International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 12, December-2016

Practical Approach to Power Factor Correction for a Commercial Electricity Consumer in Nigeria

Adesina Lambe Mutalub
Department of Engineering & Standardization,
Eko Electricity Distribution Plc (EKEDP)
Lagos – Nigeria

Ebere Iheanyichukwu
Department of Inspection and Quality Assurance,
Eko Electricity Distribution Plc (EKEDP)
Lagos – Nigeria

***Abstract*— Most loads in industrial or commercial facilities such as induction motors, welding machines, arc furnaces, fluorescent Lightings, electronic control devices and computers are highly inductive in nature. An aggregation of these loads causes a very poor lagging power factor. If this poor power factor is left uncorrected, the facility would not only place a high total power demand from the power utility but also reduce the overall power system's efficiency. Power Factor Correction (PFC) using capacitor banks has become the most widely employed technique in locally generating the high reactive energy demand on the system. The electrical distribution system in the Headquarters of a Commercial bank in Nigeria was selected as a case study in analyzing the economic importance of applying PFC. Measured data were obtained from the facility's energy meter for a 14-hour period in a day, before and after installing a 100 kVAr PFC capacitor bank. Improving the average power factor (PF) of the facility from 0.59 to 0.96 compensated the daily average kVAr demand of the facility by about 78.17%, thus reducing the average total power loading of the distribution transformer by 38%. The result obtained was then used to evaluate the total savings in energy cost made by the facility as a direct consequence of PFC. From this, the simple payback period on the customer's invested cost of installing the bank of capacitor by was calculated to be less than two months. Thus, proving that PFC is key to achieving a more technically and commercially efficient power system.**

Keywords*— Capacitor bank, Power Factor, Power Factor Correction, Inductive loads Introduction

I. INTRODUCTION

Electrical Power constitutes a major component of cost for domestic, commercial and industrial utilization. In industrial installations, power factor may become poor because of the infusion of more reactive power into the power system by inductive loads. Net industrial load is highly inductive causing very poor lagging power factor [1]. If this poor power factor, (PF) is left uncorrected, the industrial facility will require a high maximum demand from the electric power utility and also will suffer a stiff penalty for their poor power factor [1] from an economic perspective. Typical examples of such significant industrial inductive loads include power and distribution transformers, welding machines, motor drives, voltage regulators, incandescent lamps, arc furnaces, choke coils and ballast lightings.

Power factor correction/compensation (PFC) plays a major role towards the improvement of power system quality and efficient utilization of industrial power supply. In recent time, increasing attention has been paid to minimize the energy cost and inefficiency in electricity generation, transmission and distribution [2]. Power factor correction is a major issue for all industries, since a typical industrial load draws a lot of useful current from the power utility, as well as higher order harmonic currents. Power factor correction is often mandatory from the power companies, usually by charging the reactive power that the company consumes [3]. Consequently, power factor correction schemes are essential so that the net effect of these loads to the energy grid is mitigated.
Industrial Power factor is basically improved for obvious reasons that include;

Lower utility fees by Reducing peak kW billing demand and power factor penalty. Since inductive loads require reactive power for operation, the resultant increase in required reactive power (kVAr) causes an increase in required apparent power (KVA), which is what the utility supplies. So, the facility's low power factor causes the utility to increase its generation and transmission capacity in order to handle this extra demand for power. Power companies require their customers, especially those with large loads, to maintain their power factors above a specified value (usually 0.90 or higher) or be subject to additional charges [1]. Electrical engineers involved with power generation, transmission and distribution usually put the power factor of loads into serious consideration because of its effect on the efficiencies and costs for both the electrical power industry and the consumers [4] [5].
Also, increased system capacity, increased voltage levels and reduced system losses in the power system are achieved by addition of capacitors (kVAr generators) to the system.

II. PROBLEM STATEMENT

A large chunk of industrial and commercial facilities loads have pre-installed reactive power compensators built in by the Original Equipment Manufacturers (OEM) in order to minimize the reactive power expended by the load, ergo, increasing the power factor of the unit. However, the level of integration of such technologies in small and medium enterprises (SMEs) is not satisfactory [3]. This is mainly due to the fact that purchasing such equipment is not

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 12, December-2016

expected to have a justifiable economic payback for enterprises of this size [3]. In order words, before an appropriate power factor correction topology is adopted, consideration must be given to the payback period of implementing a particular PFC technique.

