(b) *Thermal maximum kilowatt demand meter*

The thermal kilowatt demand meter has a circuit as shown in Figure 10.51. A small voltage transformer in the meter has its primary connected across the line and its secondary connected in series with two non-inductive heaters of equal resistance at all temperatures, one of which is associated with each bi-metallic enclosure. With both the current and voltage applied, and assuming there is a 1:1 ratio in the voltage transformer, a current, $E/2R$, proportional to the line voltage, circulates through the heaters as shown. Current is introduced through the mid-tap in the voltage transformer secondary, and divides equally. The difference in the heating effects of the two resultant currents can be shown to be proportional to the power consumed by the load.

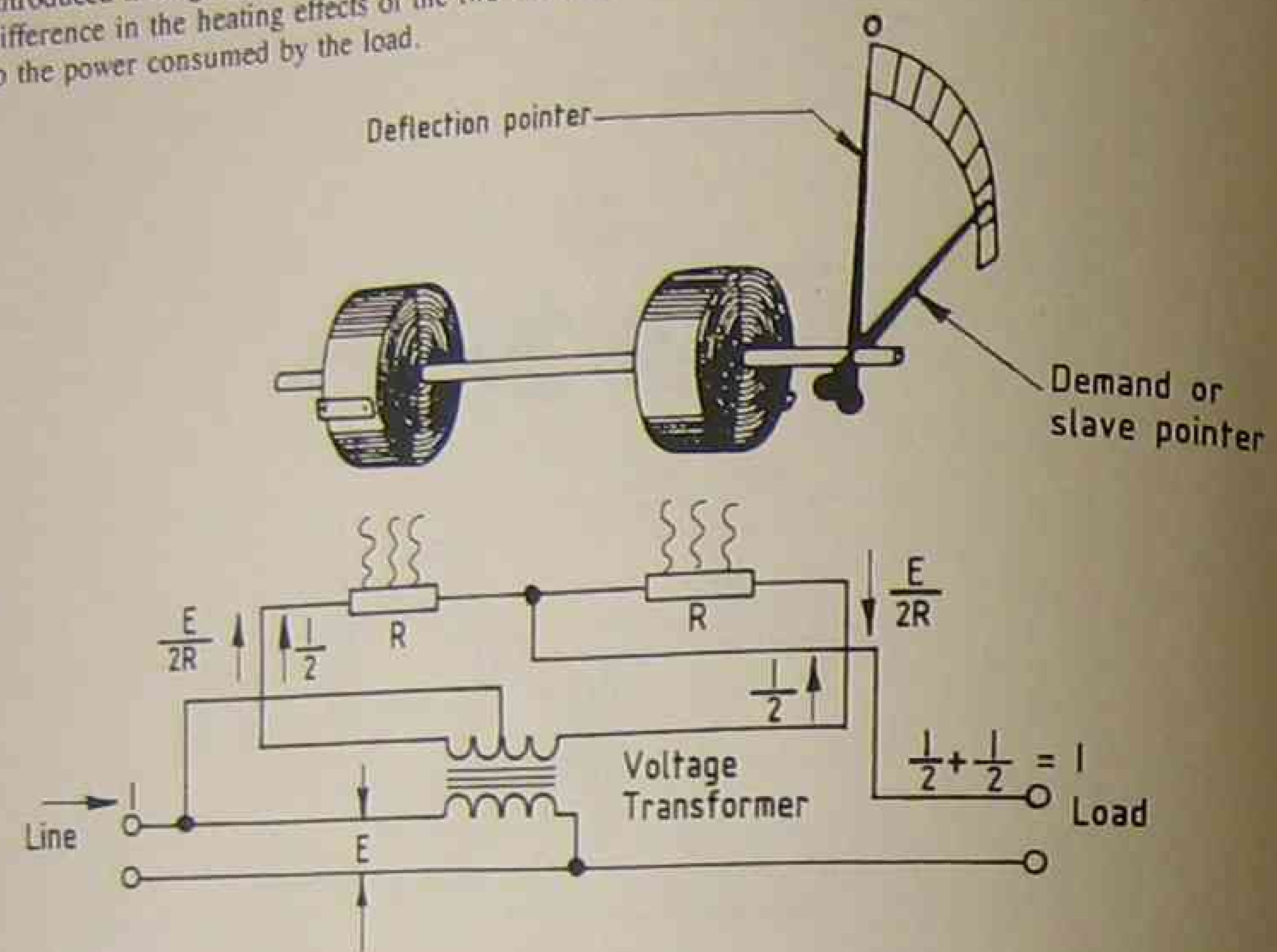


Figure 10.51
Basic thermal kilowatt-demand circuit

If the two resistors R shown in Figure 10.51 are embedded or fixed to two similar masses such as the bimetal spirals the instrument will become a meter having a slow responding characteristic that gives the logarithmic average of the energy that has passed during a given period. This makes the instrument ideally suited for maximum demand indication.

(c) *Electromechanical maximum kilowatt demand meter*

Formerly the most popular instrument of its type in Australian practice, it consists of an addition to the kilowatt-hour movement, both being housed in the one case. The kilowatt-hours are integrated for a given time, such as 30 minutes, and the average maximum demand — kW.h/time (in hours) — is shown by the pointer.

A simplified diagram of the operation of the meter is shown in Figure 10.52. The drive from the rotor is transmitted by gearing to a driving pointer which moves a slave pointer across the dial. The gear A is kept in mesh with the sector B by means of an electromagnet in series with a resistor, and energised from the supply. A timing motor starts the electromagnet every 30 minutes allowing the spring to disengage the gear A from the sector B. This in turn allows the driving pointer to return to the zero position for integrating the units used in the next 30 minutes.

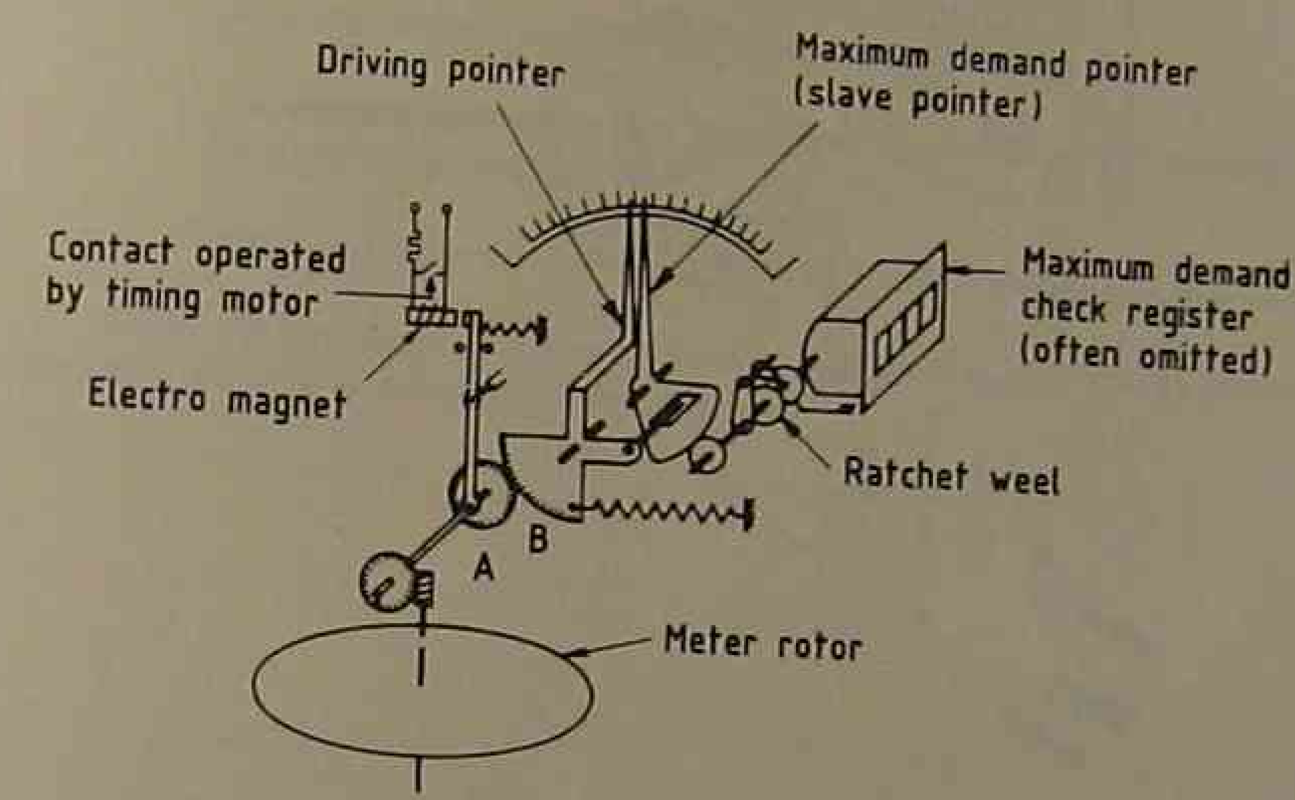


Figure 10.52
Maximum-demand mechanism

Distribution and Utilisation

2832Q

UNIT 10
Electrical Measuring Instruments

OTEN

Department of School Education

TAFE

2813X DISTRIBUTION AND UTILISATION

UNIT 10

ELECTRICAL MEASURING INSTRUMENTS

CONTENTS

OBJECTIVES

When you have worked through this unit, you should be able to:

- list the important characteristics of instruments, as applied to electrical measurement, and compare these characteristics for instruments of various types
- briefly describe, using sketches, the construction, principles of operation and characteristics of permanent-magnet moving coil, moving iron, electrodynamic and induction type instruments
- list, and briefly compare the significant characteristics of the types of instruments which may be used to measure the following: voltage, current, power, reactive voltamperes, power factor, frequency and synchronism
- describe the principle of operation and adjustments of the single-phase alternating current energy meter
- state the purpose and briefly explain the operation of lagging, integrating and time-of-use demand meters
- list the characteristics and advantages of an analogue electronic instrument
- define a transducer, define active and passive types and give examples of transducers used for electrical measurement
- state the advantages of digital instruments, and discuss their use for a.c. and d.c. measurements.

REFERENCES

The following Australian Standards need not be purchased but provide additional information useful to the study of this unit:

- *AS 1042 - 1973, Direct-acting indicating electrical measuring instruments and their accessories.*
- *AS 1284, Electricity meters*

Part 1 - 1985.	*Alternating current watthour meters*
Part 2 - 1973.	*Portable alternating current rotating standard watthour meters*
Part 3 - 1973.	*Alternating current watthour meters of two-rate and energy demand types.*

AS 1042 specifies the maximum values for intrinsic error and also maximum limits of variation in indication due to each of the influence quantities for the various types of instrument. Electrical instruments made by Australian manufacturers conform to this standard.

Part 1 of *AS 1284* specifies requirements for general purpose, single rate, induction type watthour meters for the measurement of 50 Hz a.c. electrical energy in domestic, commercial or industrial premises.

GLOSSARY

The following definitions have been selected from those given in the International Electrotechnical Vocabulary which has been endorsed as *AS 1852*. The first and the third groups of definitions are of some general terms used in the area of instrumentation, whilst the second group of definitions relate to the characteristic features of electrical indicating and measuring instruments.

General

accessory	a circuit element (resistor, inductor, capacitor, and so on) which is associated with the measuring instrument in either a permanent or non-permanent manner
direct-acting instrument	an instrument in which the indicating or marking device is directly connected to and actuated by the moving element
distortion factor	the ratio of the r.m.s. value of the harmonic content to the rms value of the non-sinusoidal quantity; expressed as a percentage
electrical measuring instrument	an instrument which measures an electrical quantity
indicating instrument	an instrument which indicates the instantaneous, rms, average, or peak value of the quantity measured
instrument with suppressed zero	an instrument in which the moving element does not deflect when the quantity to be measured is less than a predetermined value — the zero may be suppressed outside the scale by either electrical or mechanical means
ripple content of d.c. supply (%)	half the peak-to-peak value of the a.c. component divided by the d.c. component, then multiplied by 100
shunt	a resistor connected in parallel with an instrument to reduce the current which passes through it, particularly to extend its current range
transducer	a device which converts an electrical or non-electrical quantity or quality (value) to a related electrical output

Characteristic features of instruments

absolute error	the indicated value of a quantity, minus its true value, expressed algebraically
accuracy (of a measuring instrument or accessory)	is defined by the limits of intrinsic error and the limits of variations due to influence quantities
accuracy class	a class of measuring instruments (or accessories), the overall accuracy of which can be designated by the same number
class index	the number which designates the accuracy class and is applicable to the variation as well as to the intrinsic error; multi-range instruments may have more than one class index
dial	a surface which carries the scale and other marks and symbols
effective range	that part of the scale where measurements can be made with the stated accuracy
electrical zero	the equilibrium position which the index will approach when the measured electrical quantity is zero; this may or may not coincide with either the mechanical zero or the zero scale mark
error as a percentage of the fiducial value	one hundred times the quotient of the absolute error and the fiducial value
fiducial value	a value characteristic of an instrument for the purpose of specifying its accuracy; the value taken to be the fiducial value for a particular instrument depends on the type of instrument — for the simplest form of instrument the fiducial value is the upper limit of the effective range; for further details refer *AS 1042-1973*
index	the means, usually a pointer, which indicates the magnitude of the quantity being measured
influence quantity	a quantity which affects the indication of an instrument, but which is not one measured by the instrument — it covers such quantities as ambient temperature, position, frequency, pressure, and external magnetic induction; these quantities being independent of the measured quantity
intrinsic error	any error determined when the instrument and/or accessory is under reference conditions, expressed as a percentage of the fiducial value
maximum current and maximum voltage	values of current and voltage assigned by the manufacturer as those which the instrument will withstand indefinitely without damage
measuring element	the parts of a measuring instrument, the interaction between which actuates the moving element
mechanical zero	the equilibrium position which the index will approach when the measuring element (if mechanically controlled) is de-energised; this may or may not coincide with the zero scale mark — in mechanically suppressed-zero instruments the mechanical zero does not correspond to a scale mark

moving element	the moving part of an instrument, the deflection of which is observed
nominal range of use	a range of values which each influence quantity can assume without causing a variation exceeding specified limits
precision	a measure of the reproducibility of the measurements
relative error	the ratio of the absolute error to the true value of the measured quantity
residual deflection	the part of the deflection of a mechanically-controlled moving element which remains after the cause producing it has disappeared and all the measuring circuits are de-energised
resolution	the smallest change in measured value to which the instrument will respond
scale length	the length of the arc (or the segment of a circle) passing through the centres of the shortest scale marks and limited by the outermost scale marks
variation with influence quantity	the difference between two measured values of the same measured quantity when an influence quantity assumes successively two different specified values

Miscellaneous

basic current	the value of current on which the relevant performance of the meter is based
basic speed	the nominal speed of rotation of the rotor when a meter is at reference conditions and carries basic current at unit power factor
demand (mean power)	the energy divided by the time in which it is produced or absorbed
demand integration period	the interval of time upon which the demand measurement is based — standard values of the demand integration period are 10, 15, 30 and 60 minutes
direct-connected meter	a meter having its terminals arranged for connection to the circuit being measured without the use of an external measurement transformer
energy demand meter	a meter with a demand register in addition to the energy register to register both maximum demand and energy
induction type meter	a meter in which currents in fixed coils react with the currents induced in the moving element, generally a disc or discs, causing movement
maximum demand	the highest value of the mean power during successive demand integration periods between one operation of the maximum demand resetting mechanism and the next
meter constant	a constant expressing the relationship between the energy registered by a meter and the corresponding number of revolutions of the rotor, either in revolutions per kilowatt hour (rev/kWh) or as watt hours per revolution (Wh/rev) — no error is permitted in the meter constant
percentage error (e.g. energy)	the value given by the equation: $$\%\ \text{error} = \frac{(\text{energy registered} - \text{true energy})}{\text{true energy}} \times 100$$ For example, a meter which registers 99% of the true energy has an error of − 1%
rated maximum current	the highest value of current (I_{max}) at which the meter purports to comply with the standard specification
rotor	the moving element of a meter upon which the magnetic fluxes of fixed windings and of braking elements act, and which operates the register
watt-hour meter	an integrating instrument which measures active energy in watt-hours or multiples such as kWh and MWh

10.1 INTRODUCTION

10.1.1 General

Instruments are necessary to measure electrical quantities such as voltage, current, and resistance and, although the construction has varied over the years, the principal type of instrument is still the direct-acting indicating pointer type of deflecting instrument. In this construction the deflecting angle of the pointer is a function of, and thus analogous, to the value of the electrical quantity measured. The name analogue instrument has been given to this type, to distinguish it from digital instruments in which the value of the quantity is displayed in numerals.

As well as the analogue and digital instruments, there are differential instruments. In these the measurement is achieved by the manipulation of knobs and dials until a condition of balance is obtained and indicated by a galvanometer. Examples of this type are the Wheatstone bridge and the d.c. potentiometer.

Modern analogue instruments for quantities such as watts, reactive volt-amperes, power factor and frequency normally incorporate transducers driving moving coil movements. This type of instrument has, for most applications, superseded some of the types described in this unit. However, the earlier types are still in service and therefore some understanding of their operation and characteristics is necessary.

