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# A Modified Optimal Electricity Distribution Algorithm for Nigeria Machine Tools Distribution Zone

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### *Authors' contributions*

*This work was carried out in collaboration between all authors. Authors ISB and KKO designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript and managed literature searches. Authors KKO, ISB, AOA managed the analyses of the study and literature searches. All authors read and approved the final manuscript.*

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## ABSTRACT

This paper presents an improvement of power factor on inductive loads in Nigeria machine tool plant. Due to the fact that most of the electrical loads are inductive in nature and to provide reduction in distribution losses and the electricity bill charges, a form of power factor correction device is employed, usually in the form of capacitors, which draws leading reactive current to neutralize as much of the lagging reactive component of load current as possible. To improve the power factor in machine tools industries, it is required to install capacitors of appropriates ratings as near to the load as possible. This paper presents a case of an induction machine in a factory having a power factor of 0.75 and has capacity of improving its power factor to 0.928 by connecting suitable capacitors in parallel with the inductions motors.

*Keywords: Power factor; electricity bill; distribution losses; transmission line; compensation; induction motors; machine tools; electrical loads; power supply authority.*

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## 1. INTRODUCTION

One of the most essential methods of improving quality of supply is by the improvement of power factor. Low power factor causes unnecessary reactive current flows, which lead to overheating, losses in distribution system, and finally result in poor electrical efficiency. The more the power factor is reduced, the higher the apparent power drawn from the distribution network and the higher utility bill passed to the consumers. This implies that the electricity supply company must increase the generation capacity, and the size of transmission cables and lines, and use larger transformers and other distribution system devices, which otherwise would not be necessary. As a result of this, lead to much higher capital expenditures and operating costs for the Electricity Supply Company, which in many occasions is passed on to consumers in form of higher tariff rates. An economic advantage of improving power factor is by provision of good management in the consumption of reactive energy generated. It is commonly applied in Europe that based on an actual tariff structure, designed to encourage consumers to reduce their consumption of reactive energy. The installation of power-factor correction equipment on electrical loads provide reduction access to consumers electricity bill by maintaining the level of consumption of reactive-power below a value mutually agreed with the power supply authority.

In a region where marketing of electricity is being practiced, the supply of electrical energy becomes highly competitive between the supply utilities. Private distribution companies are dedicated to maintain the quality of supply at a high level to consumers, although their primary aim was to run a profitable and successful business. This competition among private electricity companies creates numerous new opportunities by providing quality supply of electricity. This is the main reason why most of the electricity Supply Companies demands reduction of the reactive load in their networks through improvement of the power factor. In many occasions, poor power factor penalize special reactive current tariffs.

Therefore, in an electric power system, linear loads with low power factor (such as induction motors) can be corrected with a passive network of capacitors or inductors. Non-linear loads, such as rectifiers, distort the current drawn from the system. In such cases, active or passive power factor correction may be used to counteract the distortion and raise the power factor. The devices for correction of the power factor may be at a central substation, spread out over a distribution system, or built into power-consuming equipment [1].

The aim of this paper is to provide reduction of the inductive load in networks through improvement of the power factor that provide reduction access to consumers electricity bill by maintaining the level of consumption of reactive-power below a value mutually agreed with the power supply authority and to identify motors contributing to the less-than-desirable power factor and improve a plant power factor to avoid future power factor charges. Towards this end, the objective of this paper shall be to:

- To provide Reduction energy costs for consumers
- To lower transmission and distribution losses in electrical system
- To provide quality and increased voltage regulation
- To increase actual working power to required capacity.
- To provide reduction in non-productive loading on the system

Scholarly works in power factor improvement have focussed on various perspectives and aspects of the project. Some of these works include [2-13]. Despite these, it has been observed that existing studies have not explored a Technical-economic Comparison of different methods of improving power factor in electrical load. Hence, the paper considers this aspect for the purpose of bridging the existing gap by conducting a research on power factor improvement in Nigeria machine tools plant through a comparative analysis approach.

## 2. METHODOLOGY EMPLOYED

Power factor is the ratio of the real power (P) to apparent power (S), and it can also be define as the cosine phase angle. Power factor represents the phase angle between the current and voltage waveforms. The power factor can vary between 0 and 1, and can be either inductive (lagging) or capacitive (leading). In order to reduce an inductive lag, capacitors are added until power factor equals 1. When the current and voltage wave-forms are in phase, the power factor is 1 ($\cos(0°) = 1$). The whole purpose of making the power factor equal to one is to ensure that the circuit is purely resistive that is, apparent power is equal to real power.

Power factor determines how effectively electrical loads consume electricity. There are basically three forms of power that are present in electrical energy. The summary of the three types of power and power factor we have is presented below.

## 2.1 Apparent Power

The apparent power has two components that possess both resistive and inductive loads. In other words they possess active and reactive power at right angle to each other. The ratio of these two types of loads give rise to apparent power and it has becomes important as more inductive equipment is added to the circuit. Apparent power is expressed in kilovolt-amperes (KVA) and determined mathematically by using the expression $KVA^2 = KW^2 + KVAR^2$.

The expression above can be represented in the form of triangle as illustrated in Fig. 1.

