BOOK CHAPTER | Requirement Enginering & Management
dx.doi.org/10.22624/AIMS/REBK2022-P5

Modelling of Power Factor Correction as Contingency to Energy Saving in Nigeria Power Systems: A Case Study

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ABSTRACT

The Nigeria power system has been undergoing several policy changes over the years in order to improve the power system and also to ensure increase in capacity and efficient electricity supply to Nigerians. However, these laudable goals are yet to be achieved and the small megawatts that Nigeria power sector generates are wasted by high reactive loads in many industrial sectors today by operating on low power factor. The aim of this research paper is to demonstrate the impact of power factor correction on energy saving in Nigeria power system. It was realised by installing power factor correction device (PFCD) in some selected consumer's premises and field measurement was carried out before and after the PFCD installation. Data were recorded during the operating hours of the selected factory site. Conclusively, it was shown that the power factor of the selected factory site was improved from 0.7 to 0.97, thereby increasing the kVA capacity of the electricity supplying transformer by 27.84%. The analyses of the results showed that the PFC device have the ability to reduce the system losses, improve the capacity and the efficiency of the system without installing additional cables and transformers, thereby saving energy for the system.

Keywords: Modelling, Power Factor Correction, Contingency , Energy Saving in Nigeria

Introduction

The electricity supply in Nigeria power system has been epileptic for the past decades, before the power reform embarked upon by the Nigeria government which aimed at improving the total megawatts of electricity generated, transmitted and distributed to Nigerians.

The Electric Power Sector Reform Act of 2005 was geared toward improving the energy sector of Nigeria. This Reform brought about the increase in megawatts production from 1500 MW to 3500 MW. In recent time the megawatt generated in Nigeria has greatly improve to 4500 MW as at December 2012, which is far below the megawatts needed by Nigerians population of over 162.5million people [1]. Despite this low production of megawatt in Nigeria power system, it is been wasted by low power factor devices used by power consumers' in Nigeria both at homes and industries. In practice, low power factor is often caused by inductive load [2].

The loads may include equipment such as induction motors, inductor operated discharge lamps, variable speed drives, electric furnaces, electric welding machines, rectifier loads and miscellaneous installations, such as electric shovel and rolling mills etc. [2]. The induction motors are widely used in industry and agriculture and they constitute a major part of load in power system [3]. The overall power factor of a system is likely below 0.7 lagging, unless corrective measures are taken to improve it [3].

The operation of power systems at low power factor is highly uneconomical to electric power consumer's and as well as the suppliers (utility companies). Hence, the impact of energy saving through appropriate power factor correction in the consumer's premises and supplier’s lines cannot be overemphasis at this era of Nigerians quest for stable power supply.

Effect of Low Power Factor

The effect of low power factor of a system is enormous on the consumers' and the power system capacity. Hence, its occurrence needs to be check for appropriate action.

The effect of low power factor on systems is listed below:

a. It increases the kVAR (Reactive Component) of the system
b. It increases the current draw from the system by consumers' devices
c. I^2R power losses are increase in the system because of increase in current draw from
the system
d. The voltage level at the load level end or consumers' is reduced
e. The kVA loading on the source of supplies generators, transformers and also on the lines are increase thereby reducing the capacity of the system etc.

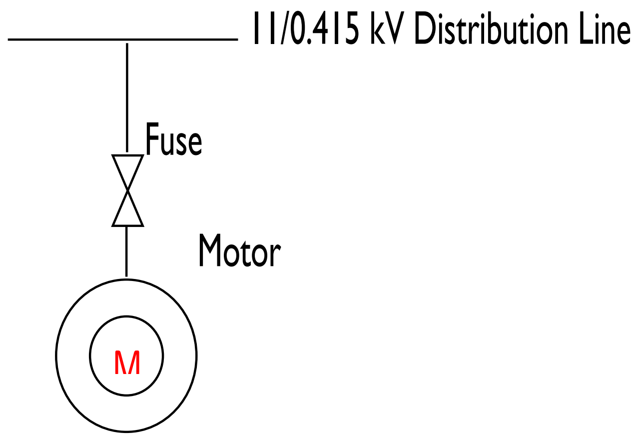


Fig.1: Single Motor without PFCD

The effect is that the capacity and the efficiency of system is greatly reduced and with great losses accompany the system when it is operated on low power factor. The Figure 1, below show a single motor operating on low power factor.

Methods of Power Factor Correction

The general method of improving the overall power factor of an installation is to connect a load having a leading power factor in parallel with the load having lagging power factor [2].

In this way although each load operates at its own power factor, but the overall power factor of the combined load is improved [2]. But in case of transmission lines the power factor correction is by connecting a leading power factor device (Capacitor) in series with the line.