Thus, a low budget solution needs to be implemented. It is preferable for these industries to have the utility companies implement a more economically viable and suitable three-phase power factor correction topology for industrial applications. The criteria used for the evaluation are mainly with regards to cost (₦/kWh), efficiency, and power density (kg/kW) [3].

On the other hand, it is worthy of note that utilities also suffer technical and non-technical power losses as a result of the negative implication of low power factors. These Non-technical losses are incurred by actions external to the utility's power system. Notable among them are electricity theft through illegal connections to the grid, non-payment of energy used by the customers, use of substandard current transformers for industrial metering and industrial usage of electricity on low power factor amounting to undercharging and hence under billing by the utility company [6]. Thus, it is very important for the utility to effectively and accurately measure the total power consumed by industrial customers, particularly those with average power factors lower than the limit tolerable by the utility.

Power factor is defined simply as the ratio of the real or active power, P (in kW) used in doing the actual work to the magnitude of the apparent (complex) power, |S| (in kVA) as shown in equation (1):

$$PF = \frac{P(kW)}{|S|(kVA)} \quad (1)$$

For sinusoidal currents, the PF is the absolute value of the cosine of the apparent power phase angle, φ as shown in equation 2:

$$PF = |cos\varphi| \quad (2)$$

from equations (1) and (2), the real power,

$$P = |S| \times |cos\varphi| \quad (3)$$

The reactive power, Q (in volt-amps reactive, VAr) is defined in equation (4) as:

$$P = |S| \times |sin\varphi| \quad (4)$$

equations (3) and (4) are derived from the power angle shown in figure (1):

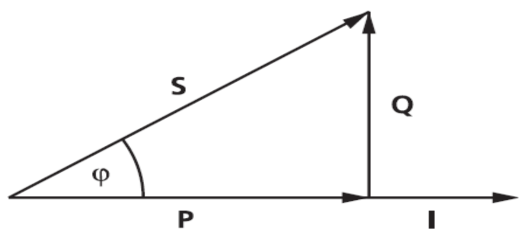

Figure 1: Power Triangle before PFC

From figure 1, it is obvious that the apparent power is given by the vector addition of active power and reactive power as shown in equation (5):

$$S = \sqrt{P^2 + Q^2} \quad (5)$$

The PF for a three-phase circuit, is given in equation 6 as:

$$PF = |cos\varphi| = \frac{P}{\sqrt{3}\times V\times I} \quad (6)$$

where,

P = Real power meter reading (kW),
V = Line-to-Line voltage (V)
I = Current (A)

Connected equipment (transformers, motors, etc.) cause a phase angle between current and voltage [7]. When the current is phase shifted, it takes more current to deliver the same amount of active power [8]. Figure (2) shows that all the reactive power Q_1 required by the motor in a facility was supplied entirely by the utility company. This results in an undesirably high apparent power, S_1 because both the active and reactive power is supplied by the utility.

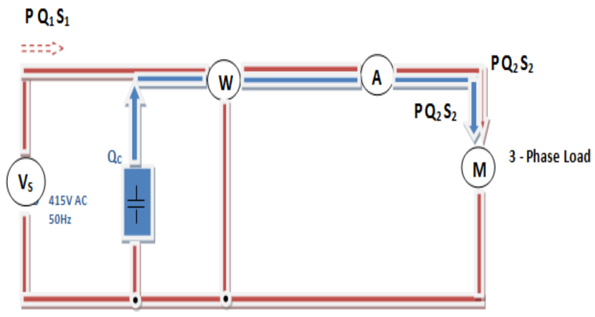

Figure 2: Line Diagram illustrating Parallel Connection of Capacitor Bank in a facility

Connecting a capacitor bank (in parallel), with the correcting reactive power Q_c, before the load means that the motor need not draw the required reactive power from the utility. Rather, it draws the only the difference [7] shown in equation (7). Therefore, a low demand of reactive power by the facility translates into a low consumption of apparent power from the utility [7].

