Comparism of Single Phase Power Factor Correction for Series and Parallel Topologies

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***Abstract*- This paper presents dc ac and ac ac converter circuits including series and parallel switch capacitors topologies for electrical power factor correction equipment. Two parallel and series connection are made and tested to know the best method of connection to achieve an improved electrical power factor for eight loads. The output of the Centre-tap-transformer is connected to the input of the power factor correction (PFC) equipment measuring circuit after dc-ac or ac-ac selecting Electromagnetic Relay 1. A Single-Throw-Single-Pole switch is connected across the circuit so as to switch between the parallel and series topologies; while the output of this section is connected to the socket where loads are applied for measurement. The values obtained from each load applied are analyzed using calculations, tables, and graphs in order to ensure accurate results. The analyzed results obtained from the two different circuit arrangement are compared so as to know the best circuit arrangement to achieve an improved power factor.**

Various measurement and calculations on eight different loads used to test the performance of constructed single phase eight kilowatt PFC equipment show that the highest correction on low power factor occurred in load 8, the television in both parallel and series correction methods with corrections 0.28 and 0.26 respectively. The least correction was observed in load 7, the refrigerator with 0.11 and 0.09 power factors respectively for parallel and series topologies

***IndexTerms*—Series and Parallel topologies, Power Factor Correction, Capacitor, Load, Equipment.**

I. INTRODUCTION

In recent years, increasing attention has been paid to reduce the energy cost and inefficiency in electricity generation, transmission and distribution. When constructing a compensation scheme (corrective measure), 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. Many methods are available to produce the required reactive energy and improve the power factor of electrical appliances. Particularly, switched capacitors at the nearest point to the loads are a well-established approach to improve low power factor. Switched capacitors are available in almost all electrical component outlets and are often used, because they are more economical and easy to maintain compare to other devices. Not only that, but also they have no moving parts, unlike some other devices used for the same purpose. Connected equipment (transformers, motors, induction motors, induction generators, heaters etc.) cause a phase angle between current and voltage. When the current is phase shifted, it takes more current to deliver the same amount of active power.

Reactive power is not used to do work but it is the power that magnetic equipment (Transformer, Motor, and Relay) needs to produce the magnetic flux needed to operate equipment (Theraja, 2000, Jinrong and Lee 1997, www.powerstudies.com, 2013). Many industrial loads are inductive such as motors, transformers, etc. The current drawn by an inductive load consists of magnetization current and power producing current. The magnetizing current is required to sustain the electromagnetic field in a device and creates reactive power. An inductive load draws current that lags the voltage, in that the current follows the voltage waveform. The amount of lag is the electrical displacement (or phase) angle between the voltage and current.

Equipment located in consumer premises emits reactive power that lowers the power factor during power transmission. Power factor is the ratio of the power needed to do work within the consumer premises to the power delivered by the utility. The power needed by the consumer premises equipment to operate is measured in kilowatts (kW) which could also be referred to as actual power, active power or real power. The amount of the power delivered by the utility is measured in kilovolt amperes (kVA). This is also known as apparent power. It is the vectorial summation of kVAR and kW.

More kVAR present in the utility system results in a low power factor, and a high current (I) present on the wire. (Jinrong and Lee, 1997, www.powerstudies.com, 2013).

II. POWER FACTOR

Definition;

Power factor is the ratio of actual power to apparent power.

$$\text{P.F.} = \frac{\text{kW}}{\sqrt{\text{kW}^2+\text{kVAR}^2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

The higher the percentage of kVARs, the lower the ratio of kW to kVAR. Thus, the lower the power factor, the lower the percentage of KVAR, the higher the ratio of kW to kVAR. As kVAR approaches zero, the power factor approaches ideal 1.0 or unity.

The power vector triangle (figure 1.0 below) illustrates the relationship between kW, kVA, kVAR and power factor (P.F.)

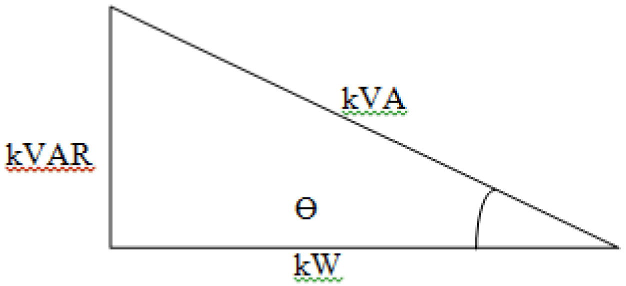


Fig. 1.0 Relationship between kW, kVAR and Power Factor (P.F)

$$P.F. = \frac{kW}{\sqrt{kW^2 + kVAR^2}} = \cos\theta \quad \ldots\ldots 2$$

$$\frac{kVAR}{kVA} = \sin\Theta \quad \ldots\ldots 3$$

$$kVA = \sqrt{kW^2 + kVAR^2} \quad \ldots\ldots 4$$

In order to have an efficient system, power factor must be closer to one (1.0) as possible.

