Synopsis

The aim of the experiment was to investigate the factors that affect power flow in a power supply system, paying particular attention to power factor. It could be deduced from the results that by balancing inductive loads, as the majority of loads are, against capacitive loads that the power factor could be raised closer to the desired value, unity and that the voltage regulation could be improved.

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Introduction

The performance of a balanced three-phase power system can be obtained by the study of a single-phase system. A ‘short’ transmission line (or feeder) that connects a generator to a load will be employed. Power flow is from source to load.

Objective

The objective of the experiment was to investigate the factors that affect power flow with particular reference to the load power factor.

Experimental procedure

Representation of power system.

The experiment was connected as fig.1 below.

Transmission lines that are short in length (less than 80km) can be represented by a series impedance as shown in the system below.

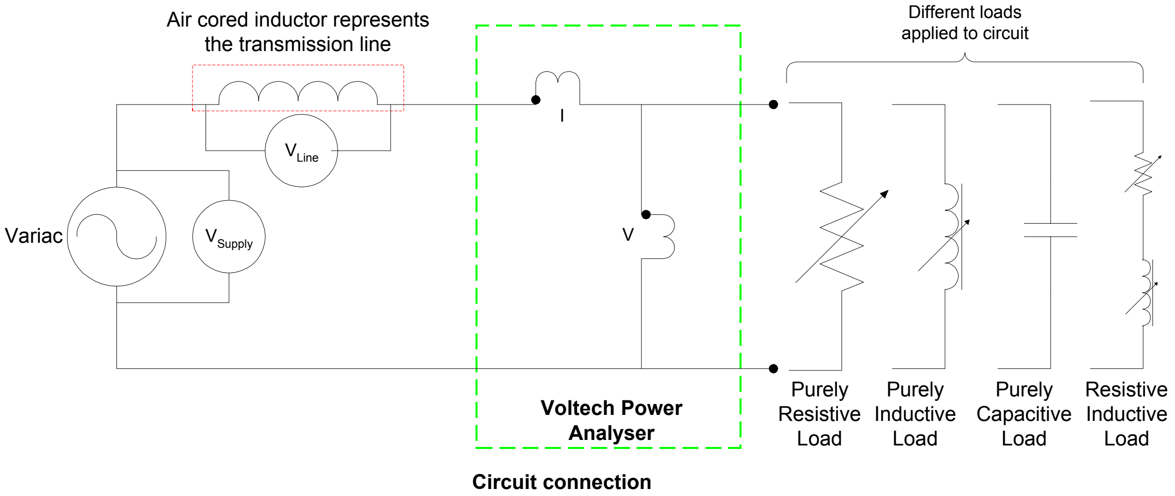


Fig.1 Circuit connection

Equipment Used

Equipment	Serial Number
Variac	EE7063
Variable Resistor	EE65.5545
Variable Inductor (Air core – line)	EE51-6487
Variable Inductor (Load)	EE51-6488
Power Analyser	EE65-1976
MC Voltmeter (V_{line})	EE51-6369
MI Voltmeter (V_{supply})	EE51-5051
Capacitor Bank – 1	EE6049
Capacitor Bank – 2	5172
Capacitor Bank – 3	EE6047

Fig.2 Equipment list

Results

Tabulated results

V_{supply} (V)	V_{line} (V)	I (A)	P (W)	p.f.
53	9.6	0.9772	47.71	-0.976
58	20.3	2.076	104.1	-0.987
62	29	2.991	147.77	-0.991
69	39	4.022	200.7	-0.994
74	48.1	4.936	241.9	-0.995

Fig.3 Purely resistive load

V_{supply} (V)	V_{line} (V)	I (A)	P (W)	p.f.
58	9.4	0.9596	1.78	-0.036
68	19.4	1.989	5.6	-0.055
78	28.9	2.993	11.19	-0.074
88	38.9	4.034	19.4	-0.094

Fig.4 Purely inductive load

V_{supply} (V)	V_{line} (V)	I (A)	P (W)	p.f.	Number of capacitor banks
27	21.3	2.2	0.06	0.000	1
10	43	4.471	1.115	0.004	2
10.5	57.5	5.991	3.2	0.010	3

Table 3: Purely capacitive load

V_{supply} (V)	V_{line} (V)	I (A)	P (W)	p.f.	$V_{inductor}$	$V_{resistor}$
54	10.1	1.035	47.06	-0.916	10.75	44.5

Fig.5 Resistive / inductive load

NOTE: Minus values for power factor indicate a lagging current.