The various devices that can be employ for power factor correction are generator excitation control, synchronous motor running over excited, synchronous compensator, and capacitor.
The most common methods employed to improve power factor correction are:

Single or Fixed Power Factor Correction Method: This is when compensating for reactive power of individual inductive loads at the point of connection thereby reducing the load in the connecting cable (typical for single, permanently operated loads with constant power) [4]. In this method of installations, capacitors are installed parallel to the equipment and they are controlled by a common switch, this is generally suited for high output induction motors, furnaces, and transformers [5].

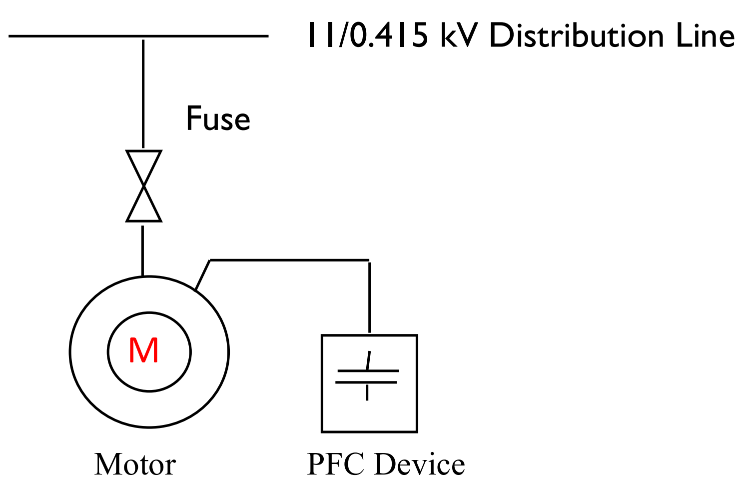


Fig.2: Single Compensation

Group Power Factor Correction Method

This method is when you connect one capacitor to a group of simultaneously operated inductive loads (e.g. group of motors, discharge lamps) [4]. This is particularly useful when small loads are connected to a common bus bar [5].

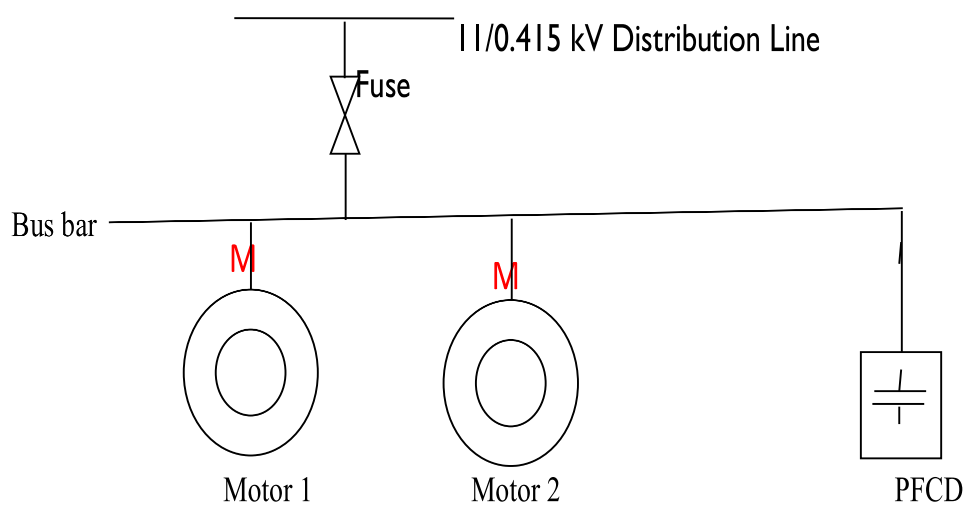


Figure 3: Group Compensation

Bulk Power Factor Correction Method

The bulk power factor correction method is typical for large electrical systems with fluctuating load where it is common to connect a number of capacitors to a main power distribution or substation [4].