The instruments and meters to be covered in this unit are as follows:

- ammeter
- voltmeter
- wattmeter
- frequency meter
- power factor meter
- synchroscope
- energy meter
- maximum demand meter

To obtain a clear understanding of this segment of the course it is necessary to become familiar with some of the terms used in the international language in the area of instrumentation and measurement. If you have not already done so, skim-read the glossary at the beginning of this unit and remember to refer back to it if you encounter an unfamiliar term later in your studies on instruments.

10.1.2 Preferred values for instrument ranges

The upper measuring limit of the effective range of ammeters, voltmeters, wattmeters and varmeters should be chosen from the following values:

1.0 1.2 1.5 2.0 2.5 3.0 4.0 5.0 6.0 8.0

or their decimal multiples or submultiples.

The rated voltage drop of shunts is normally 75 mV but may be one of the following values:

50 60 75 100 150 300 mV.

A summary of the commonly used ranges for commercial instruments is given in Table 10.1.

Table 10.1
Typical ranges of commercial instruments

Ammeters - full-scale value:	
5, 10, 15, 20, 30, 40, 50, 60, 75, 100, 150, 200, 300, 400, 500, 600, 800.	
Voltmeters	
Full-scale value	*Normal circuit voltage*
8 V	6 V (battery circuits)
35 V	24 V (battery circuits)
70 V	50 V (battery circuits)
150 V	100-120 V
300 V	200-250 V
500 V	380-400 V
600 V	415-460 V
800 V	550-660 V
3 kV	2.2 kV
4 kV	3.3 kV
8 kV	6.6 kV
15 kV	11 kV
30 kV	22 kV
40 kV	33

10.1.3 Instrument torques

The action of most deflectional measuring instruments depends upon the attainment of equilibrium between two primary forces or torques. These are:

- *an actuating or deflecting torque* dependent on the quantity to be measured
- *a restoring or control torque* dependent on the displacement of the moving pointer.

The control torque may be one of the following types:

- *flat, spiral, control springs* attached between the moving member and the instrument frame — spring control
- *a weighted arm linked to the movement* — gravity control; this type of control is not now used due to:
  - the length of time required for adjustment
  - its influence on scale shape
- *taut band construction,* where the moving member is supported on a stretched band — torsion control
- *electrical control* in which an electromagnetic or electrostatic element is arranged so as to oppose the torque developed by the main element. It is generally used in instruments of the quotient meter class, such as the ohmmeter, and in certain power-factor meters and deflectional frequency meters. The two forces are developed in the system and the deflection is measured when equilibrium is reached between them.

A third force, known as a damping force, is required to damp the oscillations of the pointer about its final rest position, to reduce the time taken to observe the reading indicated. This force is a transient one and is present only when the moving element is in a state of motion.

10.2 CLASSIFICATION OF INDICATING INSTRUMENTS

Generally, indicating instruments are classified in two ways, according to their:

- method of operation, for example, permanent-magnet moving-coil
- accuracy class.

10.2.1 Classification according to the method of operation

Indicating instruments may be divided into the following types:

- *permanent-magnet moving-coil*
- *moving iron*
- *electrodynamic*
- *induction*
- *rectifier*
- *analogue electronic*
- *digital*

Symbols have been adopted, on an international basis, indicating the method of operation of the various types of instruments. These symbols are shown later for those instruments dealt with in this unit. *AS 1042* requires that these symbols be marked:

(a) on the visible part of the case of portable instruments

(b) on the visible part of the case or near the terminals of panel instruments.

The construction and theory of operation of most of these instruments have been dealt with in subjects undertaken earlier in the course. The diagrams and comments in this unit will serve as revision and will also supplement the earlier work.

10.2.2 Classification according to accuracy class

(a) *General*

Measuring instruments are classified according to the following accuracy classes:

0.05 0.1 0.2 0.5 1 1.5 2.5 5

Interchangeable shunts, series resistors and impedances are classified according to their accuracy in one of the following classes:

0.02 0.05 0.1 0.2 0.5 1.0

(b) *Permissible intrinsic errors for instruments*

When the instrument is within the limits of its reference conditions and is used within the limits of its effective range, the intrinsic error should not exceed those listed in Table 10.2, which are expressed as a percentage of the fiducial value.

Table 10.2
Limits of intrinsic error of instruments

Class index	0.05	0.1	0.2	0.5	1.0	1.5	2.5	5.0
Limits of Error (±%)	0.05	0.1	0.2	0.5	1.0	1.5	2.5	5.0

Source: Standards Association of Australia

(c) *Permissible intrinsic error of accessories*

When the accessory is within the limits of its reference conditions the intrinsic error is expressed as a percentage of its rated value. The error should not exceed those listed in Table 10.3.

Table 10.3
Limits of intrinsic error of accessories

Class index	0.02	0.05	0.1	0.2	0.5	1.0	2.5
Limits of Error (±%)	0.02	0.05	0.1	0.2	0.5	1.0	2.5

Source: Standards Association of Australia

(d) *Effective range*

When the effective range of a normal instrument is not within the value given in Table 10.4, the limits of the effective range should be clearly marked on the scale. In the absence of marking, the effective range of an instrument is from full-scale value down to the value shown in Table 10.4.

Table 10.4
Effective ranges of instruments

Type of instrument	*Effective range*
Phase-angle meters, ohmmeters, power-factor meters, frequency meters	The whole of the scale.
	Maximum value of the effective range to:
Permanent-magnet moving-coil	1/10 of that value
Electrodynamic wattmeter	1/10 of that value
Induction wattmeter	1/10 of that value
Induction ammeter and voltmeter	1/5 of that value
Moving iron	1/5 of that value
Rectifier voltmeters, range < 15V full-scale	1/4 of that value
Electrostatic voltmeter	1/3 of that value
Electrodynamic ammeter and voltmeter	1/3 of that value
Thermal ammeter and voltmeter	1/3 of that value.

Source: Standards Association of Australia

At the lower end of the scale, high accuracy is difficult to obtain because:

- the deflecting law of the instrument influences the spacing of the scale graduations, which in some types is a square law — the square of a small quantity gives a smaller quantity — resulting in much smaller increments between graduations
- the deflecting and control torques are small in value
- instrument movements with jewelled bearings exert a frictional torque which has its greatest influence on the movement near zero where the working forces are small.

(e) *Measurement CTs*

Measurement current transformers are frequently used in conjunction with instruments to measure currents and it is desirable that both items should have matching accuracies to give results consistent with the required overall accuracy of measurement. Table 10.5 gives an indication of the accuracy classes of current transformers recommended in *AS1675-1986*, for various types of measurement and serves as a guide to the selection of instruments of suitable accuracy.

Table 10.5
Selection of class of accuracy of measurement current transformers

Application	*Class of accuracy*
As a standard for testing other current transformers	better than 0.1
Precision testing	0.1
Precision metering	0.1 or 0.2
Tariff metering	
- bulk supplies	0.2
- general tariff metering	0.5
Non-revenue measurements including power and energy	1.0
General measurements	2.0
Approximate measurements	5.0

10.3 PERMANENT-MAGNET MOVING-COIL INSTRUMENT (PMMC)

Note: Before proceeding with your study of sections 10.3 to 10.6, please refer back to the objectives for this unit. These indicate the level at which you will be assessed in these sections

10.3.1 General

This is probably the most common indicating instrument in use today. It is defined as an instrument which depends for its operation on the reaction between the current in a movable coil or coils and the field of a fixed permanent magnet. The standard symbol adopted to designate the permanent-magnet moving-coil instrument is shown in Figure 10.1.

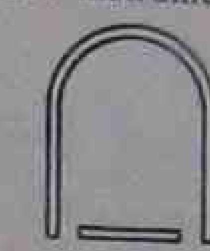


Figure 10.1
Symbol for permanent magnet moving-coil instrument

10.3.2 Principle of operation and construction

The principle of operation is that of a current-carrying conductor in a magnetic field. The deflecting force is produced by the interaction of two magnetic fields: one produced by the current flowing through the non-magnetic conductors (copper) wound on a non-magnetic former — usually made of aluminium — and the other being that of a fixed permanent magnet. The force exerted on the coil conductors causes the coil to rotate about its suspension, against the action of the control torque.

The deflection angle of the pointer is directly proportional to the coil current and the scale graduations are uniformly spaced, giving a linear scale.

Damping is produced by the action of eddy currents. The non-magnetic aluminium former may be regarded as a short-circuited conductor suspended in the field of the permanent magnet. As the deflecting force rotates the moving coil, the former cuts the magnetic field and has an e.m.f. induced in it. This causes a current to flow (known as an eddy current) which produces a flux and, according to Lenz's Law, develops a force opposing the motion of the former. This force is present only when the former is in motion.