Results (Cont.)

Graphs

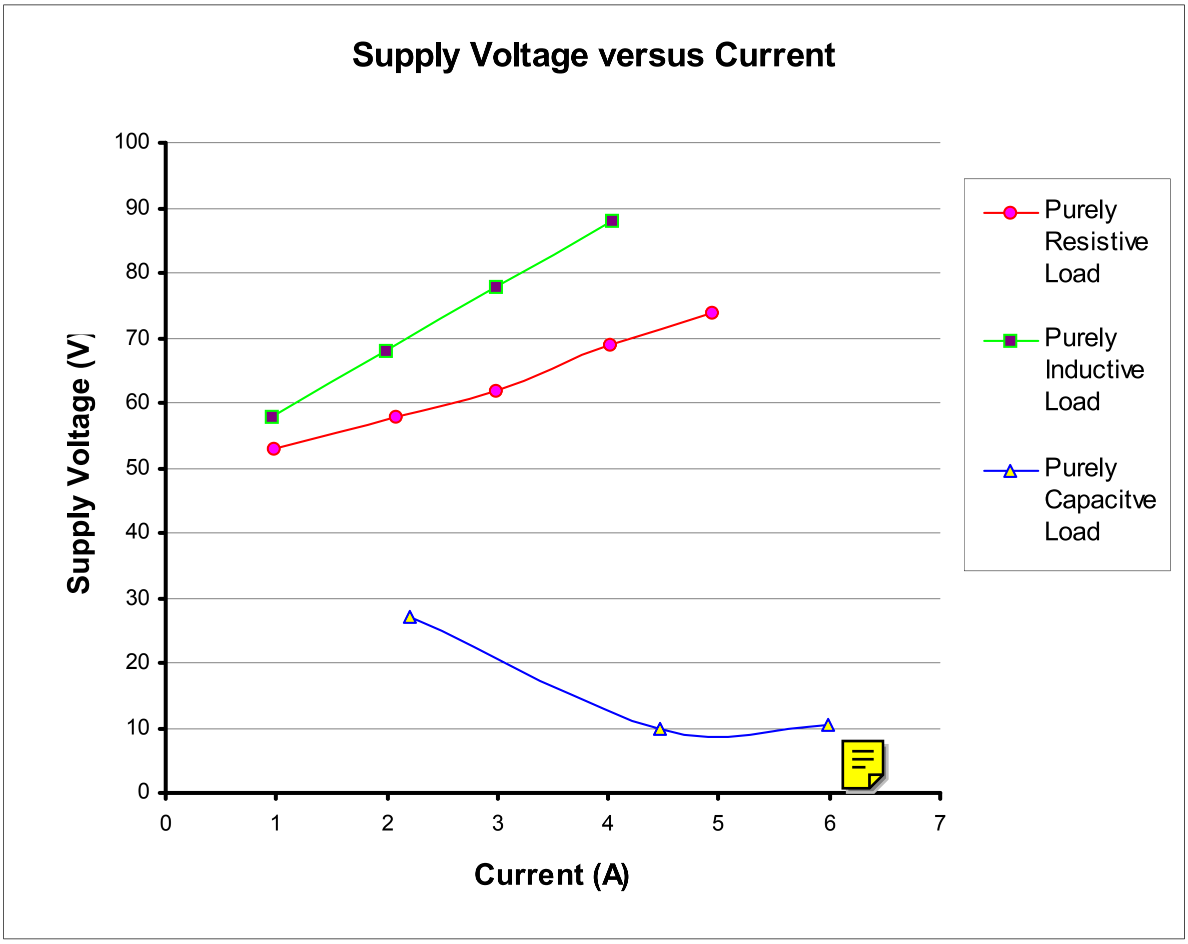


Fig.6 Graph of supply voltage versus current

Results (Cont.)