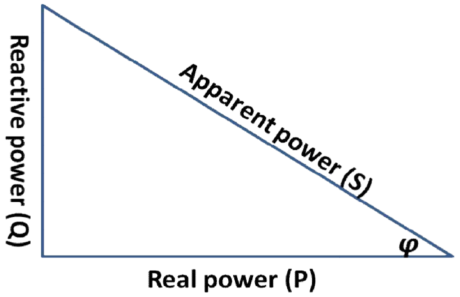


**Fig. 1. Power triangle representation**

*Mathematically,* $S^2 = P^2 + Q^2$

## 2.2 Active Power

Active or real power is the main power used by all electrical appliances to perform the function of heating, lighting, movement and other electrical functions. These types of electrical loads that use active power for their operations are called Resistive loads. Active power is expressed in kilowatt (KW).

## 2.3 Reactive Power

Electric motors, transformers, compressors or ballast that are inductive loads require reactive power to generate and sustain a magnetic field needed for their operation. Reactive power is referred to as non-working power because it an unwanted power that performs no specific operation and it is expressed as kilovolt-amperes-reactive (kVAR).

Many organizations can improve load factor by reducing demand or increasing production efficiency. Distributing loads over different times or installing energy management systems can often help. Lowering peak demand along with keeping demand stable is often a cost-effective way to maximize the use of power. Power factor can be improved in order to reduce cost of electricity supply, to reduce size of cable, to provide reduction of transmission losses in cables, Reduction of voltage drop and Increase in available power

The installation of power-factor correction equipment on electrical loads provide reduction access to consumers electricity bill by maintaining the level of consumption of reactive-power below a value mutually agreed with the power supply authority. In this particular tariff, reactive energy is billed according to the tan φ criterion.

$$tan\phi = \frac{Q(kvar)}{P(kW)}$$

The same ratio is also applies to energies as shown in the equation below

$$tan\phi = \frac{Q(kvarh)}{P(kWh)}$$

Contrary to financial advantages due to the reduction of electric billing, it is the requirement of consumers to balance the cost of installation, maintenance and purchase of the power factor correction equipment. Where stepped levels of compensation are needed, switchgear and automatic control equipment are also required. It is more economical to provide partial compensation only, due to the fact that providing 100% compensation lead to extra charges of some of the reactive energy consumed.

As for consumers whose utility bill are based on a fixed charge per kVA declared by the supply company, with a charge per kWh consumed, it is more beneficial with the reduction in the declared kVA. The primary aim of the power factor improvement is also to provide reduction in declared level of charge without exceeding it, thereby avoiding the payment of an excessive price per kVA during the periods of excess. Take for instance, if a particular industrial plant has a declared load of 122 kVA at a power factor of 0.7 lagging, i.e.an active-power load of 85.4 kW. The particular contract for this consumer was based on stepped values of declared kVA (in steps of 6 kVA up to 108 kVA, and 12 kVA steps above that value, this is a common feature in many types of two-part tariff). In the case being considered, the consumer was billed on the basis of 132 kVA.

According to DTE Energy Company (2005), Electric rates call for penalties ranging from 1 to 3 percent when the power factor is between 85 and 70 percent. Power factors below 70 percent are not permitted, and customers are required to install corrective equipment essential for the improvement the power factor above this level. Until corrections are made a 25 percent penalty charge will be applied to any billing after two consecutive months below 70 percent power factor and will continue as long as the power factor remains below this level.

Below Tables 1 and 2 are examples of how power factor affects DTE Energy Company's customer monthly electric bill.

Losses in cables are determined by the size of cable. The thicker the cable size the lower the reduction of distribution losses. These losses are proportional to the square of current flow in the distribution system and these are measured by the kWh meter of an installation. For instance, if a total current in a conductor is reduced by 10%, it will reduce the losses by almost 20%. Table 3 below shows the required increase in the size of cables as the power factor is reduced from unity to 0.4, for the same active power transmitted.

The reactive current flowing in the distribution system causes distribution Losses due to poor power factor and these losses are known as reduction loss. Reduction losses are watt-related charges and can be removed via power factor correction. Reduction loss in watts in a distribution system is calculated thus:

$$\% \text{ reduction losses} = (1- (\frac{PF1}{PF2})^2)$$

Where:

$PF_1$ = original power factor
$PF_2$ = new power factor

When there is low power factor in an installation, the total line current increases, which result to causing voltage drop. The higher the excessive current flows in the distribution system, the lower the voltage drop. As a result of this, it causes motors to be overheated and act sluggish. By adding power factor correction equipment like capacitors to the system, lead to improvement of voltage drop, and as a result of this, provide more efficient motor's performance and longer life span.

There are certain loads that contribute to poor power factor which are lightly loaded or oversized motors or transformers, most welding operations, and certain fluorescent lamp ballasts. The improvement of power factor of a load supplied from a transformer will reduced current flow through the transformer, thereby allowing additional load to be connected to the circuit. In practice, the cost of replacement of transformer to a higher unit may be more costly than to improve the power factor.