Figure 10.2 shows the construction of a permanent-magnet moving-coil instrument illustrating the various components. The permanent magnet shown is of the type used on the earlier models of instrument. It is made of a tungsten-steel alloy which was quite widely used up until the introduction of superior magnetic alloys of the alnico series and alcomax types.

The superior alloys have a much higher coercive force than the older alloys and can therefore resist demagnetising influences to a much greater extent. For a given application, modern magnets are smaller and lighter. These are very important characteristics for those applications where economy of space and/or weight reduction is essential, such as in aerospace and control room equipment where many instruments are to be observed when mounted in a close array.

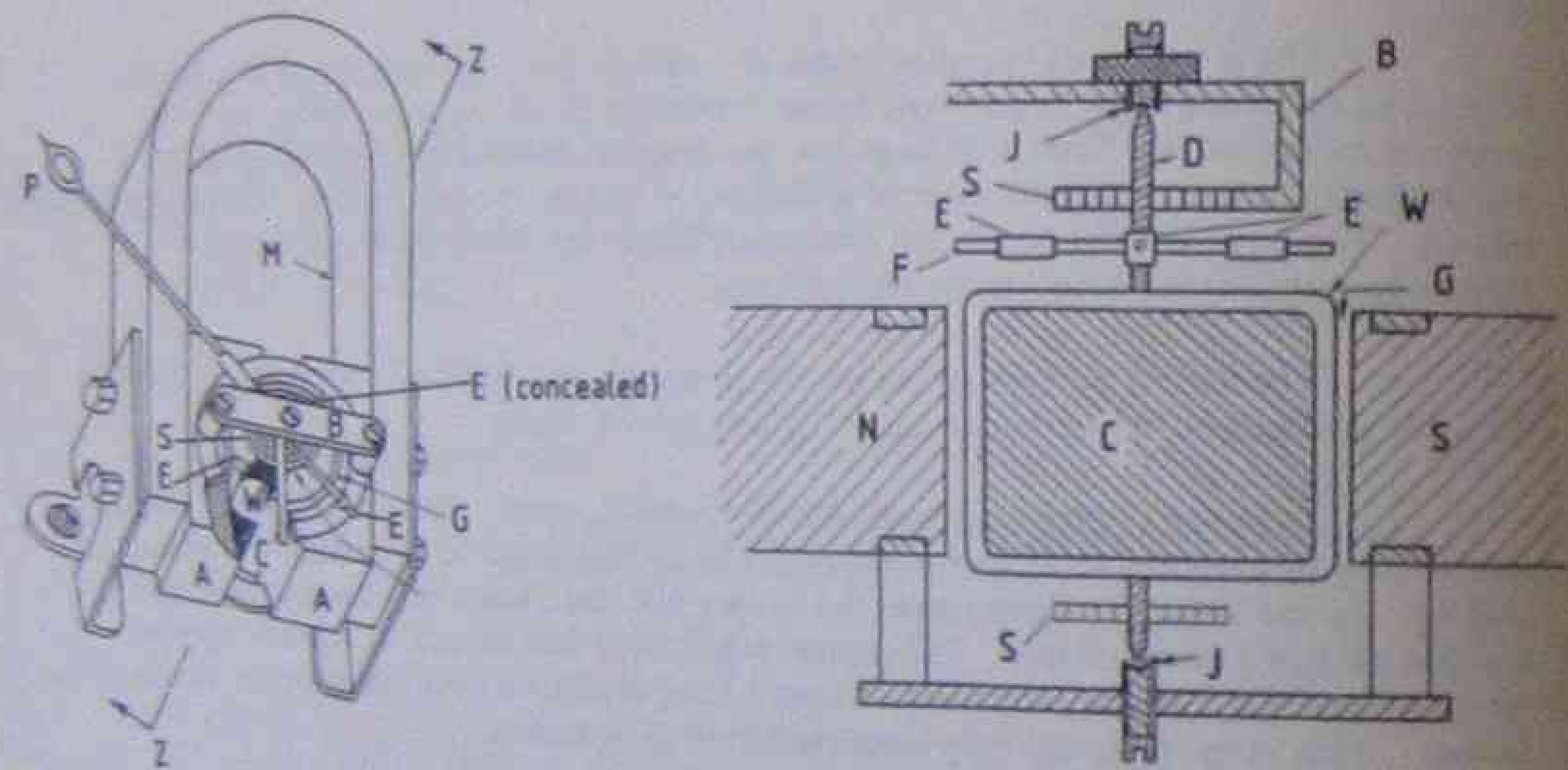
The two pole pieces and the core are made of soft iron which has the properties of low remanence and high permeability, resulting in a radial magnetic field of uniform density in the air gap. The radial field gives the maximum deflecting force and the uniform field contributes to the attainment of a linear scale.

The two control springs are in the form of an Archimedian spiral where the radius is increased by an equal amount between turns. They may be made of phosphor bronze or silicon bronze to suit the characteristics of the instrument to which they are to be fitted. The torque developed by the spring is closely proportional to the angular deflection, and it is important for the springs to have constant characteristics to ensure the accuracy of the instrument is maintained. The two springs conduct the current into and out of the moving coil.

The moving element assembly – comprising the lightweight moving coil, springs, pointer, and pivots – is statically balanced by the three balance weights and the complete assembly is supported by the jewelled bearings, which are synthetic sapphires.

Legend for Figure 10.2:

A - soft-iron pole pieces
B - bridge
C - soft-iron core
D - hardened steel pivots
E - balance weights for moving element
F - threaded arm
G - uniform air gap
J - synthetic jewels
M - permanent magnet
P - pointer - spade type
S - flat spiral control springs
W - coil wound on aluminium former.



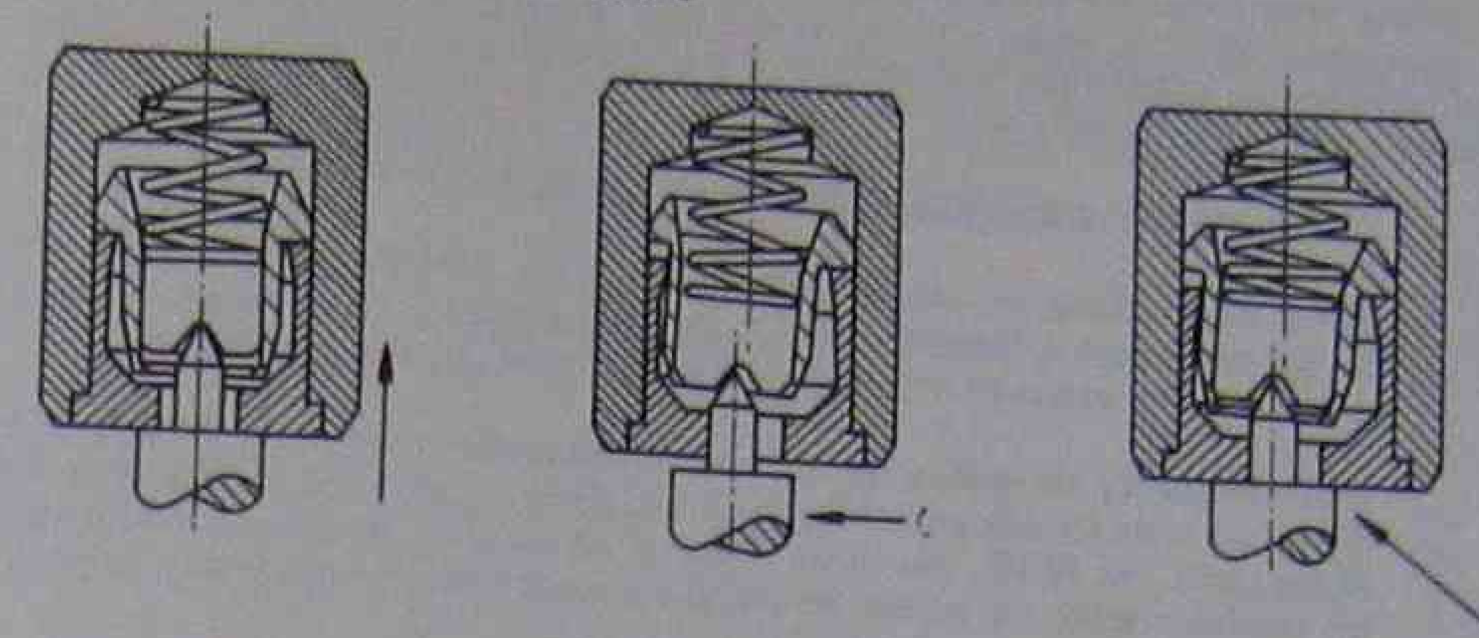
(a) Typical construction

(b) Approximate section Z-Z

Figure 10.2
Permanent-magnet moving-coil instrument

Instruments should be specially protected when subjected to vibration and shock, and, if they incorporate jewelled bearings, these should be spring-loaded to protect the bearing and pivot surfaces against damage from axial, radial, and oblique forces, as illustrated in Figure 10.3. The jewel is located in its normal position by the spring and is free to move when the shock to the instrument becomes severe.