Graphs

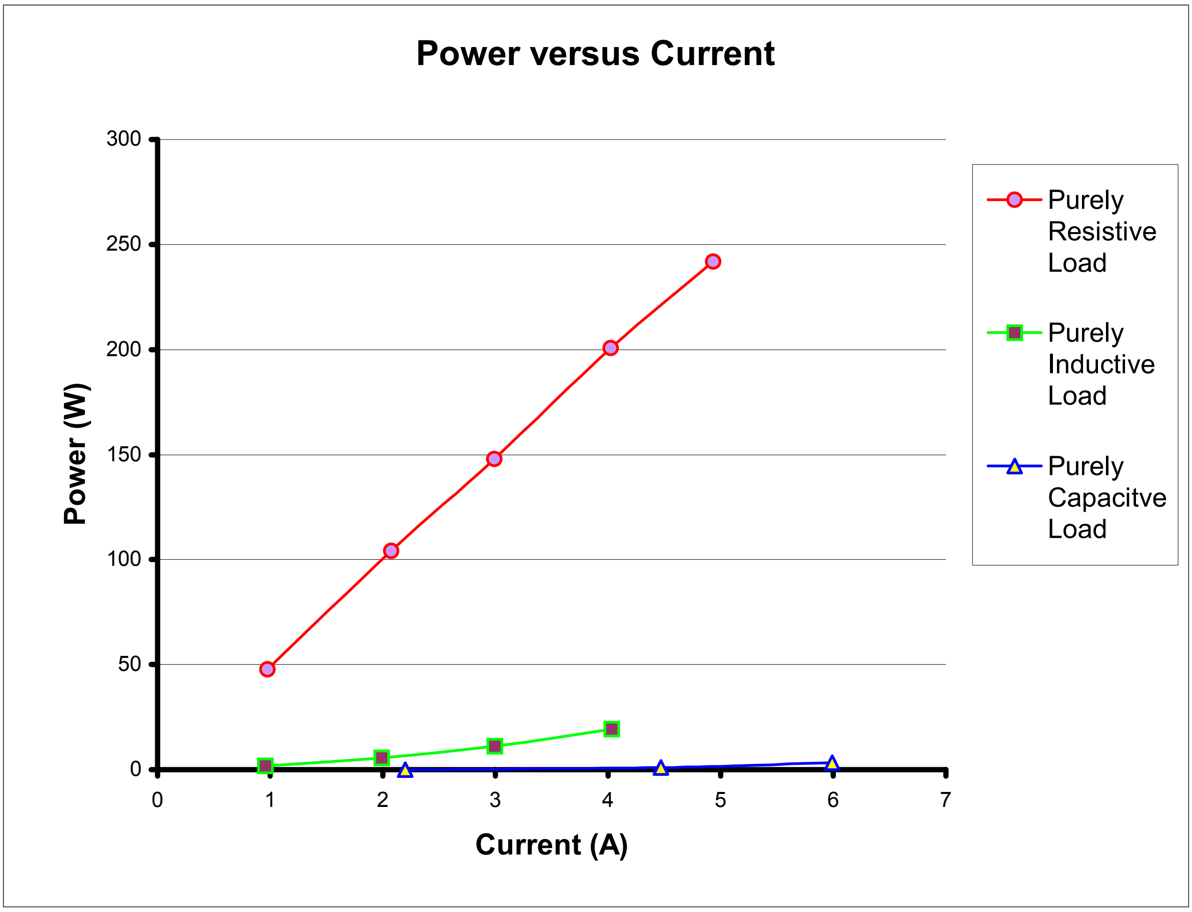
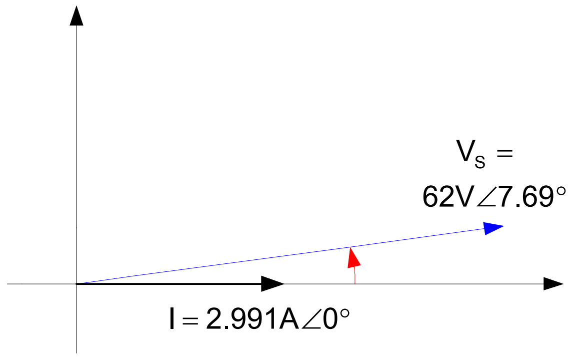


Fig.7 Graph of power versus current

Results (Cont.)