Sometimes, electrical distribution has a power factor much less than 1.0. This requires the idea of investigating the causes of and improvement on low power factor.

((Jinrong and Lee 1997, Jovanovich M.M.,et al, 1995, www.powerstudies.com ,2013).

III. CAUSES OF LOW POWER FACTOR

A poor power factor can be the result of either a significant phase difference between the voltage and current at the load terminals or it can be due to a high harmonic content or distorted/discontinuous current waveform. Poor load current phase angle is generally the result of poor load current phase angle, and is generally the result of an inductive load such as an induction motor, power transformer, lighting ballasts, welder or induction furnace, induction generators, Wind mill generators and high intensity discharge lightings.

Since power factor is defined as the ratio of kW to kVA, low power factor result when kW is small in relation to kVA. This occurs when kVAR is large in inductive loads.

These inductive loads (Which are source of reactive power) include;

- Transmission wires/lines
- Induction Motors
- Inductive generators (Wind mill generators)
- High Intensity discharge (HID) lighting.

These inductive loads constitute a major portion of the power consumed in industrial complexes (Fermandez, et al., 2005, Lucanu et al, 2007).

Reactive power (kVAR) required by inductive loads increase the amount of apparent power (kVA) in electrical distribution power result in large angle Θ (Measured between kW and kVA). Thus, as Θ increases, cosine Θ (or power factor) decreases.

IV. EFFECT OF LOW POWER FACTOR (P.F) IN POWER TRANSMISSION

1. Increases heat losses in transformers and distribution equipment,
2. It reduces electrical generator, cables and appliances life span,
3. Unstabilized voltage levels,
4. Decreases energy efficiency,
5. Increase power losses,
6. Increases electricity cost by paying power factor surcharges. (Read et al, 1961 Ridley, 1989, www.powerstudies.com ,2013).

V. METHODS OF POWER FACTOR CORRECTIONS

Various researches are necessary to examine causes of and effects of various types of loads on low power factor, the effects of low power factor on power transmission and their corrective measures.

Most loads on electrical distribution system fall into one of these three categories;

1. Resistive
2. Inductive or
3. Capacitive

Various methods employed in correcting power factors are:

Switch Capacitors, Fixed Capacitors, Static VAR compensation (SVC), Static synchronous compensation (STATCOM), Synchronous condensers

Reactive power (kVARs), cause by inductive loads, always act at 90-degree angle to working power (kW).

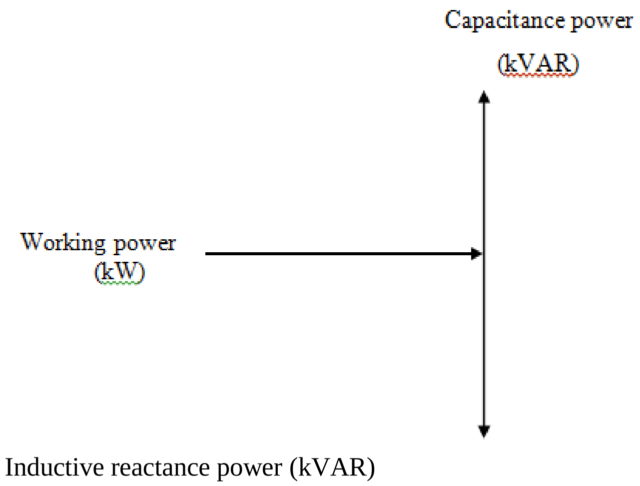


Fig.1.1 Relationship between capacitive reactance and inductive reactance as applied to working power.

Inductance and capacitance react 180 degree to each other. Capacitor store KVARs and release energy opposing the reactive energy caused by the inductor.

The presence of both a capacitor and inductor in the same circuit results in a continuous alternating transfer of energy between the two. Therefore, when the circuit is balanced, all the energy released by the inductor is absorbed by the capacitor (Hua, 1993 and Ridley, 1989, www.powerstudies.com, 2013). The approach adopted in this research is based on switched capacitor method with its various Series and Parallel circuit topologies. For an accurate measurements and calculations, the corrected p.f must be able to approach a value of 1.0. Below is the block diagram of the PFC system.