**Table 1. Power factor penalty for mid-size customer**

| % Power factor penalty | 1% | 2% | 3% |
|---|---|---|---|
| Monthly Electric Bill | $17,500 | $17,500 | $17,500 |
| Monthly Power Factor Penalty | $175 | $350 | $525 |
| Estimated Cost to Correct | $5,500 | $6,875 | $8,800 |
| Simple Payback (months) | 31 | 20 | 17 |

**Table 2. Power factor penalty for large-size customer**

| % Power factor penalty | 1% | 2% | 3% |
|---|---|---|---|
| Monthly Electric Bill | $100,000 | $100,000 | $100,000 |
| Monthly Power Factor Penalty | $1,000 | $2,000 | $3,000 |
| Estimated Cost to Correct | $6,875 | $9,075 | $11,000 |
| Simple Payback (months) | 7 | 5 | 4 |

**Table 3. Multiplying factor for cable size as a function of cos φ**

| Cross-sectional area | 1 | 1.25 | 1.67 |
|---|---|---|---|
| Cos φ | 1 | 0.8 | 0.6 |

## 3. METHODS OF IMPROVING POWER FACTOR

The major way to improve power factor mostly depends on the particular operating considerations involved. In many occasions, electrical load such as induction motors or transformers can be designed closely to the requirement of actual work to be done, but efficiency of electric loads can be more improved by improving the power factor. In order to attained effective energy management and benefit of improved power factor on a particular load, it is more encouraging to avoid motor idling or "no load" running periods. Under ideal conditions, if an electrical load is purely resistive in nature, both the current and voltage are in phase and the power factor is at its maximum value, which is 100%. This is not the case in capacitive and inductive loads such as induction motors or transformers that has power factors less than 100%, typically 70-90% can occur. Low power factor causes large amount of current to flow through power distribution lines to deliver the required kilowatts to an electrical load.

### 3.1 Capacitors

The easiest way to improve power factor or to neutralize reactive lagging power in an installation is to connect power factor correction capacitors in parallel to the electrical system. Power factor correction capacitors act as leading current generators and improve power factor by draws a leading current and partially or completely neutralizes the lagging reactive (the non-working power) used by inductive loads. This implies that the power factor correction capacitor has partially or completely reduced the phase angle between voltage and current to attained unity. Most of industrial motors are inductive in nature and they required large amount of leading reactive power for their functionality. This leading reactive power is provided by the capacitor or bank of capacitors connected in parallel to the load. The capacitors serves as a source of local leading reactive power and thus preventing large amount of lagging reactive power to flow through the line. In summary, they reduce the phase difference between the voltage and current. To determine the type of capacitor needed for an installation, the capacity rating is put into consideration. The capacitor rating is measured in KVAR and its shows how much leading reactive power the capacitor can supply. Since leading reactive power supplied by the capacitor neutralize the lagging reactive power caused by inductive load, each KVAR of capacitance of the capacitor decreases the net reactive power demand by the same amount.

In an electrical system, installation of capacitor takes place at any point. However, they are usually connected to each piece of inductive (offending) equipment and it is normally triggered with the offensive equipment(induction motors) or installed ahead of groups of induction motors.it can be also installed ahead of motor control centers, distribution panels or at main services. The improvement of power factor via capacitors is between the point of application and the power source, but the power factor between the load and the capacitor remains unchanged. On normal occasions, Power factor correction capacitor always remains ON in as much the inductive equipment is set into operation. Trigging a capacitor ON can result to production of over-voltage in the system. If problem occur as a result of over voltage, variation of speed that drives the motor will automatically turned off the motors at approximately the same time the problem occurred and this may cause switching control sequence. Faulty capacitors or harmonic current is also one of the experienced problems that may cause fuses to blown in the circuit.

Selection of right capacitors for specific installation should be put into consideration. The interaction between power factor capacitors and specialized equipment, such as variable speed drives, requires a well-designed system. Too much capacity of capacitor can cause problems, making capacitors selection extremely important. Once decision has been made regarding to benefits of power factor correction in a particular industrial plant, one need to select the right capacity rating, optimum type, size, and number of capacitors that best fit the plant. There are four basic types of capacitor needed for power factor improvement in installations: Static or fixed capacitors on linear or sinusoidal loads ,Individual capacitor, Banks of fixed or automatically switched capacitors at the feeder or substation and Switched capacitor.

### 3.1.1 Static or fixed capacitor

Static capacitor arrangement is the connection of one or more capacitor(s) to produce a constant level of compensation. This arrangement can be control manually by circuit-breaker or by load-break switch.it can also be control Semi-automatically by contactor and direct connection to switched appliance.

In situation where individual compensation would be too costly and level of load is reasonably constant, the connection of capacitor is put into consideration. These capacitors can be connected via the terminals of inductive loads like motors or transformers, the bus bars supplying power to small motors and inductive appliance. Fig. 2 shows the typical example fixed-value compensation capacitors.

### 3.1.2 Capacitor banks

The basic requirement of bank of capacitors in terms of power factor improvement in an installation is to act as a source of reactive energy. Reactive energy compensation is achieved through this arrangement. Ina low power factor inductive load, it is requires the inductive load and transmission or distribution systems to supersede lagging reactive current. This implies that current is lagging the voltage by 90° with corresponding power losses and exaggerated voltage drops, If a bank of shunt capacitors is connected to the load in parallel, leading reactive current is generated to take the same path through the power system as that of lagging reactive current of the inductive load. This leading capacitive current (IC) and lagging inductive current (IL) are in phase to each other. These two currents flowing in the same direction will neutralize each other in such a way that there will be no reactive current flow in the system, that is IC = IL =0. This can be illustrated in Figs. 3 (a), (b) and (c).

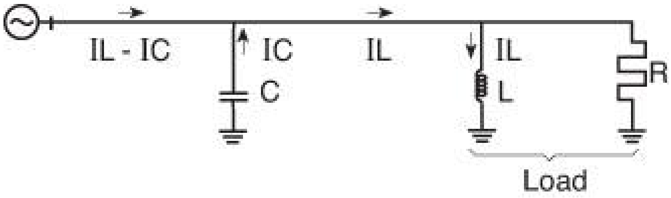
The figures only show the directions of flow of reactive components of current. R represents the active power components of the load, L represents the inductive reactive-power components of the load and C represents the capacitive reactive power components of the power-factor correction equipment, that is, the capacitors bank.