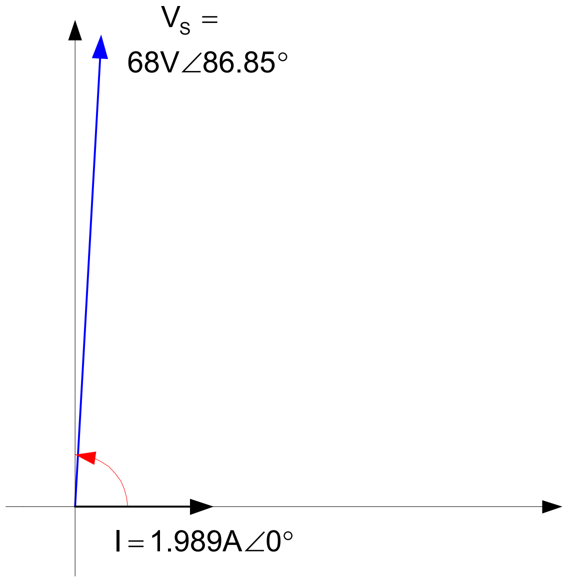
Phasor diagrams



Phasor diagram for purely resistive load

Power factor=0.991

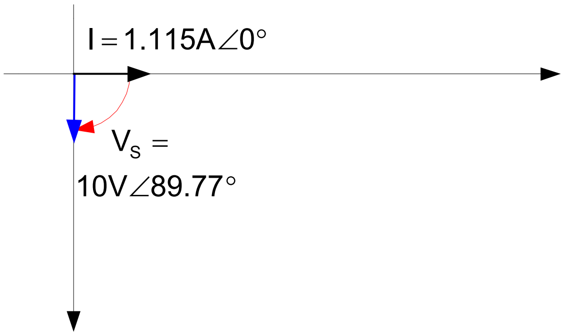
$\therefore \phi = \cos^{-1}(0.991) = 7.69°$



Phasor diagram for purely inductive load

Power factor=0.055

$\therefore \phi = \cos^{-1}(0.055) = 86.85°$



Phasor diagram for purely capacitive load

Power factor=0.004

$\therefore \phi = \cos^{-1}(0.004) = 89.77°$

Discussion of results

As can be seen in the graph of supply voltage versus current (Fig.XX), all three lines would intercept the x-axis origin at approximately 50V.
Given the equation:

$$\overline{V_S} = \overline{I} \times \overline{Z} + \overline{V_R}$$

This is in the format of:

$$y = m \times x + c$$

This is the equation of a straight line, of which they all are[1], and if no current is being taken, then $\overline{V_S}$=(0×$\overline{Z}$)+50=50V, which corresponds to the x-axis intercept.

If we look at the graph of results for power versus current (Fig.XX), taking into account:

$$P = V \times I \times \cos\Phi$$

And that:

$$P = I^2R$$

It can be seen that the plots are beginning to follow an exponential curve, as would be expected. In the experiment and results, the load is referred to as being 'purely inductive' and 'purely capacitive', but this is not strictly true. The inductor will have resistance within, and capacitance between its windings and inductive reactance, and the capacitor will have an ESR (equivalent series resistance) and a capacitive reactance. Both circuits will suffer from additional resistance and capacitance between the connections. This additional resistance causes power to be consumed (no power would be used if R=0).
As can be seen from the graph of supply voltage versus current (Fig.6), if we take a given value of current (2.5A) and look for the corresponding supply voltages for the inductive and capacitive loads, it can be seen that the inductive load requires more supply voltage to supply the same current, whereas the capacitive circuit requires less voltage for the same current. It can be seen that they both deviate away from each other in a linear fashion – a practical use for this would be for power factor correction (see next page), where they are used to balance each other and correct the power factor of an inductive load. If the supply voltage is observed at a current of 4A, it can be seen that this relationship is still true.
From data obtained from the power versus current graph (Fig.7), at currents of 2.5A and 4A, it can bee seen that both the inductive and capacitive loads consume little power. The resistive load makes best use of the supply as you can supply less voltage for a given current than an inductive load, and it will consume less start up current (i.e. no initial current spike) than the capacitive load and it has a power factor approaching unity.

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[1] The graph for purely capacitive load is linear between the first two plotted points (see conclusion)

Discussion of results (cont.)

If we look at the phasor diagrams compared with the theory we can see that:

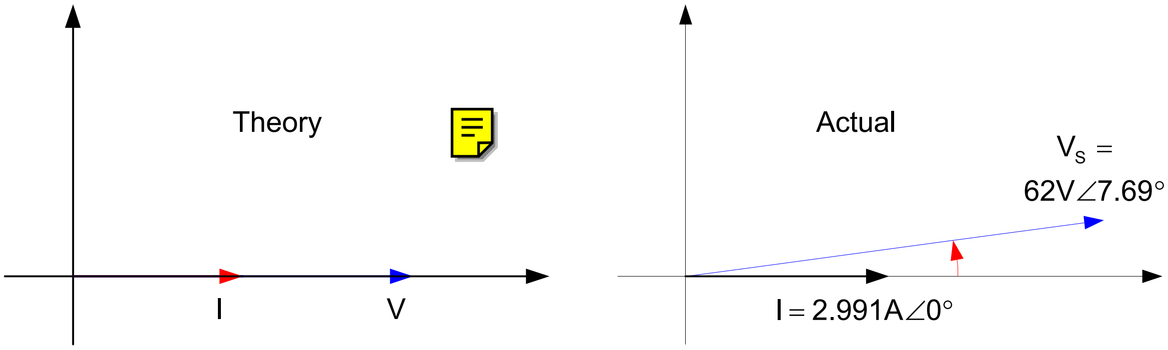

Fig.11 Theoretical and actual phasor diagrams for purely resistive loads.

In a purely resistive load, the voltage and current should be in phase with each other, but in practice, the current lags the voltage. This is due to a small amount of inductance within the circuit itself (transmission line, circuit connections etc.), and the fact that the resistive load was comprised of a wire wound resistor which itself would have an inductance.

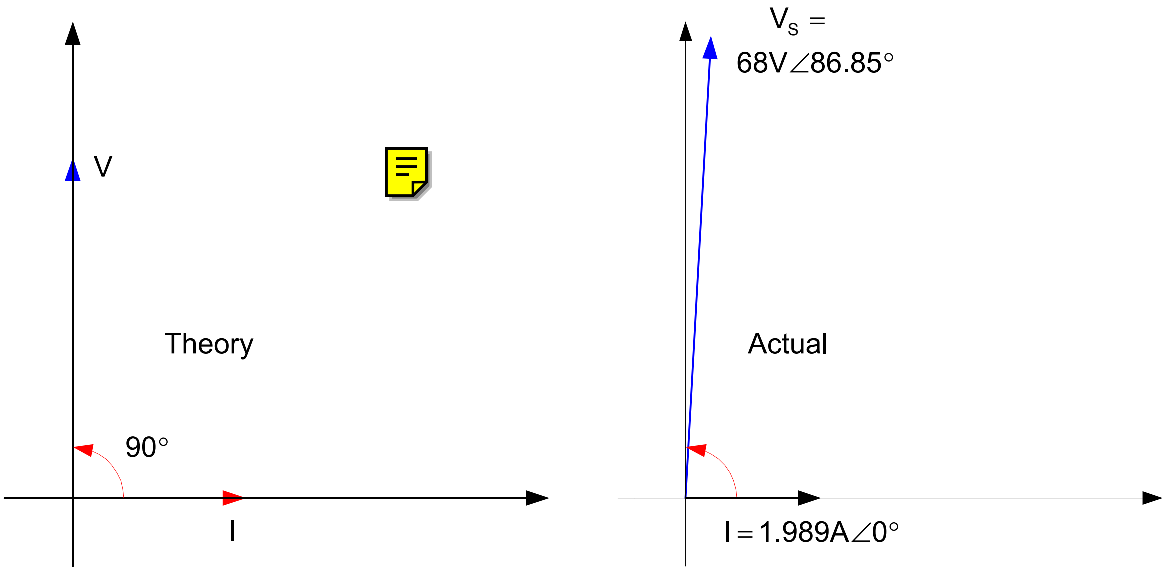

Fig.12 Theoretical and actual phasor diagrams for purely inductive loads.

In a purely inductive load theory states that the voltage should lead the current by 90°, but the practical circuit will exhibit a small amount of resistance in the coils of the inductor, transmission line and circuit connections and this is what causes the voltage to become less than 90°.

Discussion of results (cont.)