$$Q_2 = Q_1 - Q_C \quad (7)$$

where,

Q_1 = Reactive power before correction
Q_c = Correcting reactive power from PFC capacitor bank
Q_2 = Reactive power after correction

Figure (3) shows the power triangle highlighting the effect of correction:

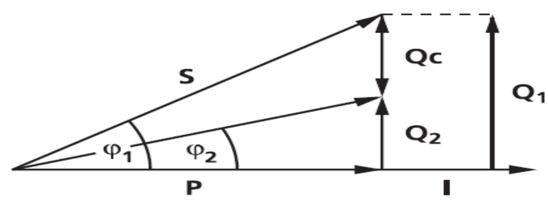

Figure 3: Power Triangle post-PFC

In terms of the capacitive reactance of the capacitor bank, the reactive power is given in equation (8) as:

$$Q_C = \frac{V^2}{X_c} = V^2 \Big/ \frac{1}{2\pi f C} = 2\pi f C V^2 \quad (8)$$

where,

Q = Reactive power of Capacitor bank
V = Mains supply voltage in Volts
X_c = Capacitive reactance in Ohms
f = System supply frequency in Hertz
C = Capacitance of the capacitor in Farads

III. PRACTICAL IMPLEMENTATION OF PFC FOR A SELECTED COMMERCIAL CUSTOMER

This research paper analyses a real life scenario, where an attempt was made to remedy the problem of low power factor and consequent dip in supply voltage, recorded by the energy meter at the headquarters of a commercial bank located in Lagos state, Nigeria. The facility is supplied with electric power from the utility - Eko Electricity Distribution Company's (EKEDC), via a 1MVA, 11/0.415 kV distribution transformer, with a voltage transformation ratio given in equation (9) feeding a Main Low Tension Board (MLTB). The maximum power demand of the facility stands at 0.7MVA.

$$k = 11/0.415 = 26.51 \quad (9)$$

The Current Transformer (CT) rating and Voltage Transformer (VT) rating installed in the power system of the facility are 50/5A and 11/0.11kV respectively. Thus, the Nominal current Ratio of the CT, $N_I = 50/5 = 10$, while that of the VT $N_V = 11/0.11 = 100$

The primary currents read by the installed energy meter for the Red (R), Yellow (Y) and Blue (B) phases are presented in Table 1. The individual primary line voltages R-Y, Y-B and B-R are also presented on the same table. These values were obtained by multiplying the average primary current and voltage components by their corresponding nominal ratios.

For the purpose of analysing the actual energy consumed by the facility, the average primary line current and voltage components are converted to their average secondary phase equivalents as follows:

For the average secondary phase current,

$$I_{Ave} = \frac{I_R + I_Y + I_B}{3} \times N_I \quad (10a)$$

and

$$I_{s=} I_{Ave} \times k \quad (10b)$$

where,

I_{Ave} = Average Primary Line Current

k = Voltage Transformation Ratio

I_R = Primary Red Phase Current

I_Y = Primary Yellow Phase Current

I_B = Primary Blue Phase Current

I_s = Average Secondary Phase Current

For the average secondary phase voltage,

$$V_{Ave} = \frac{(V_{R-Y} + V_{Y-B} + V_{B-R})}{3} \times \sqrt{3} \times N_V \quad (11a)$$

and,

$$V_{s=} \frac{V_{Ave}}{k} \quad (11b)$$

where,

V_{Ave} = Average Primary Line Voltage

k = Voltage Transformation Ratio of the transformer

V_{R-Y}, V_{Y-B} and V_{B-R} = Primary line (or phase-to-phase) Voltages

V_s = Average Secondary Phase Current

The load profile of the facility which was read from the installed energy meter are also presented in Table 1. It shows that the daily average power demand of the facility is 27.87 kVA, at a daily average power factor of 0.59. With this average power demand of 27.87 kVA, a higher rated capacitor bank is required to be selected. To this end, a 100 kVAr capacitor bank was selected to be installed at the MLTB bus to compensate for this extremely low power factor. This improved the average power factor to 0.96. The system harmonics, over voltages and the possibility of load expansion in the facility was also given due consideration in choosing the capacitor bank rating to install. The Real Power (P), Apparent power (S), Reactive Power (Q), Supply Voltage and Current values were evaluated using equations (9) to (11) for the period 10:00am to 12:00am.