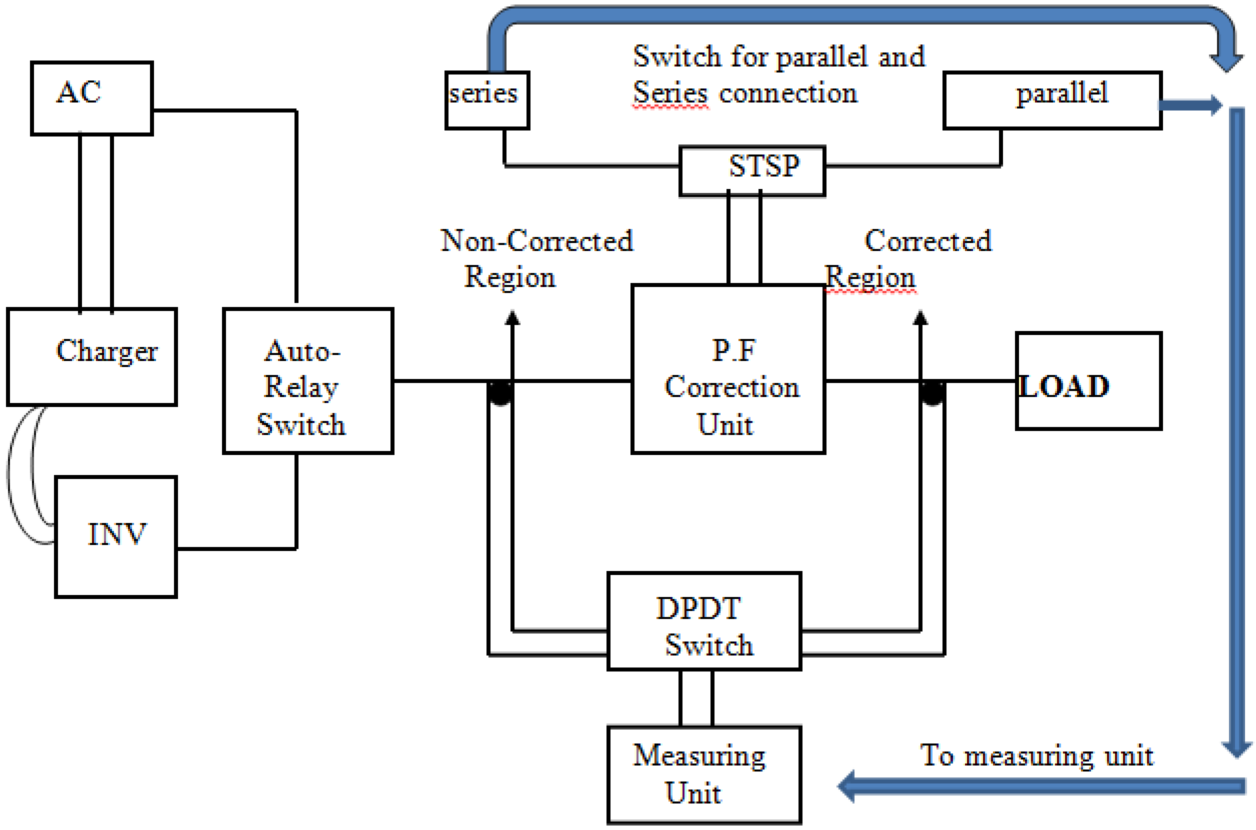


Figure 2.1 Power factor measurement block diagram

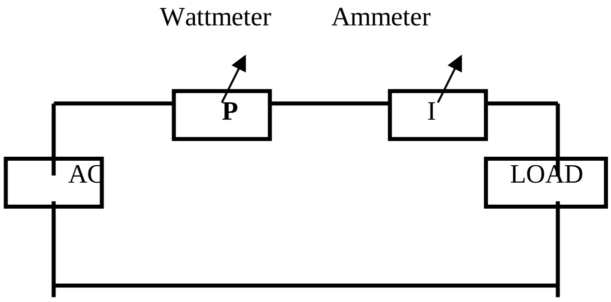


Figure 2.2 Circuit arrangement showing non P.F correction (input P.F on AC) on load