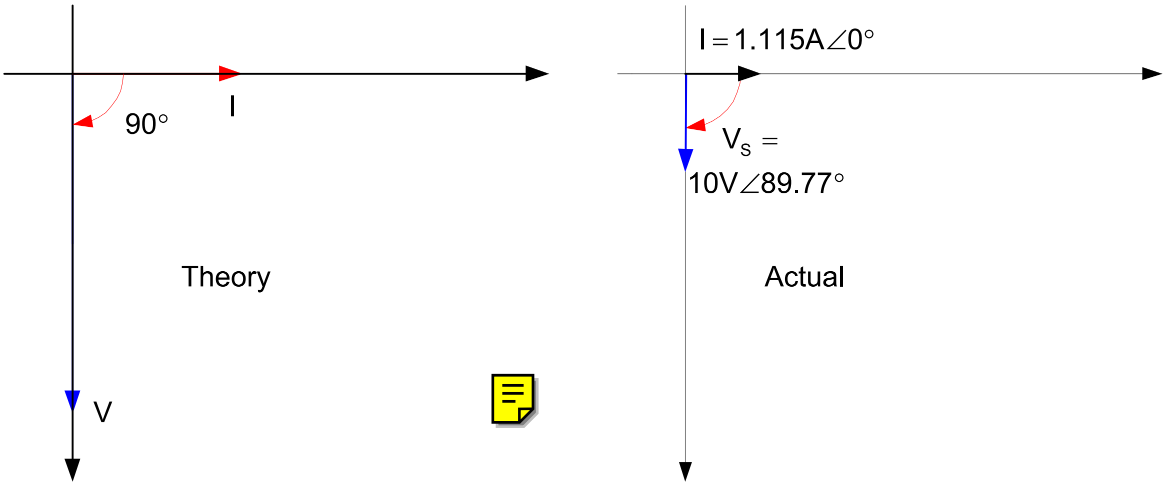

Fig.13 Theoretical and actual phasor diagrams for purely inductive loads.

In a capacitive circuit the current should lead the voltage by an angle of 90°, but small resistive losses introduced in the practical circuit (capacitors have an equivalent series resistance, transmission line, circuit connections) cause the angle to reduce slightly.

There is a voltage drop in the transmission line, $V_L = IZ$, and hence a voltage difference between the supply (or generated) voltage and the regulated (end-user) voltage. This should be kept to a minimum in order to reduce costs through wasted power for the supplier.

$$\text{Voltage regulation} = \frac{V_S - V_R}{V_S} \times 100\%$$

If we look at the voltage regulation for all three cases at a current of 2A:

$$\text{Voltage regulation for resisitve load} = \frac{V_S - V_R}{V_S} \times 100\% = \frac{58 - 50}{58} \times 100\% = 2\%$$

$$\text{Voltage regulation for inductive load} = \frac{V_S - V_R}{V_S} \times 100\% = \frac{68 - 50}{68} \times 100\% = 26.47\%$$

$$\text{Voltage regulation for capacitive load} = \frac{V_S - V_R}{V_S} \times 100\% = \frac{27 - 50}{27} \times 100\% = 46\%$$

Power factor correction is used to obtain a power factor of as close to one as is possible for the efficient use of the supplied power. A high power factor reduces the current flowing in supply system, and hence there is a corresponding reduction in the cost of cables, switchgear, transformers etc. The majority of loads connected to the distribution network will be inductive, e.g. motors, and therefore current will lag the voltage. The supply authorities encourage industrial consumers to operate with a high power factor with special tariffs in order to reduce both their own and the consumers costs.

Discussion of results (cont.)

To correct this lagging power factor, capacitors or capacitor banks can be connected across the supply to bring the power factor back to (ideally), or as close as possible to one.

In reality the capacitors used for power factor correction must be paid for and therefore a power factor of unity is unlikely due to the economies of scale involved, i.e. the law of diminishing returns.

Conclusion

If the power factor is low, then there is less power available to the load (from $P_R = V_R \cdot I \cdot \mathrm{Cos}\,\Phi$, where V_R is kept constant). Therefore, if a specific power is needed, more current must be supplied, and this causes the infrastructure that the supplier has in place (cabling, pylons, generators etc, etc) to be larger and therefore more expensive to construct. The electricity suppliers offer reduced price tariffs to encourage consumers to keep a high power factor which in turn helps keep their own costs (and the consumers) costs to a minimum. Since most loads placed in the system are inductive to some extent, power factor correction takes place with the use of capacitors and capacitor banks to balance the system. Extremes of either inductive or capacitive loads must be avoided; this will in turn lead to better voltage regulation.

Note

The meter used for measuring supply voltage (EE51-5051) was found to be ‘sticking’ at the lower end of the scale at the end of the experiment – this may account for the erroneous third reading on the graph.

Reference material

- Lecture notes – A.Faraj
- Alternating Current Fundamentals, 4th Edition, John R.Duff, Stephen L.Herman, Delmar Publishers Inc.
- Electrical and Electronic Principles and Technology, John Bird, Newnes
- Hughes electrical technology, 7th Edition, I McKenzie Smith, Longman
- Direct and Alternating Current Circuits, Bernard Grob, McGraw-Hill

Index of drawings, tables and graphs