In the Fig. 3(b), all the reactive current of the load is appeared to be supplied by capacitor banks C. This type of capacitors is sometimes referred to as generators of leading VAR.

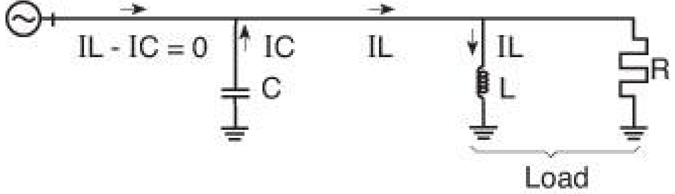
In the Fig. 3(c), the active power component IR has been connected in parallel and shows that full compensation has occurred i.e. the power factor has become unity due to the fact that both IR and IC will meet and neutralize each other.

Fig. 4 shows the phasor power diagram to illustrate the principle of compensation by reducing a large reactive power Q to a smaller value Q' by means of a bank of capacitors having a reactive power Qc.

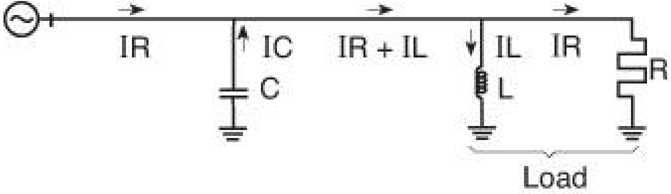
**Fig. 2. Example of fixed-value compensation capacitors**



***(a) Reactive current components only flow pattern***



***(b) When IC = IL, all reactive power is supplied from the capacitor bank***



***(c) With load current added to case (b)***

**Fig. 3(a), (b), (c): Showing the essential features of power-factor correction**

In doing so, the magnitude of the apparent power S is seen reduced to S'. Qc can be calculated by the following formula deduced from Fig. 3:

$Q_c = P. (\tan(\phi) - \tan(\phi'))$

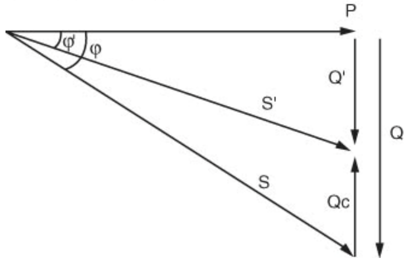


**Fig. 4. Diagram showing the principle of compensation: Qc = P (tan ϕ - tan ϕ')**

Take for instance, if an induction motor used 100 kW at a power factor of 0.75 i.e. $\cos \phi = 0.75$, then $\phi = \cos^{-1} 0.75$, the value of phase angle $\phi$ is $41.41^{\circ}$. The value of the tangential angle is now 0.88 i.e. $\tan \phi = 0.88$. To improve the power factor to 0.93 implies that $\cos \phi = 0.93$, then $\phi = \cos^{-1} 0.93$, the value of phase angle $\phi$ is equals to 21.57°. The value of the tangential angle i.e. $\tan \phi = 0.4$. The value of reactive power of the capacitor bank can be calculated from the equation given above, that is the value of capacitor bank must be: $Q_c = 100\ (0.88 - 0.4) = 48$ KVAR.

In the light of the expression above, the level of compensation selection is based on the calculation of capacitors bank rating required in the installation. Before the commencement of any compensation project, a number of precautions should be observed. In particular, oversizing of motors should be avoided, as well as the no-load running of motors. In the no load running motor, reactive energy consumed by the motor leads to very low power factor. This is because the kW taken by the motor (when it is unloaded) is very small.

### 3.1.3 Automatic capacitor bank

Automatic capacitor banks provide automatic control of compensation, maintaining the power factor within close limits around a selected level. This type of power factor correction capacitor is applied at points in an installation where active-power and reactive-power variations are relatively large. This point of application may be at the busbars of a general power distribution board or at the terminals of a heavily loaded feeder cable. Fig. 5 show example of automatic compensation capacitor.

**Fig. 5. Example of automatic-compensation-regulating equipment**

The main principle of operation of automatic compensation in large industries is that automatically-regulated banks of capacitors allow an immediate adaptation of compensation to match the level of load. A bank of capacitors is divided into a number of sections, each of which is controlled by a contactor. Closure of a contactor switches its section into parallel operation with other sections already in service. The size of the bank can therefore be increased or decreased in steps, by the closure and opening of the controlling contactors [14].

A control relay monitors the power factor of the controlled circuit(s) and is arranged to close and open appropriate contactors to maintain a reasonably constant system power factor (within the tolerance imposed by the size of each step of compensation). The current transformer for the monitoring relay must evidently be placed on one phase of the incoming cable which supplies the circuit(s) being controlled, as shown in Fig. 6.

Power factor correction equipment including static contactors (thyristors) instead of usual contactors is particularly suitable for a certain number of installations using equipment with fast cycle and/or sensitive to transient surges. The advantages of static contactors are: Immediate response to all power factor fluctuation (response time as low as 40ms according to regulator option), Unlimited number of operations, Elimination of transient phenomena on the network on capacitor switching and fully silent operation.

By closely matching compensation to that required by the load, the possibility of producing overvoltage at times of low load will be avoided, thereby preventing an overvoltage condition, and possible damage to appliances and equipment. Overvoltage due to excessive reactive compensation depends partly on the value of source impedance [14].