Legend for Figure 10.3: E - seat, J - jewel, L - sleeve, P - pivot, S - staff.



Axial Shock The vertical pressure of the pivot pushes the jewel until the seat of the staff touches the seat outside. The pressure of spring immediately replaces the jewel into its initial position.

Radial Shock The radial pressure of the pivot makes the sleeve sewing by the medium of the jewel against the spring power until the pivot side touches the hole wall. Then the spring recentres the system instantaneously.

Oblique Shock The system has a combined movement resulting from both radial and axial shocks.

Figure 10.3
An instrument jewel bearing and its behaviour under adverse conditions

Source: University Paton Instruments Pty Ltd

10.3.3 Temperature errors and compensation

The permanent-magnet moving-coil ammeter is actually a millivoltmeter used in conjunction with an internal or external shunt accessory. The preferred rated voltage drop across the potential terminals of the shunt, when the rated current is flowing, is 75 mV. The electrical circuit between the shunt potential terminals is partly made up of (a) the moving-coil copper winding, (b) two copper shunt connecting leads and (c) two copper-alloy control springs. These components will increase in temperature when an electric current passes through them and/or the ambient temperature increases. All of these components have a positive temperature coefficient of resistance; hence their resistance will increase, making the instrument read low for a given current.

The temperature error may be reduced by connecting a 'swamping' resistor in series with the moving coil circuit. The series resistor is made from a material having a negligible temperature coefficient of resistance such as manganin, a copper-manganese alloy or constantin, a copper-nickel alloy.

In the case of the permanent-magnet moving-coil voltmeter, temperature compensation is more easily obtained due to the voltages to be measured being generally much in excess of the 75 mV voltage drop across the shunt used with the permanent-magnet moving-coil ammeter. The voltage-multiplier resistor, in series with the moving coil, becomes the swamping resistor and automatically provides temperature compensation if it is made of material having a negligible temperature coefficient of resistance.

10.3.4 Characteristics of the permanent-magnet moving-coil instrument

(a) The pointer deflects up scale for coil current in one particular direction only; that is, the instrument is 'polarised' and is suitable only for the measurement of direct currents. The terminals are marked to identify correct polarity for connection.

If low frequency alternating current was applied to the moving coil, the pointer would deflect up scale for one half of the cycle and down, or off scale, for the other half of the cycle. At 50 Hz, due to the action of the damping system and the inertia of the moving system, the pointer would quiver around the zero graduation seeking the average value.

The instrument may be used for the measurement of a.c. quantities only if they are rectified.

(b) It measures the *average value* of the current passing through the moving system.

(c) There are *uniformly spaced scale graduations*, that is, it is a linear reading d.c. instrument.

(d) It has *comparatively low power consumption* – down to approximately 20 μW for full-scale deflection

(e) It has *high current sensitivity* – low current for full-scale deflection and high ohms/volt rating.

(f) It has *very good immunity* from stray magnetic fields.

(g) It has consistent *high accuracy*.

(h) It has *good frequency response*; with rectifiers, may be used at frequencies over the range from approximately 20 Hz to 100 kHz.

(i) It is *versatile* – with the aid of internal and sometimes external accessories, it may be used for the measurement of a wide range of a.c. and d.c. quantities, for example, the multimeter.

(j) The instrument is at a price disadvantage when compared to, say, the moving-iron instrument, but the price gap has narrowed due to increased demand, allowing it to be produced in greater quantities.

10.3.5 Developments in permanent-magnet moving-coil instrument construction

(a) *Standard magnet design*

The standard design for many years has used an external magnet of a design such as that shown in Figure 10.4. This design offers the largest magnet in a given space, and is used when maximum flux in the air gap is required in order to provide an instrument of lowest possible power consumption and low current for full-scale deflection.

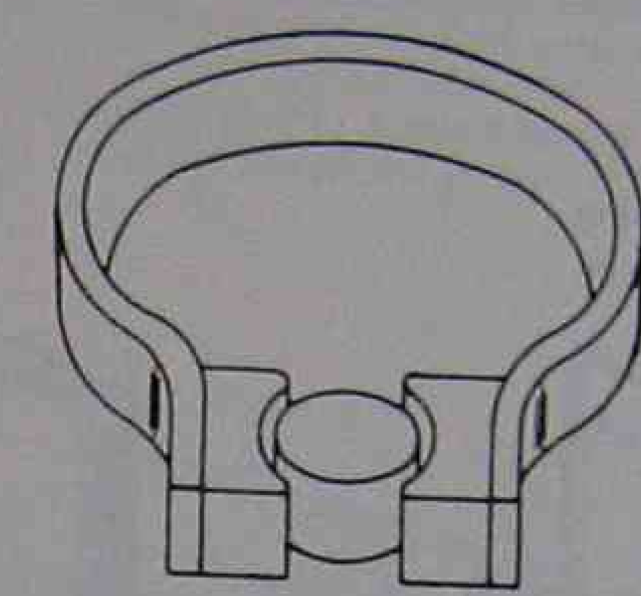


Figure 10.4
Magnetic circuit for moving-coil instrument – transitional design from the old to the new type of permanent magnet alloy

(b) *Core magnet design*

In recent years, with improved magnetic materials, it has become feasible to design a magnetic system in which the magnet serves as a core. These mechanisms have the advantage of being relatively resistant to external magnetic fields, thereby allowing for the elimination of the magnetic shunting effect of steel panels and the need for magnetic shielding in the form of iron cases. (See Figure 10.5.) This type of construction enables instruments to be made smaller in size.

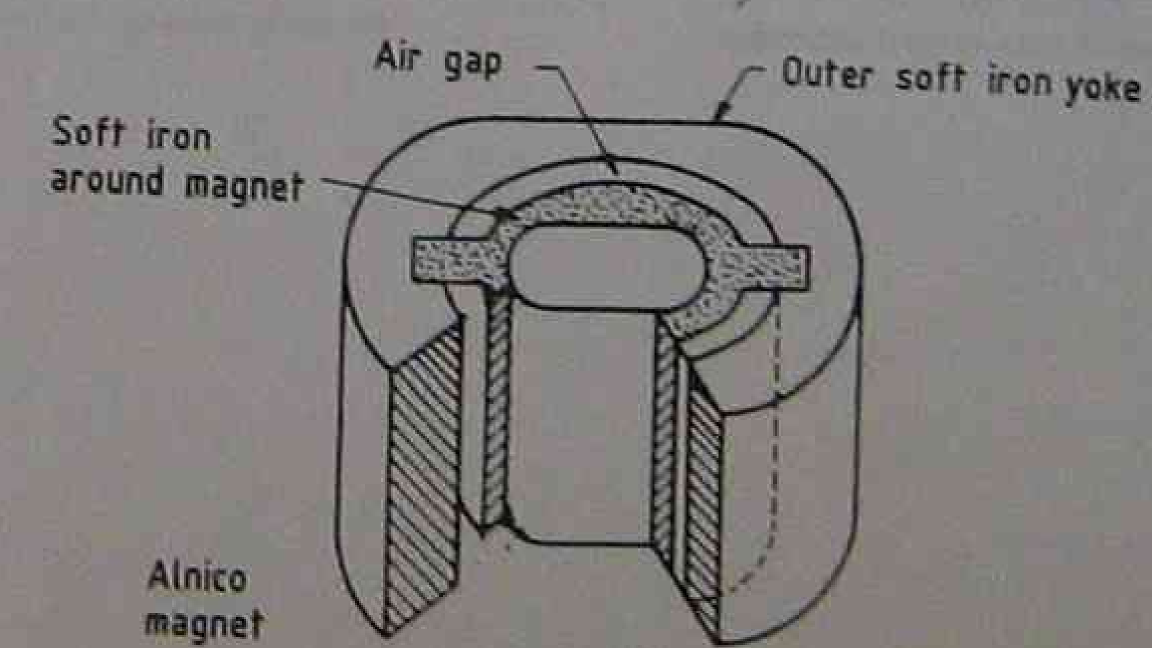


Figure 10.5
Core-type magnetic circuit for moving-coil instrument

(c) *Moving coil assemblies*

Most coils for PMMC voltmeters have metal frames for damping, while for ammeters the coil is sometimes frameless, the coil turns being started at the shunt. The moving system is balanced for all positions by a number of adjustable balance weights.

