95$$

$$\emptyset_2 = cos^{-1} * 0.95$$

$$\emptyset_2 = 18.19^{\circ}$$

Where :

$$cos\,\emptyset_2 = \frac{P}{S_2}$$

S_2=$0 \cdot 95 * \ 100 * 10^3$ $S_2 = 95000VA$

$$tan\,\emptyset_2 = \frac{Q_2}{P}$$

Q_2=$\tan(18.19) * 100 * 10^3$

$Q_2 \ = 32868.4\,VAr.$

Where, $Q_1 = \ Q_{cap} + \ Q_2$

, $Q_{cap} = \ Q_1 - \ Q_2$

$$Q_{cap} = 61974.4 - 32868.4$$

$$Q_{cap} = 29106VAR = 29KVAr$$

Obtaining the value for C;

Recall: $C=\frac{Q_C}{V_{rms}^2 * 2\pi f}$

Note: standard frequency in Nigeria = 50Hz

$$C=\frac{29.1*10^3}{415^2*2\pi*50}$$

C=537.9*10^{-6} Farads ≈ $537.9\mu F$

10) Undertake a comparative analysis as an Electrical Power Management Consultant and use techno – economic facts and data to advice a client (Globacom Nigeria Ltd) requiring a 20kW induction motor to power its intended fruit juice factory from motor choices M_1 *and* M_2 given the following details:

Motor/parameters	M_1	M_2
kW	20	20
Phases	3	3
Line Voltage	415	415
pf	0.85	0.95
S	S_1	S_2
Q	Q_1	Q_2
PREVIOUS METER READING (kWhr)	23,000	
NEW METER READING (kWhr)	25,000	
kWhr charge	#55/kWhr	
Demand(kW) Charge	#35/kW	
Capacity (kVA) Charge	#70/kVA	
Reactive Power (kVAR) Charge	#25/kVAR	

Justify clearly your choice of recommended motor.

Solution:

As an Electrical Power Management Consultant, I would recommend Motor M_2.

Justifying this:

There is a wide range of barrier that affect the implementation of motor systems efficiency measures, including operating issues that affect decisions regarding allocation of resources. In other to power a fruit juice factory, an effective motor, as well an economic utilization of power supply is required. And for this, I have recommended M_2 for the following reasons:

1) **From the calculated values below, it can be deduced that (M_2) has a lower reactive power which will not only reduce the problems of low power factor, cables and windings of the motor insulation failure and direct tripping of the motor but also reduce the utility bill charged per reactive power (**this can be seen from the below calculations**).**

Given the details in the table above:

- Load 20kW at a PF of 0.85 (M_1):

The reactive power can be calculated as : Q=P tanØ

$$\emptyset = COS^{-1}0.85 \qquad \emptyset = 31.788$$

$$Q = 20*10^3 * \tan(31.79) \qquad Q_{0.85} = 12394.88 \text{ KVAr}$$

The cost of reactive power is given as : 12394.88*#25/kVAR = #309,872 .

- Load 20kW at a PF of 0.95 (M_2):

The reactive power can be calculated as: Q=P tanØ

$$\emptyset = COS^{-1}0.95 \qquad \emptyset = 18.19$$

$$Q_{0.95} = 20*10^3 * \tan(18.19)$$

$$Q_{0.95} = 6573.68.$$

The cost of reactive power is given as: 6573.68*#25/kVAR = #164,342.

2) The apparent power which is the most useful power has to be of low operating cost and reasonable consumption: knowing that the KVA is most considered when billing. It can be observed from the calculations that M_2 has a lower cost in apparent power than M_1.

Given the details in the table above:

- Load 20kW at a PF of 0.85 (M_1):

The Apparent power can be calculated as:

$s_{0.85}$= P/Cos (Ø)

$s_{0.85} = 20 * 10^3/0.85$

$s_{0.85}$= 23529.411 VA

The cost of Apparent power is given as: 23529.411* #70/kVA = #1,647,058.77

- Load 20kW at a PF of 0.85 (M_1):

The Apparent power can be calculated as:

$s_{0.95}$= P/Cos (Ø)

$s_{0.95} = 20 * 10^3/0.95$

$s_{0.95}$= 21052.63 VA

The cost of Apparent power is given as: 21052.63* #70/kVA = #1,473,684.1

3) Poor power factor means drawing more power from the electricity network to do the same amount of work. Therefore, the cables need to be larger and this will cost more money. Also, low power factor can cause losses in the motor parts, increase in heat gain and reduce the life span of the motor. So, M_2 with a high-power factor has been recommended to prevent the above issues.