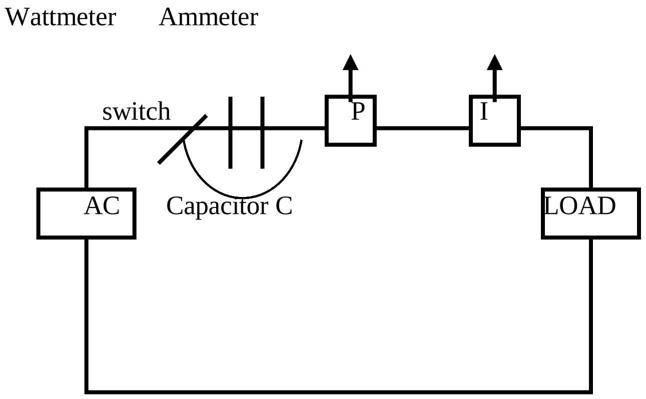


Figure 2.3. Series circuit arrangement for measurement of effect of load on P.F for input AC and measurement of correction of P.F on loads.

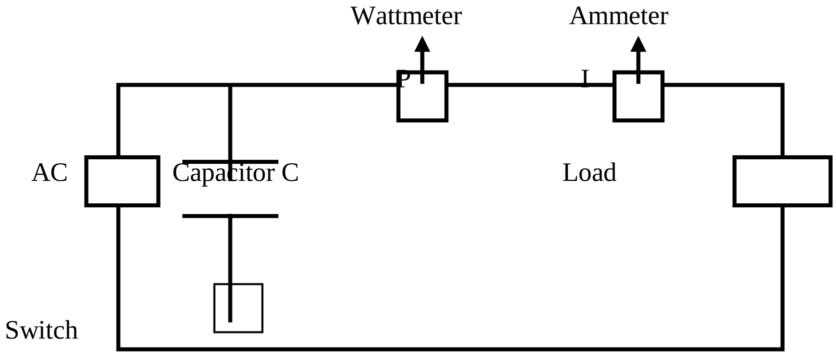


Figure 2.4 Parallel circuit arrangements for measurement of the effect of load on p.f on input AC and measurement of correction of P.F on loads.

Applying Kirchhoff's Mesh Rule;
Series PFC topology Equation:

$$(R_T)^2 = (Xc)^2 + (R)^2 + (XL)^2 + (Xlc)^2 \text{………………………………….}(5)$$

$$r_t = \sqrt{(Xc)^2 + (r)^2 + (xl)^2 + (xcl)^2}$$

$$(r_t)^2 = \left(\frac{1}{2\pi fc}\right)^2 + (R)^2 + (2\pi fl)^2 + \left(\frac{1}{2\pi fc_L}\right)^2 \text{…………………………....}(6)$$

$$(r_t)^2 = \left(\frac{1}{2\pi fc}\right)^2 + \underbrace{R^2 + (2\pi fl)^2 + \left(\frac{1}{2\pi fc_L}\right)^2}_{\text{Load}} \qquad \text{..................(7)}$$

Theoretically, it seems that a series correction for low power factor will increase the resistance in the circuit

Parallel PFC topology Equation:

$$(R_T)^2 = \left(\frac{1}{2\pi fc}\right)^2 \qquad \text{.......................................(8)}$$