(d) *End-pivoted coil design*

The end-pivoted or off-centre permanent-magnet moving-coil mechanism shown in Figure 10.6 is a variation of the more common centre-pivoted type. In this arrangement only one side of the coil is situated in the air gap allowing a full-scale deflection as high as 270°. The off-centre coil type is extensively used for edgewise panel instruments, having vertical, sector-type scales. The deflection is usually limited to 60°. It is popular for use in locations such as boiler houses where instruments, matched for shape, are mounted in a close arrangement on the one panel. They are used for measuring a wide range of electrical and mechanical quantities such as current, speed, steam and draft pressures, temperature, air pollution, and so on.

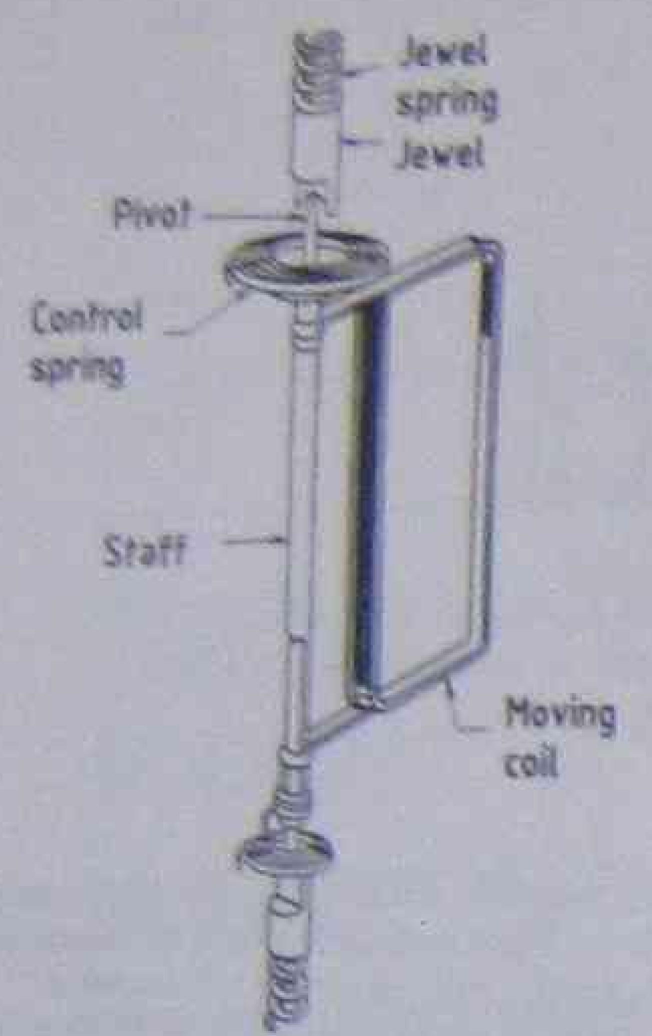


Figure 10.6 (a)
End-pivoted moving-coil assembly

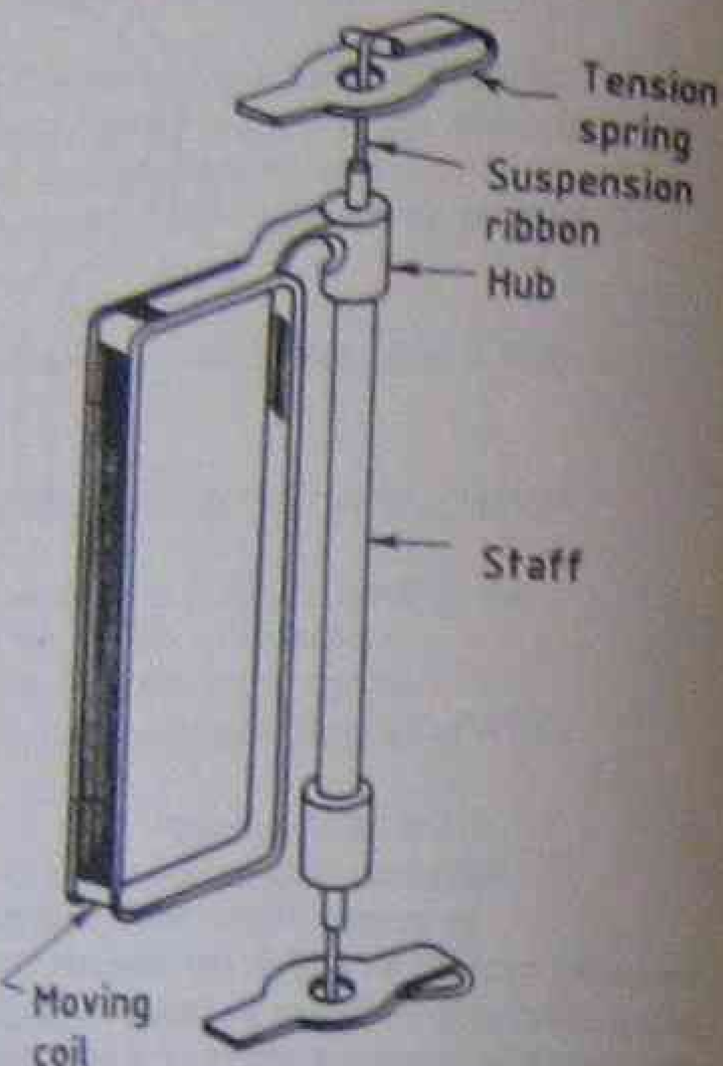


Figure 10.6 (b)
Pivotless moving-coil assembly

(e) *Suspensions*

Jewelled bearings were discussed briefly in 10.3.2.

The more recent design of suspension is the 'taut-band' or pivotless construction where the bands, when twisted, provide the control torque (refer Figure 10.7). This construction has the advantage of absence of friction between pivots and jewels and by placing the ribbons under sufficient tension, the instrument can be used in any position without sag. Generally speaking, taut-band suspension instruments can be made with higher sensitivities than those using pivots and jewels, and can be used in almost every application where, at present, pivoted instruments are used. They are relatively insensitive to shock and temperature, and are capable of withstanding greater overloads. A comparison of pivoted and pivotless assemblies can also be seen in Figures 10.6(a) and 10.6(b).

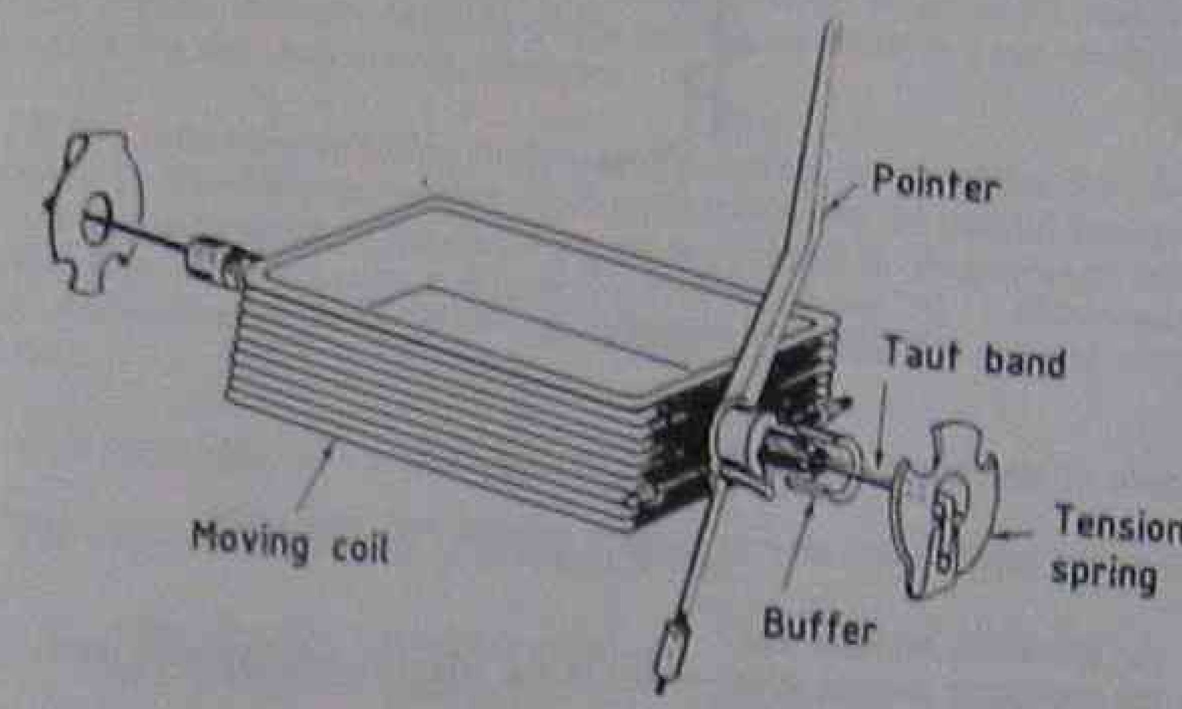


Figure 10.7
Taut band suspension

Source: Paton Electrical Pty Ltd

10.4.1 General

A moving-iron instrument is simply defined as an instrument comprising a movable piece of ferromagnetic material which is actuated by a fixed coil carrying a current, or by a fixed piece of ferromagnetic material magnetised by the current. The standard symbol adopted to designate the moving-iron instrument is as shown in Figure 10.8.