Power factor correction capacitor can be installed in different ways depending on the kind of compensation and installation needed. There is a substantial cost increase in serving customers with low power factor loads. These costs are not reflected in metered use of working power. Therefore, special provisions are made for compensation.

Global Compensation can be applied where a load is continuous and stable. The principle of global compensation is that the capacitor bank is connected to the busbars of the main LV distribution board for the installation, and remains in service during the period of normal load.

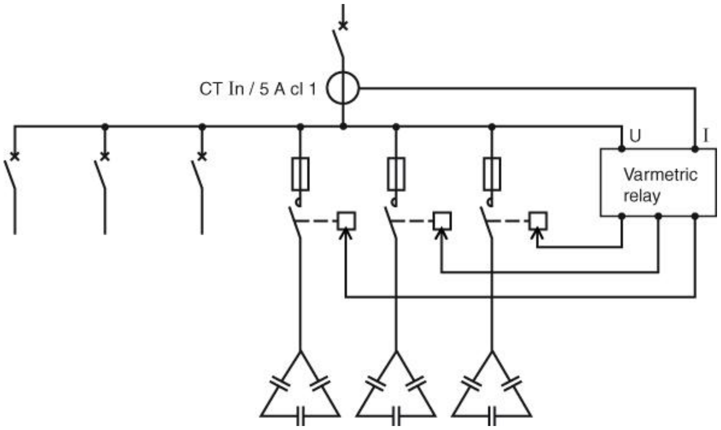


**Fig. 6. The principle of automatic-compensation control**

Global compensation has the advantages of reduces the tariff penalties for excessive consumption of kvars, Reduces the apparent power kVA demand, on which standing charges are usually based and Relieves the supply transformer, which is then able to accept more load if necessary [14].

Compensation by sector is recommended when the installation is extensive, and where the load/time patterns differ from one part of the installation to another. The principle is that Capacitor banks are connected to busbars of each local distribution board, as shown in Fig. 7.

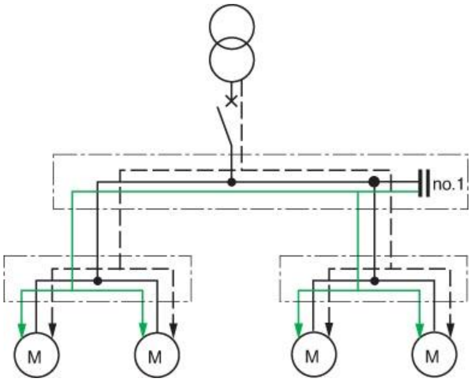


**Fig. 7. Global compensation**

A significant part of the installation benefits from this arrangement, notably the feeder cables from the main distribution board to each of the local distribution boards at which the compensation measures are applied.

Compensation by sector has the advantages of Reduces the tariff penalties for excessive consumption of KVARs, Reduces the apparent power kVA demand, on which standing charges are usually based, Relieves the supply transformer, which is then able to accept more load if necessary, The size of the cables supplying the local distribution boards may be reduced, or will have additional capacity for possible load increases and Losses in the same cables will be reduced [14].

*Individual compensation* should be considered when the power of motor is significant with respect to power of the installation. It principle is that Capacitors are connected directly to the terminals of inductive circuit, as shown in Fig. 8. Individual compensation should be considered when the power of the motor is significant with respect to the declared power requirement (kVA) of the installation.

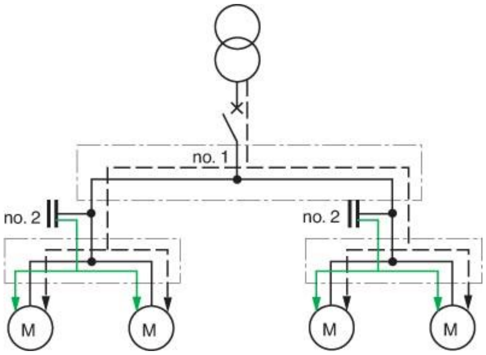


**Fig. 8. Compensation by sector**

The KVAR rating of the capacitor bank is in the order of 25% of the kW rating of the motor. Complementary compensation at the origin of the installation (transformer) may also be beneficial.

Individual compensation had the advantages of reduces the tariff penalties for excessive consumption of KVAR, Reduces the apparent power kVA demand and reduces the size of all cables as well as the cable losses [14].

### 3.1.4 Switched capacitors

Switched capacitors are capacitors connected to one or groups of induction motors. Intermittent Inductive loads such as large motors or compressors used by most industrial plants make uses of switched capacitors. Switched capacitors are only in action when the motor load is turned on or capacitors may be switched on and off depending on system power factor. The switching feature is only required for large capacitors that cause an undesirable leading power factor when turned off.

Switched capacitors take full control of the operation. The capacitors cannot develop any problems on the system during light load conditions, separation of switching between the capacitors and motors are not required since they both need to set into operation at the same time. Switched capacitors lead to improvement of induction motors performance due to the fact that the capacitors has provide more efficient power and reduced voltage drops, location of both motors and capacitors can be easily changed, selection of appropriate capacitors for the load is quiet easy, it also reduced distribution losses in the line and to Provide increment in system capacity.

### 3.2 Synchronous Condenser

They are three phase synchronous motor with no load attached to its shaft. The synchronous motor has the characteristics of operating under any power factor leading, lagging or unity depending upon the excitation. For inductive loads, synchronous condenser is connected towards load side and is overexcited. This makes it behave like a capacitor. It draws the lagging current from the supply or supplies the reactive power [1].