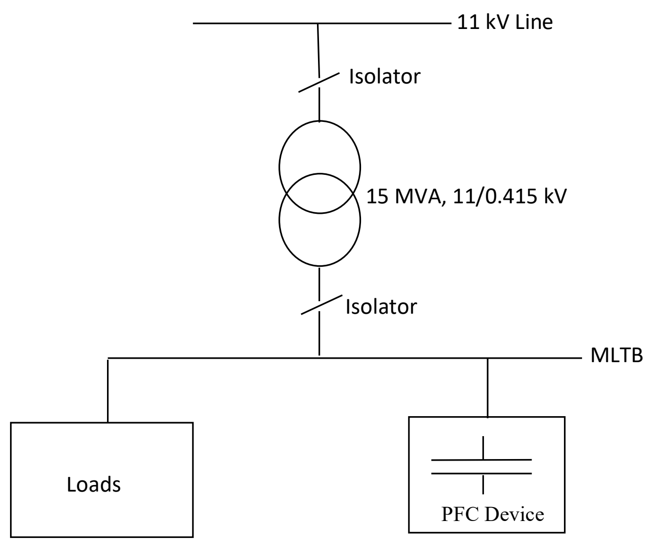


Figure 4: Bulk Compensation

The capacitors are controlled by a microprocessor-based relay which continuously monitors the reactive power demand on the supply [4]. The relay connects or disconnects the capacitor to compensate for reactive power of the total load and to reduce overall demand on the supply [4]. A typical power factor correction system would incorporate a number of capacitor sections determined by the characteristic and the reactive power requirements of the installation under consideration [4]. Section of 12.5 kvar, 25 kvar and 50 kvar are usually employed [4].

Large stages (e.g. 100kvar and above) are achieved by cascading a number of smaller sections [4]. This has the beneficial effect of reducing fluctuations in the mains caused by the inrush currents to the capacitors and minimises supply disturbances [4]. Where harmonies distortion is of concern, appropriate systems are supplied, incorporating detuning reactors [4].

Location of Power Factor Correction Device

The location and positioning of power factor correction device (PFCD) should be place as close as possible to the load end (i.e. the PFC device should be place closer to the lagging power factor equipment). With appropriate calculation of the PFC device rating, the leading power that will be supplied by the PFCD should be able to cancel the lagging power of the system to a desired value. Hence, the closer the PFCD to the load better the power factor correction by the PFC device in the system.

Figure2 and Figure3, shows the diagrams of PFCD connected the lagging or low power factor device (motors) and Figure 4, also show PFCD connected to the main low tension Board (MLTB) of a consumers' premises to better the power factor of the consumer's installation in order to reduce the total power or apparent power consume by the consumer's. The location of the capacitors will have an impact on system resonance. If a resonant condition is expected or does occur, simply moving the capacitor bank can change the effective impedance seen by the nonlinear load. Carefully applied, this approach can change the resonant frequency to a frequency that is not presenting the load current.

Economical Limit of Power Factor Correction

In power factor correction it's important to save cost and energy but exceeding the limit of correction it become expensive to acquire the PFC device as compare to the cost of energy and electric bill been save. Hence, it's important to know the economical limit of power factor correction for a particular system. The power factor correction by engineers, it should be noted that is not necessary to convert a lagging power factor to unity.

This is because the cost of power factor improvement beyond certain limit or value may outweigh the cost of the energy been save or tariff saving that could be made. Therefore, the need for economical limit of power factor correction [2]. Note that when designing a compensation scheme, one should attempt to achieve the most economical solution in which the saving achieved in the equipment cost is significantly greater than the procurement cost of the reactive power [6].

The amount of power factor correction that would be necessary to reduce energy waste to minimum level is formulated below;

Amount of PFC Required = $kVA_1 - kVA_2$ (1)

Capacitor Rating Required ($kVAR_C$) = $kVAR_1 - kVAR_2$ (2)

Since, $kVAR_1 = kW\tan\varphi_1$ (3)

and

$kVAR_2 = KW\tan\varphi_c$ (4)

$kVAR_C = KW\tan\varphi_1 - kW\tan\varphi_c = kW(\tan\varphi_1 - \tan\varphi_c)$ (5)

$kVAR_C$ is the leading kVAR supplied by the PFC device

kVA maximum demand = $kVA_1 - kVA2$ (6)

$KVA_{max} = KVA_1 - KVA2 = \left(\frac{KW}{\cos\phi 1} - \frac{KW}{\cos\phi c}\right)$ (7)

Where: kVA is the apparent power, kW is the active power and kVAR is the reactive power

Let the charge per kVA_{max} be X_{naira}, the energy saving or cost electricity bill saving per annual =

$X\left(\frac{KW}{\cos\phi 1} - \frac{KW}{\cos\phi c}\right)$ (8)

Assuming the cost of PFC device per kVA is Z_{naira} and the rate of interest and depreciation is Q per year.

Then, the cost per annum is = $\frac{ZQ}{100}(kWtan\phi 1 - kWtan\phi c)$ (9)

The total yearly energy saving =

$X\left(\frac{KW}{cos\phi 1} - \frac{KW}{cos\phi c}\right) - \frac{ZQ}{100}(KWtan\phi 1 - Kwtan\phi c)$ (10)

The total yearly energy save is maximum when $dE/d\varphi_c = 0$ (11)

$dE/d\varphi_c = d/d\varphi_c[X\left(\frac{KW}{cos\phi 1} - \frac{KW}{cos\phi c}\right) - \frac{ZQ}{100}(KWtan\phi 1 - KWtan\phi c)]=0$ (12)

$-XKWSec\varphi_c tan\varphi_c + \frac{ZQ}{100}KWSec^2\varphi_c = 0$ (13)

Using trigonometric identities

$sin\varphi_c = \frac{ZQ}{100X}$ (14)

From the above expression, φ_c and $cos\varphi_c$ can be determined.