After installing the capacitor bank at the MLTB, the Voltage, Current and Power meter readings obtained are presented in Table 2.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 12, December-2016

TABLE I METER READINGS BEFORE PFC (2/9/2016)

End of Period	I_R (A)	I_Y (A)	I_B (A)	I_{Ave} (A)	I_S (A)	V_{R-Y} (V)	V_{Y-B} (V)	V_{B-R} (V)	V_{Ave} (kV)	V_S (V)	PF	S (kVA)	P (kW)	Q (kVAr)
10:00 AM	0.10	0.11	0.12	1.07	28.34	61.20	61.70	61.50	10.65	401.58	0.51	19.71	9.97	17.00
10:30 AM	0.16	0.14	0.15	1.51	40.03	61.30	61.90	61.60	10.67	402.61	0.71	27.91	19.73	19.74
11:00 AM	0.18	0.18	0.16	1.72	45.60	60.30	60.90	60.60	10.50	396.07	0.75	31.28	23.44	20.71
11:30 AM	0.17	0.17	0.17	1.70	45.07	60.00	60.50	60.20	10.43	393.53	0.80	30.72	24.52	18.51
12:00 PM	0.17	0.17	0.17	1.68	44.54	60.00	60.60	60.20	10.44	393.75	0.81	30.38	24.54	17.90
12:30 PM	0.17	0.18	0.17	1.72	45.60	60.00	60.60	60.30	10.44	393.96	0.78	31.11	24.23	19.52
1:00 PM	0.17	0.16	0.17	1.68	45.54	60.20	60.90	60.50	10.48	395.49	0.77	31.19	23.97	19.96
1:30 PM	0.15	0.15	0.16	1.52	40.30	60.00	60.60	60.30	10.44	393.96	0.72	27.50	19.81	19.08
2:00 PM	0.13	0.13	0.13	1.30	34.46	60.20	60.90	60.50	10.48	395.49	0.64	23.60	15.18	18.07
2:30 PM	0.16	0.13	0.16	1.48	39.23	60.50	61.10	60.60	10.52	396.79	0.69	26.96	18.57	19.54
2:39 PM	0.19	0.16	0.19	1.80	47.72	60.30	60.90	60.50	10.49	395.71	0.79	32.71	25.79	20.12
6:00 PM	0.15	0.14	0.17	1.52	40.30	63.10	63.60	63.20	10.96	413.56	0.34	28.87	9.76	27.17
6:30 PM	0.10	0.11	0.13	1.13	29.96	62.60	63.20	62.90	10.89	410.95	0.30	21.32	6.45	20.32
6:54 PM	0.09	0.11	0.13	1.06	28.10	62.10	62.80	62.40	10.81	407.90	0.32	19.85	6.30	18.82
11:30 PM	0.14	0.16	0.17	1.57	41.62	65.00	65.90	65.50	11.34	427.72	0.22	30.83	6.87	30.05
12:00 AM	0.15	0.16	0.18	1.63	43.21	65.00	65.90	65.40	11.33	427.50	0.22	32.00	6.96	31.24

TABLE II METER READINGS AFTER PFC (5/10/2016)