An over-excited synchronous motor has a leading power factor. This makes it useful for power factor correction of industrial loads. Both transformers and induction motors draw lagging (magnetizing) currents from the line. On light loads, the power drawn by induction motors has a large reactive component and the power factor has a low value. The added current flowing to supply reactive power creates additional losses in the power system. In an industrial plant, synchronous motors can be used to supply some of the reactive power required by induction motors. This improves the plant power factor and reduces the reactive current required from the grid [15].

A synchronous condenser provides step-less automatic power factor correction with the ability to produce up to 150% additional vars. The system produces no switching transients and is not affected by system electrical harmonics (some harmonics can even be absorbed by synchronous condensers). They will not produce excessive voltage levels and are not susceptible to electrical resonances. Because of the rotating inertia of the synchronous condenser, it can provide limited voltage support during very short power drops [16].

### 3.3 Phase Advancer

Phase advancers are used to improve the power factor of induction motors. The low power factor of an induction motor is due to the fact that its stator winding draws exciting current which lags behind the supply voltage by 90 degree. If the exciting ampere turns can be provided from some other A.C. source, then the stator winding will be relieved of exciting current and the power factor of the motor can be improved. This job is accomplished by the phase advancer which is simply an A.C exciter. The phase advancer is mounted on the shaft as the main motor and is connected in the rotor circuit of the motor as shown in Fig. 9. It provides exciting ampere turns to the rotor circuit at slip frequency. By providing more ampere turns than required, the induction motor can be made to operate on leading power factor like an over-excited synchronous motor [17].

### 3.4 Dynamic Power Factor Correction (DPFC)

This sometimes referred to as "real-time power factor correction," is used for electrical stabilization in cases of rapid load changes (e.g. at large manufacturing sites). DPFC is useful when standard power factor correction would cause over or under correction. DPFC uses semiconductor switches, typically thyristors, to quickly connect and disconnect capacitors or inductors from the network in order to improve power factor.

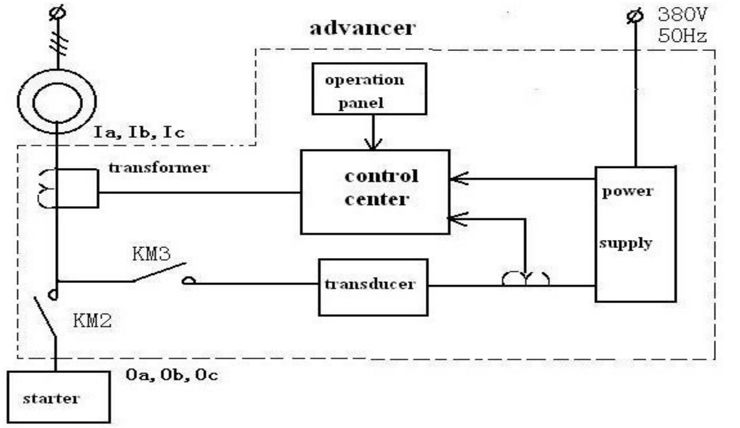


**Fig. 9. Connection of phase advancer in an installation**

When deciding the selection of power factor corrections method that may suitable for a particular plant, the advantages and disadvantages of each type of power factor correction must put into consideration. It is also mandatory to consider several plant variables which include size of load, type of load, load constancy, capacity of load and methods of starting motor.

#### 3.4.1 Types of load

It more advisable to install both types of power factor improvement capacitors to Industrial plant that comprises of both small and large motors. Industrial plant with large induction motors rating will be subjected to some kind of special installation that is quite different from installation of small motor. It is more economical to connect one capacitor per motor whose rating is 50hp and above. Whenever the induction motor starts, both the capacitor and motor are in operation at the same time. Industrial plant with small motors, that is 25hp below, can be group together and corrective capacitor is installed at central point in the distribution system.

#### 3.4.2 Size of load

Industrial plant with large loads has advantage of banks of fixed capacitor and automatically-switched capacitor units that control the combination of individual load and group of loads. On the other hand, small plant only required one capacitor at the control Centre or board. If a plant possesses special induction machines like welding machines, induction heaters, or DC drives, power factor improvement may from an isolated trouble spot. Additional capacitors may not be required for the improvement of overall power factor of the plant if the feeder serving the inductive loads is corrected.

#### 3.4.3 Load constancy

Load constancy offer greatest economy if a particular plant operate 24/7 having a constant load demand and fixed capacitors rating. Moreover, if a load operates half a day, one will want more switched units to decrease capacitance during times of reduced load.

#### 3.4.4 Capacity of load

When feeders or transformers are overloaded, and additional load is required for the installation, power factor correction equipment must apply to the load. If the plant has sufficient or over amperage, it is encourage installing the bank of capacitors at the main feeders. Automatic switching is the best way to improve power factor where there is variation of load.

## 4. DATA PRESENTATION AND ANALYSIS

In this report the subject of investigation is a Nigeria Machine Tools Limited NMTL factory in Oshogbo, Osun State, Nigeria. First of all, the whole plant is studied thoroughly and the electrical energy distribution systems found. The facility consists of 4 assembly and heavy machine shops, 3 light machine shops, and a foundry with independent pattern and casting shops. During plant study, many inductive loads are identified motors.