Recall; $sin^2\varphi_c + cos^2\varphi_c = 1$ (15)

Thus, the most economical power factor correction is cosφc =

$\sqrt{1 - sin^2\phi c}$ (16)

From equation (14), $cos\varphi c = \sqrt{1 - sin^2\phi c} = \sqrt{1 - (\frac{ZQ}{100X})^2}$ (17)

Hence, the economical power factor correction (PFC) for a particular system is given as

$$\cos\varphi_c = \sqrt{1 \quad \left(\frac{ZQ}{100X}\right)^2} \tag{18}$$

Note that; Z is the cost of PFC device per KVA
Q is the rate of interest and depreciation per year
X is the charge per KVA maximum demand

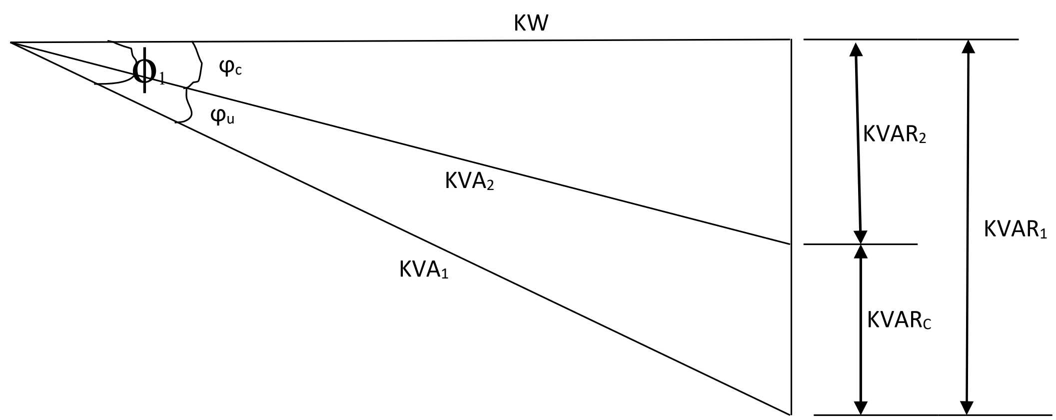


Figure.5: PFC Value Requirement Triangle

Selection and Calculation of PFC Device Required Power (kVAR)

Knowing the right power rating of the PFC device is paramount to the designer or power factor correction engineer. There are different ratings of PFC device that are available in the market today, selecting the accurate power rating from the power calculation of PFC devices will mitigate against harmonies that will be produce in the system.

The amount of reactive power consume by motors depends largely on various factors (parameters), such as:

a. The power rating of the motor
b. Loading capacity of the motor
c. The rated speed of the motor
d. The motor designs

Hence, the choice of capacitor output should be maximized (say 90% of the apparent power of asynchronous motor under no load conditions). It is paramount to note this because to avoid dangerous self-excitation of the motor.

The required power calculation of the PFC device can be obtained by knowing the reactive power which is necessary to achieve a desire power factor correction (PFC) in that particular system. To do this the following show how to calculate PFC device reactive power.

$$KVAR_C = KW\tan\varphi_I - KW\tan\varphi_c = KW\,(\tan\varphi_I - \tan\varphi_c) \quad (19)$$

The required reactive power is gotten from equation (19), which is the targeted power for the system improvement. The original or old power factor can be estimated from the following empirical formula.

$$\cos\varphi_I = \frac{1}{1+\left(\frac{W_R}{W_A}\right)^2} \quad (20)$$

Where: W_R is the reactive energy consumed
W_A is the active energy consumed

Case Study

A Grinding Mill Factory was selected as a case study for this research work. The grinding mill is supply by a 33/11 kV injection substation through a power transformer of 500 kVA, 11/0.415 kV, three phases. The transformer is feeding the Main Low Tension Board (MLTB) of the mill factory through a Switchgear and Electric Meter (Watt-Meter). The maximum energy needed by the mill factory as recorded by the Watt-Meter is 266 kW (Active or Working Power). The grinding machines operate at 0.7 power factor, the maximum apparent power consumed by the grinding mill machines amount to 380 kVA when the measurement was carried out.

In the research work, measurement was carried out for certain numerated time to determine the Active, Reactive and Apparent power, Current and the power factor at that time of measurement. The various times were selected during the operation of the Grinding Mill Factory as shown in Table2 and Table3 below. A 125 kVAR Capacitors Bank was installed at MLTB of the Grinding Mill Factory to increase the power factor state.