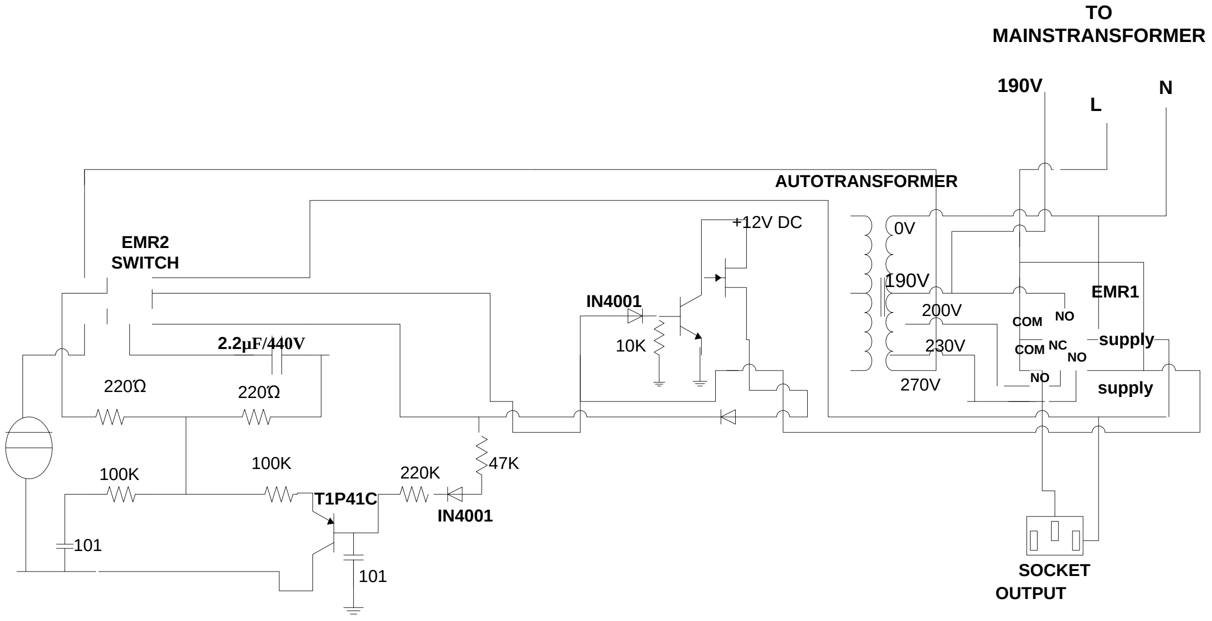
$$\left(\frac{1}{2\pi fc}\right)^2 = \underbrace{R^2 + (2\pi fl)^2 + \left(\frac{1}{2\pi fcl}\right)^2}_{\text{Load}} \qquad \text{.................................(9)}$$

VI. THE POWER FACTOR CORRECTION (P.F.C) MEASURING SECTION FOR SERIES AND PARALLEL TOPOLOGY

The power factor measuring stage/section is the most important aspect of this research. In this section two connections are made (parallel and series connection). These two circuits arrangements are made to be tested to know the best method of connection to achieve an improved P.F for various loads applied during P.F correction measurement.

The output of the Centre-tap-transformer is connected to the input of the P.F.C measuring circuit via Electromagnetic Relay 1, (E.M.R.1) to the circuit. A Single-Throw-Single-Pole (STSP) switch is connected across the circuit so as to switch between the parallel and series arrangement for load power factor measurement, while the output of this section is connected through E.M.R.2 to the socket (outlet), where loads are applied for measurement as shown in figure 3.9 below.

The input load voltage and uncorrected output load factor values and as well as corrected output load factor values are displayed on the LCD via measuring meters of the power factor correction (P.F.C) measuring section of the device. The corrected and the uncorrected power factors shall be calculated using power factor formula in the section.



.DIAGRAM OF POWER FACTOR CORRECTION(P.F.C) MEASURING CIRCUIT

Figure 2.9 P.F.C. measuring circuit sections

VII. TESTS AND MEASUREMENT OF POWER FACTOR FOR SERIES AND PARALLEL TOPOLOGY IN ELECTRICAL APPLIANCES

Measurement:

The following electrical appliances/loads were selected as case study for this research works, these appliances were supplied with AC/DC through power factor correction power supply device at their different maximum power demand.

1. Electric Heater (Boiling Ring)
2. Desktop Computer Set
3. Electric Standard Fan
4. Electric Blender
5. Electric Cooker
6. Electric Iron
7. Refrigerator
8. Television Set (T.V. Set)

The above listed electrical loads shall be tested and measured one after the other for uncorrected p.f and for corrected p.f

The measurement of power factor (p.f.), Active power (P), Reactive power (Q), Apparent power (S) and current (I) is be taken for each load applied. The initial and the required i.e. Uncorrected and corrected power factor for individual load for different topology shall be calculated, and later illustrated in the tables and graphs.

CALCULATIONS ON VARIOUS LOAD APPLIED

The following results were obtained for each load applied for power factor correction measurements (both series and parallel connection).

Load (1)

ELECTRIC BOILING RING

For parallel circuit arrangement

Before P.F.C.