End of Period	I_{Ave} (A)	I_S (A)	V_{Ave} (kV)	V_S (V)	PF	S (kVA)	P (kW)	Q (kVAr)
10:00 AM	0.57	15.03	10.65	401.56	0.95	10.45	9.97	3.13
10:30 AM	1.11	29.42	10.66	401.97	0.96	20.49	19.73	5.52
11:00 AM	1.33	35.36	10.57	398.75	0.96	24.42	23.44	6.84
11:30 AM	1.39	36.89	10.43	393.56	0.98	25.15	24.52	5.59
12:00 PM	1.40	36.99	10.44	393.75	0.97	25.23	24.54	5.82
12:30 PM	1.38	36.52	10.45	394.01	0.97	24.92	24.23	5.86
1:00 PM	1.36	36.04	10.48	395.46	0.97	24.69	23.97	5.90
1:30 PM	1.13	29.98	10.45	394.01	0.97	20.46	19.81	5.13
2:00 PM	0.88	23.26	10.48	395.47	0.95	15.93	15.18	4.83
2:30 PM	1.06	28.17	10.55	397.77	0.96	19.41	18.57	5.63
2:39 PM	1.47	38.91	10.47	394.93	0.97	26.61	25.79	6.58
6:00 PM	0.55	14.44	10.97	413.67	0.94	10.34	9.76	3.41
6:30 PM	0.36	9.62	10.89	410.95	0.94	6.85	6.45	2.30
6:54 PM	0.36	9.45	10.82	408.00	0.94	6.68	6.30	2.22
11:30 PM	0.37	9.91	11.27	425.14	0.94	7.30	6.87	2.45
12:00 AM	0.38	10.04	11.27	425.14	0.94	7.39	6.96	2.50

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 12, December-2016

IV. ECONOMIC BENEFITS OF POWER FACTOR CORECTION

One of the direct implications of improving the PF of a power system is that it increases the scalability of the system, thus permitting more load to be added to the system in an economically efficient way. In order words, the probability of the transformer to become overloaded is greatly reduced. From the results generated, improving the PF from 0.59 to 0.96 decreased the total power demand on the facility to 427.45 kVA. This is estimated using equation (12) as follows:

$$\frac{S_{final}}{S_{initial}} = \frac{PF_{initial}}{PF_{final}} \quad (12a)$$

so that,

$$S_{final} = \frac{PF_{initial}}{PF_{final}} \times S_{initial} \quad (12b)$$

where,

S_{final} = kVA demand after PFC

$S_{initial}$ = kVA demand before PFC

PF_{final} = Power Factor after PFC

$PF_{initial}$ = Power Factor before PFC

Therefore,

$$S_{final} = \frac{0.585}{0.958} \times 700 = 427.45\ kVA$$

Thus, the capacity of the installed 1 MVA transformer, with a maximum power demand of 0.7 MVA, is improved by 38.94%, which is equivalent to a kVA release of 272.55 kVA.

The savings in energy made by the customer as a result of applying PFC is calculated as follows;

The unit cost of electricity that EKEDC charges the facility is approximately 36 NGN per kWh at a power factor of 0.85.

The facility consumes its initial maximum energy demand of 700 kVA (or 595kW) supplied by EKEDC, 14 hours per day for 30 days. Therefore,

$$\text{Total Monthly Cost of Energy} = 595 \times 30 \times 14 \times 36$$

$$= 8{,}996{,}400\ NGN$$

After power factor correction,

$$\text{Total Monthly Cost of Energy} = 427.45 \times 0.85 \times 30 \times 14 \times 36 = 5{,}493{,}587.40\ NGN$$

The total savings in cost per month due to released kVA after PFC = $272.55 \times 0.85 \times 30 \times 14 \times 36$

$$= 3{,}502{,}812.60\ NGN.$$

This result can be verified by calculating the difference between the total monthly cost of energy before and after PFC as shown in equation (13);

$$\text{Total savings in monthly energy cost} = \text{Energy cost before PFC} - \text{Energy cost after PFC} \quad (13)$$

$$= 8{,}996{,}400 - 5{,}493{,}587.40$$

$$= 3{,}502{,}812.60\ NGN.$$

If the total investment cost for the installation of 100 kVAr capacitor bank is estimated at 4,500,000 NGN, then the simple payback period is calculated using equation (14);

$$\text{Simple payback period (in months)} = \frac{\text{Total Investment Cost}}{\text{Total Savings in Cost}} \quad (14)$$

$$= \frac{4500000}{3502812.60} = 1.28\ months$$

Therefore, the payback period of this investment is just about 38 days.

V. DISCUSSION OF RESULTS

Tables 1 and 2 shows that improving the average daily power factor by 63.76% compensated the consumed average reactive power in the facility by 78.17%, since the average Q consumed before and after installing the capacitor bank are 21.110 kVAr and 4.607 kVAr respectively. Consequently, the average total power loading on the transformer was reduced by 38%, which indicates a fall from 27.871 kVA to 17.269 kVA before and after performing PFC respectively.