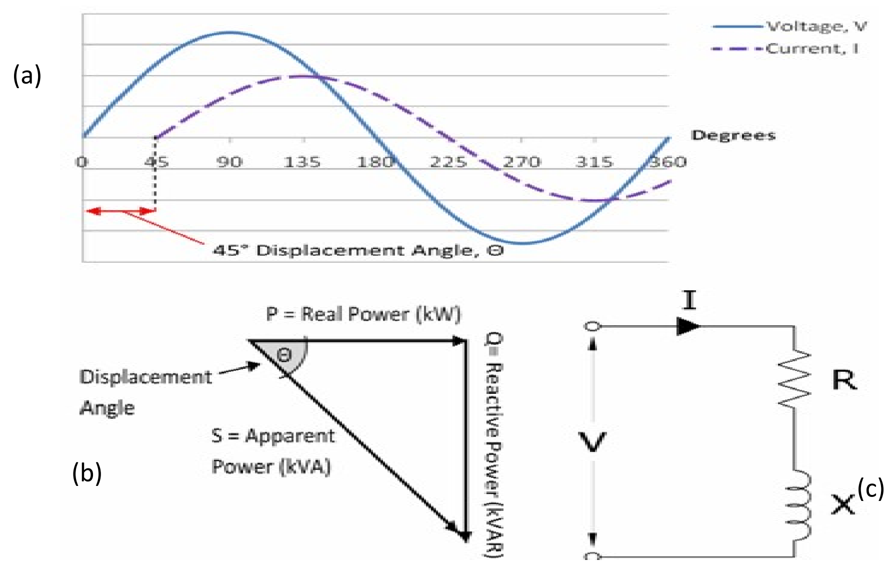
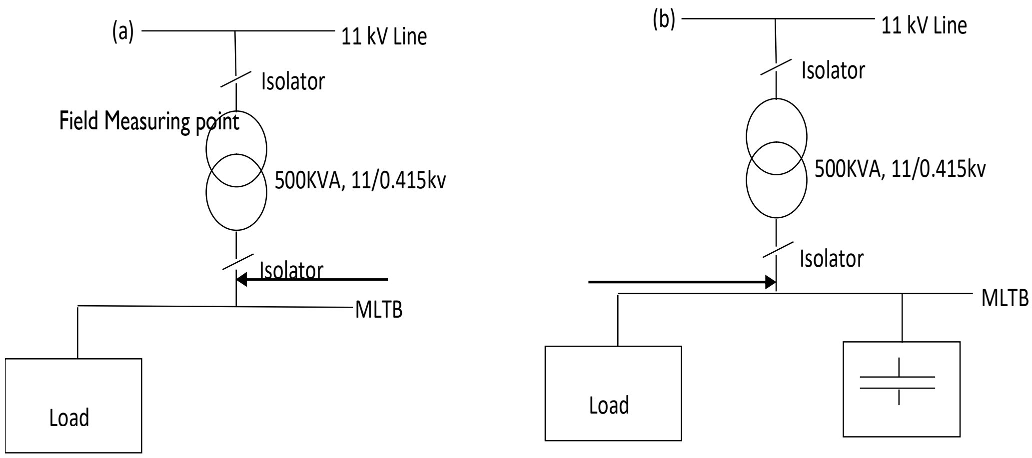


Figure 6: The general circuit of the system under study

Where: (a) The sine graph of voltage and current, (b) Power Triangle, and (c) System Circuit



(a) System Without Compensation (PFCD) (b) System with Compensation (PFCD)

Figure 7: The general schematic diagram of the system under study.

Below shows the values of active power, apparent power, reactive power, currents and power factors measure from the system under study.

Table 1: Measurement without PFC Device

Time (Hours)	**PF (cosφ)**	**P (kW)**	**Q (kVAr)**	**S (kVA)**	**I (Ampere)**
7:00	0.70	56	57	80	112
9:00	0.72	77	74	107	149
11:00	0.74	92	83	124	173
13:00	0.71	86	85	121	169
15:00	0.71	86	85	121	169
17:00	0.75	88	77	117	163
19:00	0.74	84	76	113	158

Table 2: Measurement with PFC Device

Time (Hours)	PF (cosφ)	P (KW)	Q (KVAR)	S (KVA)	I (Ampere)
7:00	0.97	56	16	58	81
9:00	0.98	77	18	79	110
11:00	0.97	92	24	95	133
13:00	0.98	86	19	88	123
15:00	0.96	86	27	90	126
17:00	0.98	88	19	90	126
19:00	0.97	84	23	87	122

Graphical Analysis of Results

The results from the field measurement were tabulated as shown in Table 1 and 2 above and the results were graphically analysed as shown from Figure 8 to Figure 13. From Figure 8, it is seen that the Capacitor compensated 72.73% of the total reactive power consumed by the system, since the average reactive power before compensation was 77 kVAR and after compensation the reactive power became 21 kVAR.   Figure 9, it is seen that the losses in the system (cable, coil, breaker) was reduced by 38.48% of totally losses, since the current passing through the system before compensation is 529A and after compensation the current through the system became 382A.