After studying the plant, few of the electric motors are selected for power factor improvement. The saving in electrical energy is found by analyzing these inductive loads and looking for capacitor retrofit to improve the power factor. The procedure to analyze the load for power factor improvement is shown in Fig. 10.

Data extracted are presented below:

### 4.1 Part Machine and Non-traditional Machine Shop

The Heavy Machine shop is equipped with large 3-phase 230/400V CNC machines and manual lathes including the following:

## 5. MACHINE SHOP

The light machine shop is equipped for the production of small and medium tools. Table 4 and table 5 show various induction machines and their parameters.

Equipment in the light machine shop includes:

## 6. RESULTS AND DISCUSSION

In the plant, the saving in electrical energy is found by analyzing some of the electrical motors and looking for capacitor installation to improve the power factor of the loads and increase the efficiency of the motors. Sample parameters of one of the electrical motor (666Kva Centreless Grinding Machine) are given in Table 6, which include rated and measured parameters of 10hp centreless grinding machine. It is required to improve the power factor of a 666 kVA installation from 0.75 to 0.928.

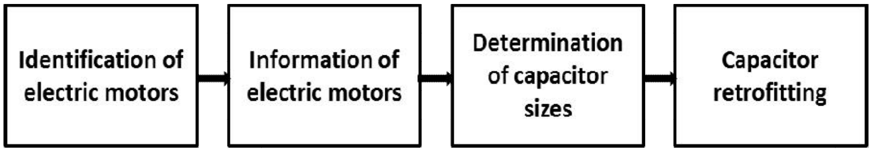


Fig. 10. Procedure to analyze the inductive load

**Table 4. List of induction machines and their parameters in Non-traditional machine shop**

| Name of machines | Power rating(KW) | Induction motors rating (hp) | Present power factor |
|---|---|---|---|
| Vertical Machining Centre | 30 | 10 | 0.7 |
| CNC Slide way grinding Machine | 37 | 50 | 0.7 |
| CCGH induction hardening Machine | 7.5 | 20 | 0.75 |
| Universal Milling Machines | 7.5 | 70 | 0.7 |
| Various CNC and Manual lathes Machines | 110 | 20 | 0.75 |
| Wire Cut and Spark Erosion Machines | 7.5 | 20 | 0.75 |
| Horizontal Balancing Machine | 37 | 75 | 0.7 |
| Double Column CNC Plano – Miller | 22 | 75 | 0.7 |
| Hydraulic Cylinder Honing Machine | 30 | 20 | 0.7 |
| CNC L45 Lathe (5000mm Between centers | 22 | 75 | 0.7 |
| Horizontal Machining Centre HMC 1,000 | 22 | 30 | 0.7 |

**Table 5. List of induction machines and their parameter in light machine shop**

| Name of machines | Power rating(KW) | Induction motors rating (hp) | Present power factor |
|---|---|---|---|
| Centreless Grinding Machine | 500 | 10 | 0.75 |
| CNC Thread and Worm Grinding Machines | 15 | 50 | 0.7 |
| Deep Hole Boring Machine | 15 | 20 | 0.75 |
| Broaching Machines | 15 | 70 | 0.7 |
| Tool Reconditioning Section | 75 | 20 | 0.75 |
| Lathe machines of various sizes | 7.5 | 75 | 0.75 |
| Gear Cutting Machines (Hobbing and Shaping | 7.5 | 10 | 0.7 |
| Universal, Vertical and Horizontal Milling Machines | 75 | 20 | 0.7 |
| Internal and External Grinding machine | 55 | 75 | 0.7 |
| Bolts Milling Machine | 55 | 75 | 0.7 |

## 6.1 Calculated Parameters

The active power demand is 666 x 0.75 = 500 kW.

Phase angle of the present power factor ($PF_1$) $=\emptyset_1= \cos^{-1} 0.75= 41.4°$

Phase angle of the required power factor ($PF_2$) = $\emptyset_2= \cos^{-1} 0.928= 21.9°$

KVAR rating of the required capacitor = $P\times[\tan \emptyset 1 - \tan \emptyset 2]$

$= 500\times (\tan 41.4 - \tan 21.9)$

$=239.810$ KVAR

Reduction in distribution loss = $\left(1- \left(\frac{PF1}{PF2}\right)^2\right)$

$$= 1- \left(\frac{0.75}{0.928}\right)^2\times 100$$

$$= 34.68\% = 35\%$$

From the Table 6 below, it can be seen that, to raise the power factor of the installation from 0.75 to 0.928 will require 2.084 KVAR per kW of load. The rating of a bank of capacitors at the busbars of the main distribution board of the installation would be 239.810 KVAR. This simple approach allows a rapid determination of the compensation capacitors required, albeit in the global, partial or independent mode.

Analysis done on light machine shop in Nigeria Machine Tools for power factor improvements are shown Table 7 below.