Real power (p) = 1.2kw = 1200w

Load voltage (Vrms) = 255v

Apparent power (s) = Vrms x Irms

S = 255v x 6.28A

S = 1601.4 VA

Power factor (p.f) $= \frac{Real\ Power}{Apparent\ Power} = \frac{P}{S}$

$$\text{p.f.} = \frac{1200}{1601.4}$$

p.f = 0.75

Where:

$$\text{kVA} = \sqrt{kW^2 + kVAR^2} \text{ or,}$$

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

Where kVAR = reactive power (Q)

Therefore,

$$\text{kVAR}_1 = \sqrt{kVAR^2 - kW^2}$$

$$Q_1 = \sqrt{(1601.4)^2 - (1200)^2}$$

kVAR_1 = 1060.42 or

Q_1 = 1.60kVAR

After power factor correction in parallel

Real power (p) = 1200w

Load voltage (Vrms) = 220v

Load current (Irms) = 5.62A

Apparent power (s) = (220 x 5.62) VA

S = 1236.4VA

$$\text{p.f} = \frac{1200}{1236.4}$$

p.f = 0.97

Therefore,

$$\text{kVAR}_2 = \sqrt{S^2 - P^2}$$

$$Q_2 = \sqrt{(1236.4)^2 - (1200)^2}$$

kVAR_2 = 297.80 or Q_2 = 0.30KVA

Hence, the amount of power required to boost power factor from initial to required one = $\text{kVAR}_1 - \text{kVAR}_2$

Q required = 1060.42 – 297.80

VAR required = 762.62

For series circuit arrangement

Before p.f.c.

Real power (p) = 1200w

Load voltage (Vrms) = 255v

Load current (Irms) = 6.28A

Apparent power (s) = 255v x 628A

S = 1601.440VA

p.f $= \frac{P}{S} = \frac{1200}{1601.4}$

p.f = 0.75

$Q_1 = \sqrt{S^2 - P^2}$

$Q_1 = \sqrt{(1601.4)^2 - (1200)^2}$

$kVAR_1 = 1060.42$

$Q_1 = 1.60\ kVAR_1$

After p.f.c in series

Real power (p) = 1200w

Load voltage (Vrms) = 22.3v

Load current (Irms) = 5.6A

Apparent power (s) = 223v x 5.6A

= 1248.8VA

p.f $= \frac{P}{S} = \frac{1200}{1248.8}$

= 0.96

$kVAR_2 = \sqrt{S^2 - P^2}$

$Q_2 = \sqrt{(1248.8)^2 - (1200)^2}$

kVAR2 = 345.69 or, $Q_2 = 0.35KVAR_2$

Q required = $Q_1 - Q_2$

= 1060.42 – 345.69

= 714.73

Q required = 714.73

LOAD 2

DESKTOP COMPUTER SET

For parallel circuit arrangement

Before p.f.c

Real power (p) = 1200w

Load voltage (Vrms) = 237v

Load current (Irms) = 6.66A

Apparent power (s) = 237 x 6.66

S = 1578.42VA

p.f $= \frac{P}{S}$

= 0.76

$Q_1 = \sqrt{S^2 - P^2}$

$Q_2 = \sqrt{(1578.42)^2 - (1200)^2}$

$Q_1 = kVAR_1 = 1025.38$ or $1.03KVAR_1$

After p.f.c in parallel

Real power (p) = 1200w

Load voltage (Vrms) = 230v

Load current (Irms) = 5.32A

Apparent power (s) = 230v x 5.32A

= 1223.6VA

p.f $= \frac{1200}{1223.6} = 0.9$

$Q_1 = \sqrt{S^2 - P^2}$

$Q_2 = \sqrt{(1223.6)^2 - (1200)^2}$

Q2 = 239.16 or

$Q2 = 0.24kVAR_2$

Q required = $Q_1 - Q_2$

= 1025.38 – 239.16

VAR = 786.22

Q required = 786.22VAR

For series circuit arrangement

Before p.f.c

Real power (p) = 1200w

Load voltage (Vrms) = 237V

Load current (Irms) = 6.66A

Apparent power (s) = 237 x 6.66

S = 1578.42VA

$$p.f = \frac{1200}{1578.42}$$

$$= 0.76$$

$$Q_1 = \sqrt{S^2 - P^2}$$

$$Q_2 = \sqrt{(1578.42)^2 - (1200)^2}$$

Q_1 = 1025.38

Q_1 = 1.03kVAR

After power f.c in series

Real power (p) = 1200w

Load voltage (Vrms) = 232v

Load current (Irms) = 5.39A

Apparent power (s) = 232v x 5.39A

$$p.f = \frac{1200}{1250.48}$$

p.f = 0.96

$$Q_2 = \sqrt{S^2 - P^2}$$

$$= \sqrt{(1250.48)^2 - (1200)^2}$$

Q_2 = 351.71

Q_2 = 0.35kVAR

Q required = $Q_1 - Q_2$

= 1025.38 – 351.71

Q required = 673.67VAR

Similar calculations are done for loads 3 to 8 to get the summarized tables that follow.