In Figure 10, the average power factor improved by 25.5% as the power factor of 0.7 before compensation increase to 0.97 after compensation. Figure 11, show the graphical analysis of the system loading, the average loading on the transformer was released by 33.33% of total loads, since the average loading kVA was 112 kVA before compensation and it became 84 kVA after compensation. Figure 12 and Figure 13, shows the power factor vs active power and current vs active power respectively.

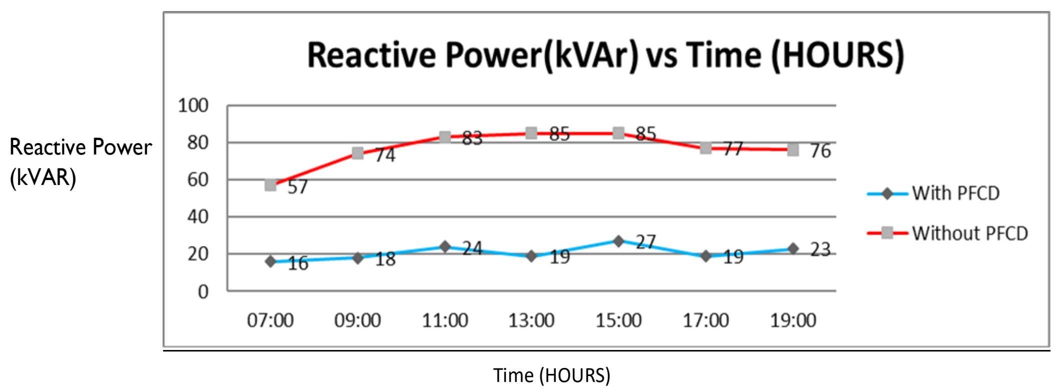


Figure 8: Reactive Power vs Time

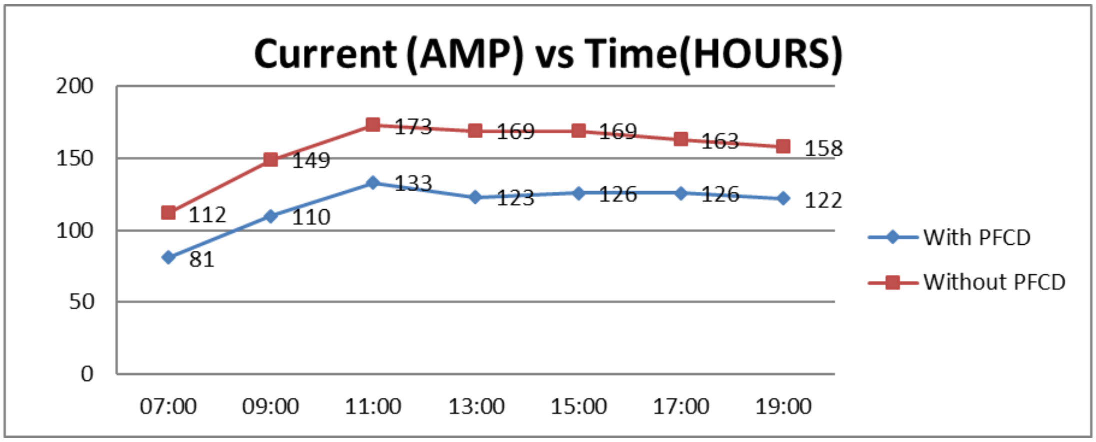


Figure 9: Current vs Time

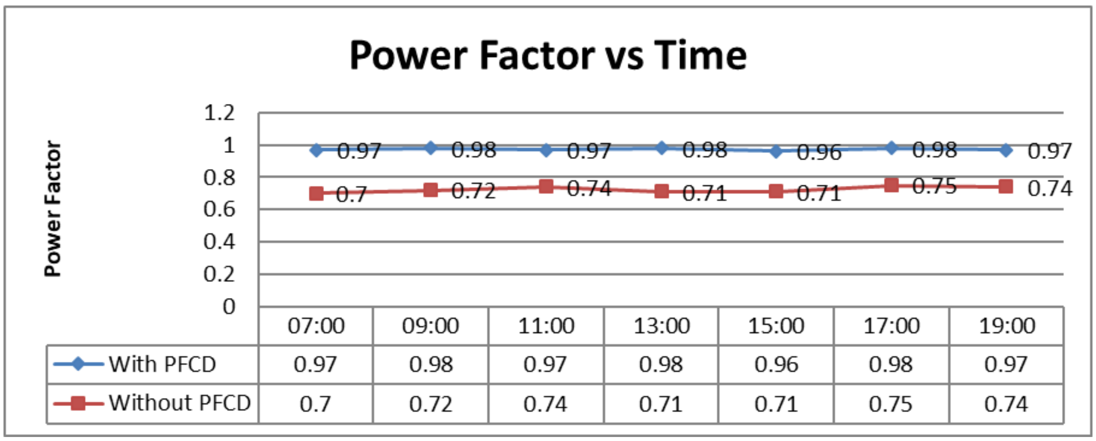


Figure 10: Power Factor vs Time

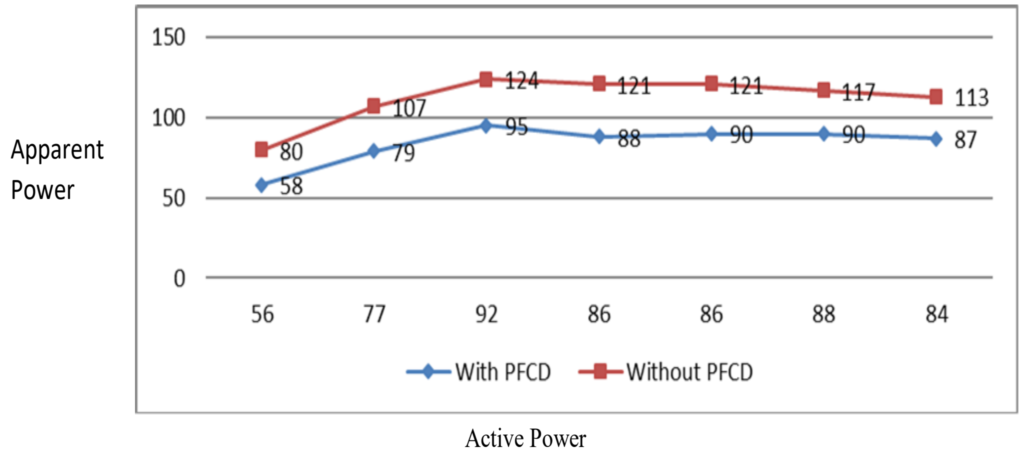


Figure 11: Apparent Power vs Active Power

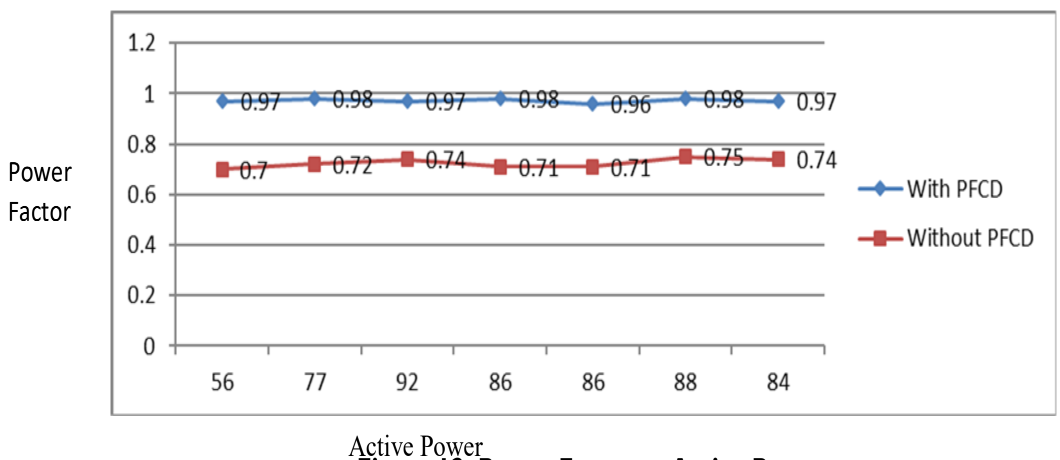


Figure 12: Power Factor vs Active Power

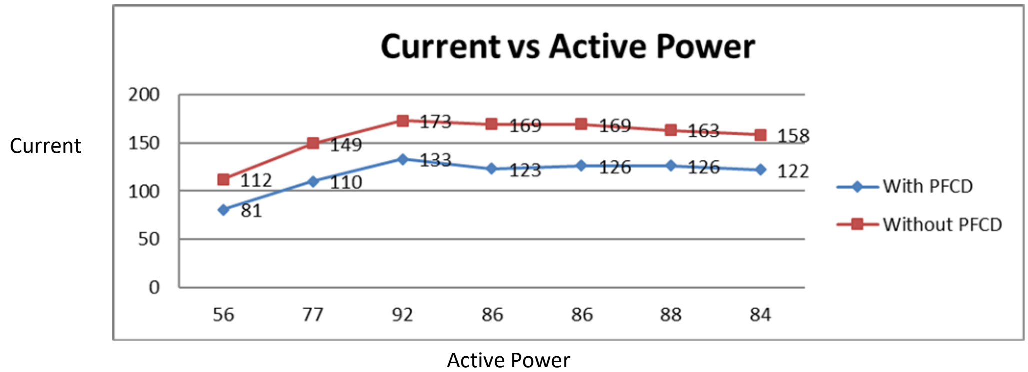


Figure 13: Current vs Active Power

The Impact of Energy Saved in the System

The following are the listed impact of energy saved by PFC device (capacitor) in system:

System Losses

The system losses can be reduced by placing capacitor (PFCD) near the load point of the system and the result is improved power factor. The losses of the system can be estimated by adding the losses in the cables, transformer and motors. Since, system losses is proportional to the square of the current and the resistance of system (I^2R), when the capacitor (PFCD) was installed in the system, the system total current (load current) reduced from 528.66A to 381.51A.

Hence, current reduction in the system results to power losses reduction in the feeder's cables and transformers. Although, the economic benefit from system losses alone may not be sufficient to justify the installation of capacitors, it's an additional benefit, especially in the facilities with many transformers and long feeders that serve low power factor loads. Since, the system losses are proportional to the square of the current and the current has been reduced, hence losses has also been reduced, thereby saving energy for the entire system and also current reduction is directly proportional to the power factor improvement.