The addition of the PFC capacitor also showed a ripple effect in terms of reduction of I^2R losses in the overall system resulting from a sharp decline in the average daily current flowing through the distribution system. Thus, with a reduction in current consumption, these losses were reduced by 37.46% since the currents before and after implementing PFC were 39.976 A and 25 A respectively. In addition, there will be a considerable reduction in the heating effect of high currents on the cables and switchgear [9]; hence, an improvement in their aggregate reliability.

The currents and PF data illustrated in Tables 1 and 2 also prove that the supply current at any point in time is inversely proportional to the power factor of the entire system.

Moreover, the calculated payback period of the investment signifies good project liquidity [10], since the calculated value shows that the original investment is expected to be recouped in less than two months.

VI. CONCLUSION AND RECOMMENDATIONS

Low power factor in a power system is a highly undesirable condition as it places an unnecessarily high current demand, thus high active power losses are incurred in the system. Distribution losses in any power system can be scaled down to the barest minimum by simply boosting the power factor by adding capacitors. Unwanted reactive current generated by inductive loads circulates between the utility company's generator and the consumer units, converting electrical energy into heat energy in the power distribution system. The resultant effect of this condition is that cables, switchgears and transformers become unnecessarily overloaded, while Energy (or I^2R) losses are incurred.

From the utility's view point, poor power factors in industrial or commercial facilities increase the cost of power supply to the consumers. It is recommended for utility companies in Nigeria to impose stiff low power factor taxes on the responsible customers. This will help protect the utilities from bearing all the cost of additional technical power loses incurred. Therefore, it is also recommended that an energy meter suited for recording reactive energy alone should be installed alongside that for recording the active energy.

Finally, from the standpoint of industrial and commercial customers, it is advisable to explore other PFC techniques, such as installing synchronous alternators, synchronous compensators and static VAr compensators, while giving due consideration to the relative cost and ease of installation of the chosen technique.

REFERENCES

[1] K. Tiwari, D. Sharma and V. Sharma, "Automatic Power Factor Correction Using Capacitor Bank" International Journal of Engineering Research and Appications, vol. 4, issue 2, February 2014, pp. 393-395.

[2] J. Karatzaferis, N. Papanikplaou, E. Tatakis, M. Loupis and J. Spanoudakis, "Comparison and Evaluation of Power Factor Correction Topologies for Industrial Applications", Journal of Energy and Power Engineering, vol. 5, no. 6, August 2013, pp. 401-410.

[3] Omeish, T. and Omeish, F. "Effect of Low power Factor in Libyan Electrical Distribution System". International Conference on Electrical Distribution CIRED, May 2013.

[4] H. Keith, "Power System Commissioning and Maintenance Practice" Institution of Engineering and Technology, UK., December 1998.

[5] J. C. Stephen, "Electrical Machinery and Power System Fundamentals" 3rd ed. USA: McGraw Hill Compaies inc, 1999.

[6] L.M. Adesina and A. Ademola "Determination of Power System Losses in Nigerian Electricity Distribution Networks" International Journal of Engineering and Technology, vol. 6, no. 9, September 2016, pp. 322-326.

[7] A. A. Osam and , K.A. Ahmad, "Impact of Power Factor Correction on the Electrical Distribution Network of Kuwait – A Case Study" The Online Journal of Power and Energy (OJPEE), vol. 2, no. 1, pp. 173-176.

[8] T. Miller, "Reactive Power Control in Electrical Systems" John Wiley & Sons, 1982.

[9] B. Samarjit, A. Choudhury and H. Jariwala, "Case Study on Power factor Improvement" International Journal of Engineering Science and Technlogy, vol. 3, no. 12, December. 2011, pp. 8372-8378.

[10] S.O. Tze and H.T. Chan, "Net Present Value and Payback Period for Building Integrated Photovoltaic Projects in Nigeria" International Journal of Academic Research in Business and Social Sciences, vol. 3, no. 2, February 2013, pp. 153-171.