**Table 6. Rated and measures parameter of centreless grinding machine**

| Induction rating (hp) | Power drawn (KW) | Present power factor | Required power factor |
|---|---|---|---|
| 10 | 500 | 0.75 | 0.928 |

**Table 7. Power Factor Improvement on light machine shop in Nigeria machine tools**

| Name of machines | Power rating(KW) | Induction motor rating(hp) | Present power factor | Required power factor | Required capacitor (KVAR) | Reduction in distribution losses (%) |
|---|---|---|---|---|---|---|
| Centreless Grinding Machine | 500 | 10 | 0.75 | 0.928 | 239.810 | 35 |
| CNC Thread and Worm Grinding Machines | 15 | 50 | 0.72 | 0.95 | 9.828 | 42.6 |
| Deep Hole Boring Machine | 15 | 20 | 0.73 | 0.95 | 9.6 | 41 |
| Broaching Machines | 15 | 70 | 0.7 | 0.95 | 10.63 | 45.7 |
| Lathe machines of various sizes | 75 | 20 | 0.9 | 0.97 | 12.05 | 13.9 |
| Gear Cutting Machines (Hobbing and Shaping | 7.5 | 75 | 0.7 | 0.95 | 4.485 | 46 |
| Universal, Vertical and Horizontal Milling Machines | 7.5 | 10 | 0.76 | 0.95 | 3.484 | 36 |
| Internal and External Grinding machine | 55 | 75 | 0.75 | 0.95 | 25.7 | 37.7 |
| Bolts Milling Machine | 55 | 75 | 0.78 | 0.95 | 21.21 | 32.6 |

### 6.2 Utility bills for Centreless Grinding Machine

From the Table 6 above, an uncorrected 666kVA demand, 230/400V, three-phase at 0.75 power factor.

Billing from power Supply Company: ₦5 .50/kVA demand
Correct to 0.928 power factor.

**Solution:**

kVA × power factor = kW
666 × 0 .75 = 500 kW actual demand

$$\frac{kw}{pf} = KVA$$

$$\frac{500}{0.928} = 539\ KVA\ correct\ billing\ demand$$

From Table 6 above, 239.810kvar capacitor is required to raise the power factor from 0 .75 to 0.928.

Uncorrected original billing:
= 666 kVA × ₦5 .50 = ₦3663/month
Corrected new billing:

= 539 KVA × ₦5 .50 = ₦2964.5/month

Amount saved per month due to PF improvement = ₦698.5

Amount saved per annual due to PF improvement = ₦8382

From Table 8 below, the bill of electricity consumed by centreless grinding machine before power factor correction at the end of the month is ₦3663 while the bill after the power factor correction is ₦2964.5. It is now glare that the improvement of power factor of the motor had saved ₦689.5 for the month which in turn will save total of ₦8382 per annual. The bill of electricity consumed by CNC thread and worm grinding machine before power factor correction at the end of the month is ₦4246 while the bill after the power factor correction is ₦3932. It is now glare that the improvement of power factor of the motor had saved ₦314 for the month which in turn will save total of ₦3768 per annual. The bill for Deep Hole boring machine before power factor correction is ₦3240 while the bill after the power factor correction is ₦2498. The improvement of power factor of the motor had saved ₦742 for the month which in turn will save total of ₦8904 per annual and the same goes for others machines.

**Table 8. Light machine shop in Nigeria machine tools for utility bill**

| Machine names | Bill before PFC (₦) | Bill after PFC (₦) | Amount saved/month (₦) |
|---|---|---|---|
| Centreless Grinding Machine | 3663 | 2964.5 | 698.5 |
| CNC Thread and Worm Grinding Machines | 4246 | 3932 | 314 |
| Deep Hole Boring Machine | 3240 | 2498 | 742 |
| Lathe machines of various sizes | 2845 | 2641 | 204 |
| Broaching Machines | 2859 | 2522 | 337 |
| Gear Cutting Machines (Hobbing and Shaping | 3167 | 2639 | 528 |
| Universal, Vertical and Horizontal Milling Machines | 5016 | 4830 | 186 |

From the analyses presented above, findings show that among other methods of improving power factor, correction capacitors are the simplest way to improve power factor of an electrical system. A machine tools plant has major electrical load in the form of induction motors. Power factor of typical motor is in the range of 0.75 to 0.90 and the average of the selected load is 0.8. After installing capacitor, this power factor becomes 0.928. This analysis also shows that power factor improvement finds a great scope to save electrical energy by reducing the distribution losses. Future scope exists in the terms of reduction in Total Harmonic Distortion on account of non-linear load.

Recent studies indicate the level of knowledge and implementation of motor system energy-efficiency measures is low. A plethora of information on motor system design, best practices, purchasing, and management is widely available, but few companies have embraced it. Training opportunities and tools to deepen the knowledge base of end-users is necessary to apply motor and motor system efficiency measures at the plant level [18].

It is hereby recommended that Over-correction should be avoided, if the size of power factor correction equipment is appropriates. Basically the power factor correction capacitor employed for individual motor is based on the magnetizing power since the reactive load of a motor is comparatively constant compared to actual kW load over compensation should be avoided.

It is also recommended that special care should be taken when applying star or delta type control power factor correction so that rapid on-off-on conditions are avoided on the capacitors. Typically the correction capacitors would be connected to either the delta or main contactor circuits.

## 7. CONCLUSION

There is a wide range of barriers that affect the implementation of improving power factor on electrical motors system, including operating issues (i.e. cost of installation of power factor correction equipment) that affect decisions regarding allocation of resources. Improvement of inductive motor’s efficiency in the plant results to the need to create high level knowledge on the plant and tools necessary to improve motor systems. Decision makers reviewing motor management practices the need to decide their adequacy in satisfying the improvement effectiveness and savings goals that many organizations are dealing with. Improvements of motors efficiency, purchasing, and training can lead to significant, sustainable savings. It can be therefore concluded that in order to ensure most favorably conditions for a supply system (electricity supply companies) and to prevent excessive utility charges to consumers, it is therefore extremely important to improve power factor as close to unity as possible.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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