In other words, losses are inversely proportional to the square of the power factor. Raising the power factor from 0.7 to 0.97reduces the total energy consumed by the system thereby increasing the capacity of the system without installing any additional transformer or plant. The percentage of energy saves for other loads to use is given as:

$$\% \text{ of Energy Save} = [1- (PF_{old}/PF_{new})^{2}] \times 100 \quad (21)$$

System Capacity

The system capacity is increased by power factor correction, this permit addition of more loads to the existing system (i.e. the existing system serves more loads without installing more plants or transformers). Improving the power factor of the system is the most economical means of reducing the system current. Hence, capacitor compensation is one of the economical ways of reducing losses in a system thereby increasing the capacity of the system and saving more energy when the system current is reduced by compensation (PFCD).

These allow the system to serve more loads; the current reduction for the system is shown below:

$$I_{old} = S_{old}/\sqrt{3}V \quad (22)$$

$$I_{old} = 380/\sqrt{3}x0.415 = 528.66A$$

$$S_{new} = (PF_{old}/PF_{new})\ xSold \quad (23)$$

$$S_{new} = (0.7/0.97)\ x380 = 274.23KVA$$

$$I_{new} = S_{new}/\sqrt{3}V \quad (24)$$

$$I_{new} = 274.23/\sqrt{3}x0.415 = 381.51A$$

When the power factor was improved from 0.7 to 0.97, the capacity of system is increased or released by 27.84%, which is equal to108.57KVA power or energy saved for the system. Hence, the percentage of energy save is proportional to the percentage of current reduction and the percentage power factor improvement or correction in the system.

System Wear and Tear