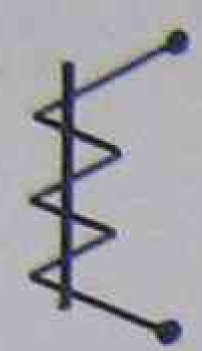


Figure 10.8
Symbol for moving-iron instrument

10.4.2 Principle of operation and construction

Moving iron instruments may be divided broadly into two types:

- the attraction moving-iron
- the repulsion moving-iron, which is the type more commonly used.

Figure 10.9 is an example of the attraction type while Figures 10.10 and 10.11, are examples of the repulsion moving-iron type.

The fixed coil of the instrument shown in Figure 10.9 has lower power consumption than the repulsion type, and minimum self-inductance.

The scale is non-uniform due to the:

- law of the deflecting torque
- influence of the gravity control torque (not now used)
- shape of the moving-iron.

B - balance weight
C - fixed flat coil
D - air damping mechanism
M - shaped moving soft iron
P - pointer
S - scale
V - vane
W - gravity control weight

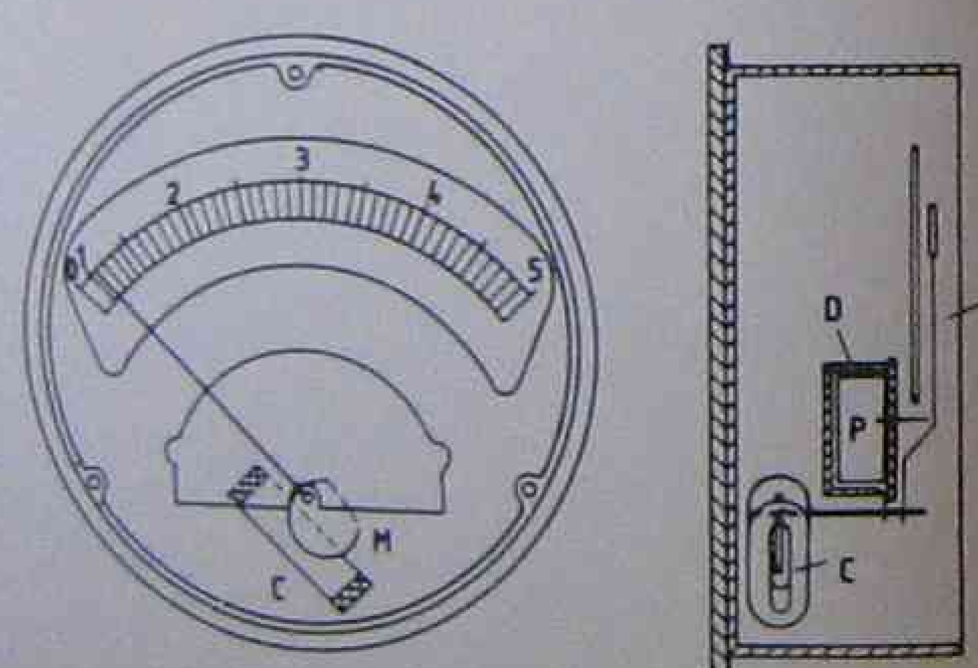


Figure 10.9
Attraction-type switchboard moving-iron instrument with gravity control

For repulsion-type movements, if the flux density in the irons is kept low to avoid saturation, the pole strength for each iron will be proportional to the ampere turns of the coil. Since the force between the irons, at a given separation, is proportional to the product of their pole strengths, it follows that this deflecting force is proportional to the square of the ampere turns of the magnetising coil. As the number of turns for a given instrument is a fixed value, the deflecting force varies as the square of the current. Hence the spacing of the scale graduations of the moving-iron instrument follow a square law. The resultant spacing is generally not satisfactory, and may be greatly improved up-scale by suitably shaping the fixed iron, as shown in Figure 10.10.

The control torque is provided by a flat spiral control spring. Only one spring is required as no current flows in the moving system.

Damping is obtained by a lightweight radial aluminium vane, moving in a totally enclosed air chamber. Due to compression and expansion of the air as the vane moves in the chamber, air is transferred from one side of the vane to the other at a rate proportional to the clearance between the vane and the chamber.

When used on alternating current, the pulsating nature of the deflecting torque may cause the pointer tip to vibrate depending on the relationship of the natural frequency of vibration of the moving system to the frequency of the current flowing through the coil. The rigid, trussed design of the pointers shown in Figures 10.10 and 10.11 eliminates this vibration over a wide frequency range as well as resisting mechanical damage when exposed to severe overloads.

(a) *Concentric vane mechanism (refer Figure 10.10)*

The features of this type of instrument are:

- vanes slip laterally under repulsion
- only moderately sensitive
- square-law scale characteristics
- short magnetic vanes resulting in small direct-current reversal and residual-magnetism errors (errors introduced when used on direct current with change of polarity).

For greater strength, the construction provides:

- trussed shape at pointer
- thin aluminium damping vane having ribbed surface and returned edges.

With this mechanism it is also possible to shape the vanes to secure special characteristics, thereby opening the scale where needed.

A - moving iron vane
B_1 - fixed iron vane — rectangular
B_2 - fixed iron vane — shaped to improve scale — superimposed on B_1
C - current carrying magnetising coil
P - pointer
S - flat spiral control spring
V - air type damping vane

Note: only one or the other of B_1 and B_2 would be used in the instrument element.

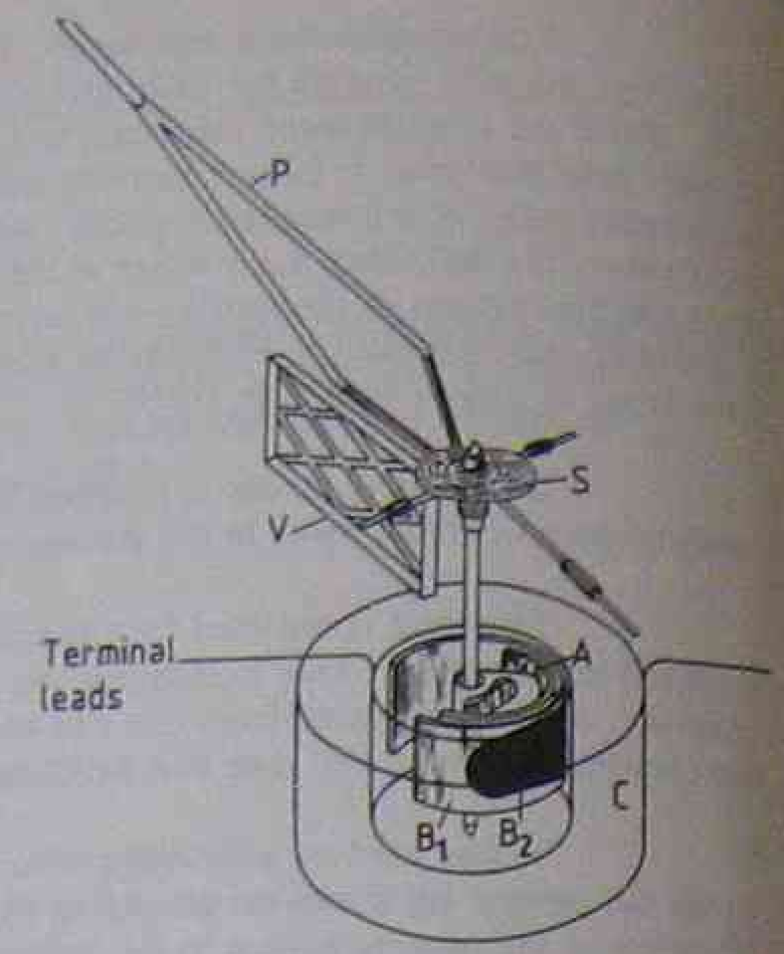


Figure 10.10
Repulsion-type moving-iron instrument element with spring control, concentric vane type (phantom view)

(b) *Radial vane mechanism (refer Figure 10.11)*

The features of this type of instrument are:

- opens up like a book under repulsion
- most sensitive
- most linear scale
- requires better design and better magnetic vanes for good grades of instruments.