VIII. RESULTS AND DISCUSSION

RESULTS

The calculated values for uncorrected and corrected power factor for each load applied (both parallel and series circuit arrangement) on AC input in this research are summarized in the following tables. The inverted power was not used so as to minimize experimental cost arising from purchase of new deep cycle battery.

Table 1:
Before P.F.C. on AC supply for each load applied
[Uncorrected power factor]

S/N	**LOAD**	**VOLTAGE (V)**	**P.F.**	**P (KW)**	**Q (KVAR)**	**S (KVA)**	**I (A)**
1.	Boiling Ring	255	0.75	1.2	1.06	1.60	6.28
2.	Desktop Computer Set	237	0.76	1.2	1.03	1.58	6.66
3.	Electric Fan	257	0.68	2.3	2.48	3.38	13.16
4	Electric Blender	243	0.65	1.8	2.11	2.77	11.40
5	Electric Cooker	260	0.77	1.5	1.24	1.95	7.49
6	Electric Iron	253	0.74	1.2	1.09	1.62	6.40

7	Refrigerator	251	0.78	2.0	1.61	2.57	10.23
8	T.V. Set	230	0.68	1.1	1.18	1.61	7.0

The table (table 1) shows that electric blender produced the lowest power factor while the refrigerator has the highest power factor before the power factor correction.

Table 2:
After P.F.C. on AC supply with parallel connection for each load applied

S/N	**LOAD**	**VOLTAGE (V)**	**P.F.**	**P (KW)**	**Q (KVAR)**	**S (KVA)**	**I (A)**
1.	Boiling Ring	220	0.97	1.2	1.30	1.24	5.62
2.	Desktop Computer Set	230	0.98	1.2	1.24	1.22	5.32
3.	Electric Fan	233	0.95	2.3	2.73	2.41	10.35
4	Electric Blender	228	0.92	1.8	2.77	1.96	8.58
5	Electric Cooker	240	0.94	1.5	1.55	1.59	6.65
6	Electric Iron	235	0.98	1.2	1.23	1.22	5.20
7	Refrigerator	230	0.89	2.0	1.04	2.25	9.80
8.	T.V. Set	225	0.96	1.1	1.32	1.15	5.09

Table 2 shows that refrigerator produced the lowest power factor while the electric iron and desk top computer have the highest power factor before the power factor correction in parallel

Table 3:
After p.f.c on AC supply with Series connection for each load applied

S/N	**LOAD**	**VOLTAGE (V)**	**P.F.**	**P (KW)**	**Q (KVAR)**	**S (KVA)**	**I (A)**
1.	Boiling Ring	223	0.96	1.2	0.35	1.25	5.60
2.	Desktop Computer Set	232	0.96	1.2	0.35	1.25	5.39
3.	Electric Fan	236	0.93	2.3	0.91	2.47	10.48
4	Electric Blender	230	0.90	1.8	0.87	1.99	8.69
5	Electric Cooker	243	0.93	1.5	0.59	1.61	6.67
6	Electric Iron	237	0.97	1.2	0.30	1.24	5.22
7	Refrigerator	233	0.87	2.0	1.14	2.29	9.87
8.	T.V. Set	228	0.94	1.1	0.39	1.17	5.13

Table 3 shows that electric blender has the least power factor while electric iron has the highest power factor after series power factor correction.

Table 4:
Table illustrating the corrected power factor (p.f), for both parallel and series connection on each load applied.

S/N LOAD	UNCORRECTED P.F.	CORRECTED P.F. IN PARALLEL	CORRECTED P.F. IN SERIES
1.	0.75	0.97	0.96
2	0.76	0.98	0.96
3	0.68	0.95	0.93
4	0.65	0.92	0.90
5	0.77	0.94	0.93
6	0.74	0.98	0.97
7	0.78	0.89	0.87
8	0.68	0.96	0.94

The following graphs were plotted below in order to compare the values of data collected for various power factor measurements.