The reduction of the average reactive power from 77 kVAr to 21 kVAr by power factor correction or improvement translate into a reduction in generation requirements and reduction in the amount of capacity required from the system [7]. Hence, the system capacity is improved by improving the power factor of the system. The power factor correction in the system, results in less wear and tear on the system because losses are reduced by reduction of the current thereby reducing heat production in the system. Hence, tear and wear of the system equipment is reduced by the percentage of the power improvement or correction.

Conclusion

Low power factor is highly undesirable as it causes increase in current, thereby resulting to additional losses in all equipment in the system. From the case study it was found out that in order to have a better and economical system, it is important to optimise the power factor between 0.92 to 0.97.

This improved power factor will eliminate waste in electrical energy and increase the output without installing additional transformers and cables. Indeed, the PFC device in the system will release the transmission and generation capacities. The most positive impact of improving the power factor is the energy saves, thereby saving money for sector in question and also, improving the overall efficiency of the system.

The improved power factor results in:

1. Increase of the system capacity
2. Increase of the overall system efficiency
3. Overloading reduction of cables and transformers
4. Losses reduction in the system, thereby prolonging the system life

From the case study it's shown that capacitors are veritable equipment for reducing losses in a system or for improving power factor.

It is recommended that if the power factor of every heavy reactive loads in the Nigeria sectors equipment's is improved by PFC device, there will be a considerable amount of energy saves for Nigerians. The power factor of the compensated equipment's should be check periodically to ascertain their pre-set values whether they are still operating within the set power factor correction value and also, penalty should be place and enforce on the offender.

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