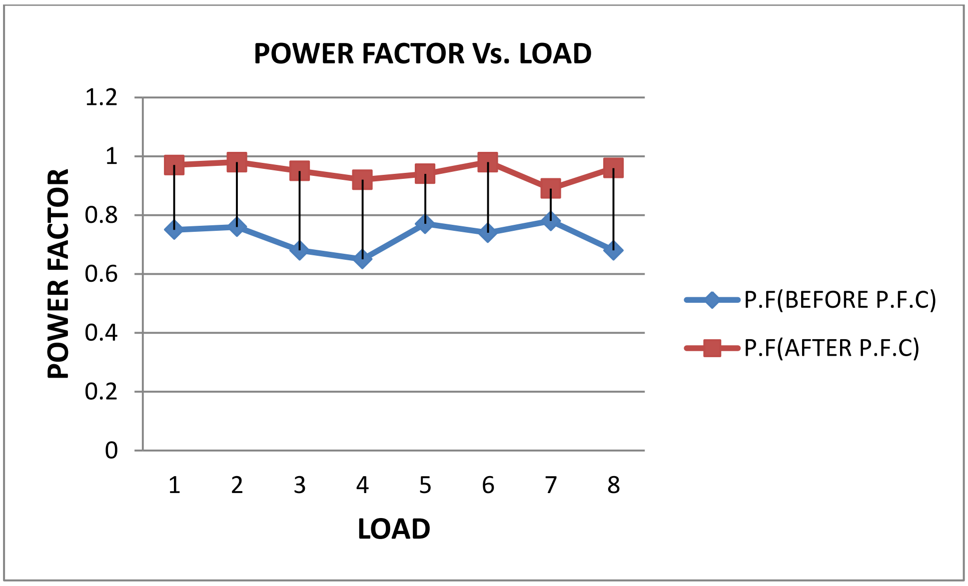


Figure 4.1 Power factor Vs. Load for parallel connection

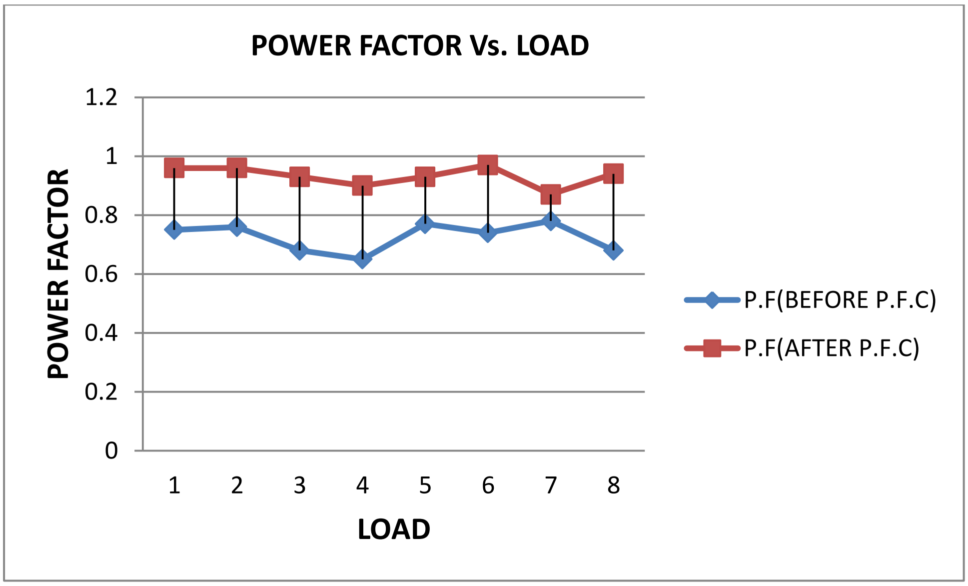


Figure 4.2 Power factor Vs. load for series connection

IX. DISCUSSION OF RESULT

The various measurements and calculations show that parallel circuit arrangement of the produced the nearest appropriate p.f values closer to unity (1.0), more than series circuit arrangement throughout hence series method of P.F.C consumed more power compare to that of Parallel arrangement method. The highest correction on low power factor occurred in load 8, the television in both parallel and series correction methods with corrections 0.28 and 0.26 respectively. The least correction was observed in load 7, the refrigerator with 0.11 and 0.09 power factors respectively for parallel and series topologies

When a system power factor is increased or corrected, the amount of reactive current flowing and the reactive power in the system is lowered thus reducing electrical power loss, the system working capacity is improved, the electrical plant maintenance costs will be reduced and the generator and electrical appliances will also last longer.

X. CONCLUSION

The research using two different circuit connections (series and parallel) has increased power factor due to loads applied to an AC supply. The methods of P.F.C equipment construction made it possible to analyze the best circuit arrangement to achieve a better improved power factor. The power factor measurement result made it clear by comparison that power factor of loads applied that were relatively low were sufficiently improved when switched from series to parallel circuit topology.

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