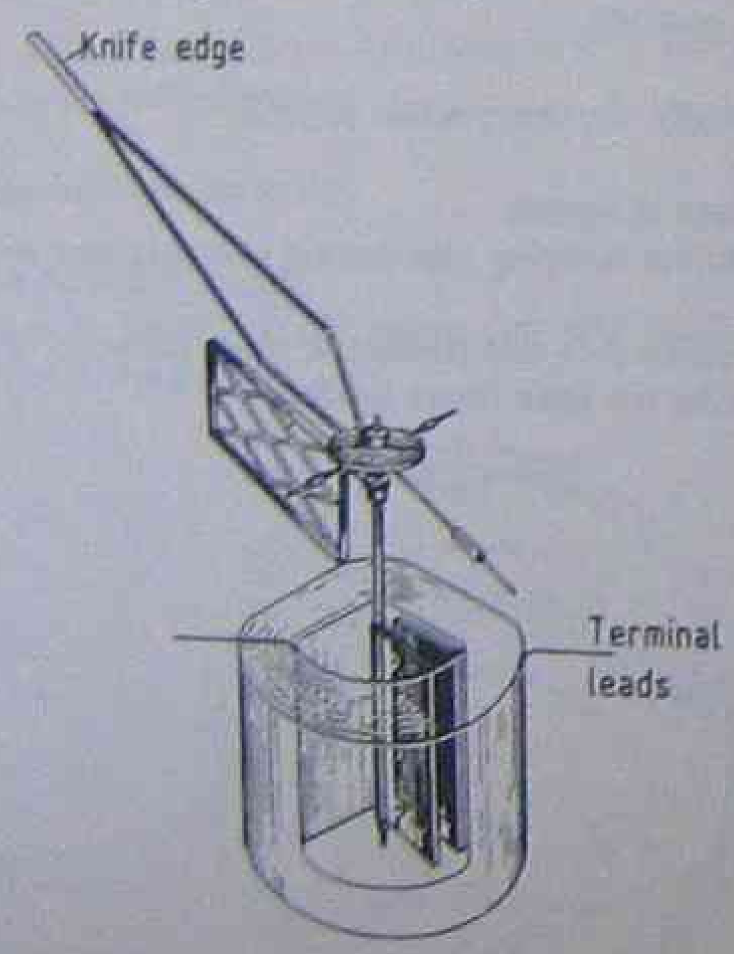


Figure 10.11
Repulsion-type moving-iron instrument element with spring control, radial vane type (phantom view)

10.4.3 Characteristics of the moving-iron instrument

(a) The instrument does not distinguish polarity and may be used for the measurement of both direct current and alternating current quantities. It is commonly used for a.c. measurement.

(b) It has comparatively low current sensitivity.

(c) The scale graduation spacing tends to follow a square law and hence is non-uniform.

(d) The iron vanes may be shaped to obtain special scale characteristics.

(e) Accuracy may be impaired when reading high and low alternating current values. Should the irons be working at a flux density near saturation, then the instrument will, if calibrated on direct current, read low when used on alternating current. At low values of flux density, that is, low values of current, the peak a.c. value gives a greater deflection per unit of current than does the average d.c. value. This causes the instrument to read high on alternating current at the lower end of the scale.

(f) Losses due to hysteresis of the iron vanes and eddy currents induced in the metal parts forming the framework of the instrument affect the accuracy of measurement.

(g) The coil of a moving-iron instrument is comparatively large and possesses a relatively high inductance. The inductive reactance of the coil will vary with a change of frequency and hence introduce an error in the measurement. Moving-iron instruments are usually designed for use at power frequencies in the range of 20 to 125 Hz but with special design may be used up to frequencies of approximately 2 kHz.

(h) Its accuracy is consistent and its construction is rugged, making it capable of withstanding severe overloads.

(i) It is relatively inexpensive.

10.5.1 General

This instrument, also referred to as a dynamometer type, makes use of the force exerted between fixed and moving coils carrying currents, and does not incorporate ferro-magnetic material. The standard symbols used to designate the ironless electrodynamic instrument are shown in Figure 10.12.

Figure 10.12
Symbols for electrodynamic instrument

The electrodynamic type of instrument movement is probably one of the most important movements devised. It may be used for a variety of applications, such as the precise measurement of direct and alternating voltages and currents, and as a standard instrument for the calibration of other d.c. and a.c. instruments. For calibration work its own small errors are determined by a d.c. potentiometer using a standard cell as the reference standard. The electrodynamic instrument may then be used for the calibration of d.c. instruments and/or as a transfer standard – direct current to alternating current – for the calibration of a.c. instruments.

With minor design alterations it may be used as a wattmeter, a reactive power meter, a power-factor meter or a frequency meter, although recently the moving coil type of instrument, complete with appropriate transducer, has been preferred for the measurement of these quantities.

10.5.2 Principle of operation and construction

The electrodynamic instrument is somewhat similar to the permanent-magnet moving-coil instrument in that it comprises a moving coil, carrying a current, suspended in a magnetic field. However the magnetic field is produced by the current flowing through the fixed coils and is not provided by a permanent magnet. Since the flux path is through air, the magnetic reluctance is high and the field strength is about one-fiftieth that of the permanent-magnet moving-coil instrument.

The deflecting torque (T_D) is dependent on the same quantities as those of the permanent-magnet moving-coil instrument – the flux density (B) of the field coils, the current through the moving coil (I_m), the area enclosed by the coil (A), and the number of turns on the moving coil (N), that is:

$$T_D = BI_mNA \text{ (Nm)}.$$

It is evident that the field flux is proportional to the field current (I_f) and that the deflecting torque is proportional to the product of the two currents I_m and I_f that is:

$$T_D \propto I_m \times I_f.$$

When the two currents have the same value, as is the case for milliammeters and voltmeters, $T_D \propto I^2$ and the scale graduation spacing follows a square law, resulting in a non-linear scale.

The control torque is provided by two flat spiral control springs which also conduct the current into and out of the moving coil.

Air-vane damping can be used to damp out the oscillations of the moving system. However, eddy-current damping is also now being used on dynamometer type movements using a small fixed permanent magnet and a lightweight, highly conductive aluminium disc attached to the moving element, which rotates through the air gap of the magnet.

The complete measuring element is protected from stray magnetic fields by a laminated magnetic shield.

Figure 10.13 illustrates the positioning arrangement of the fixed and moving coils. Two identical fixed coils connected in series and shown sectionalised, are spaced a small distance apart to provide clearance for the spindle to which the moving coil is attached. The moving system complete with the pointer is supported by pivots and jewelled bearings (not shown).

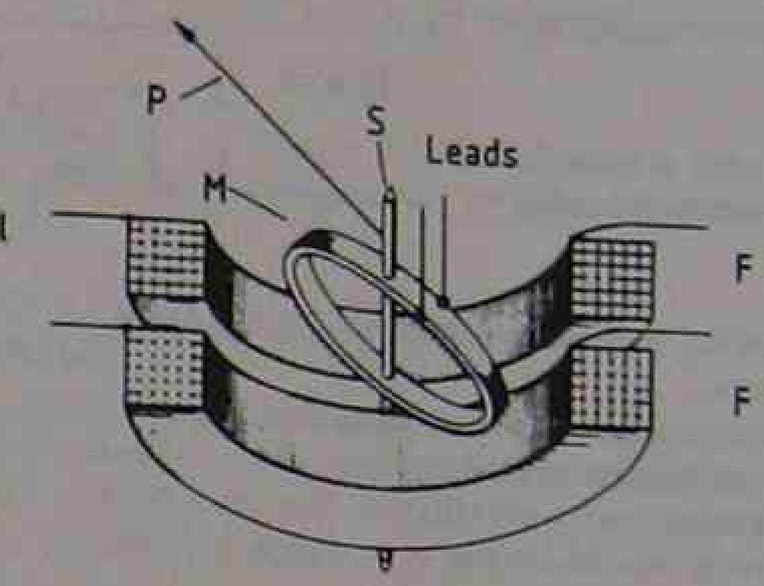


Figure 10.13
Single-element electrodynamic instrument coil arrangement

Figure 10.14 is a circuit diagram of the connections used for a milliammeter or, with a slight modification, for a voltmeter. Figures 10.15, 10.16, and 10.17, show a variety of arrangements and connections for the electrodynamic instrument when used for other single-phase and polyphase measurements.

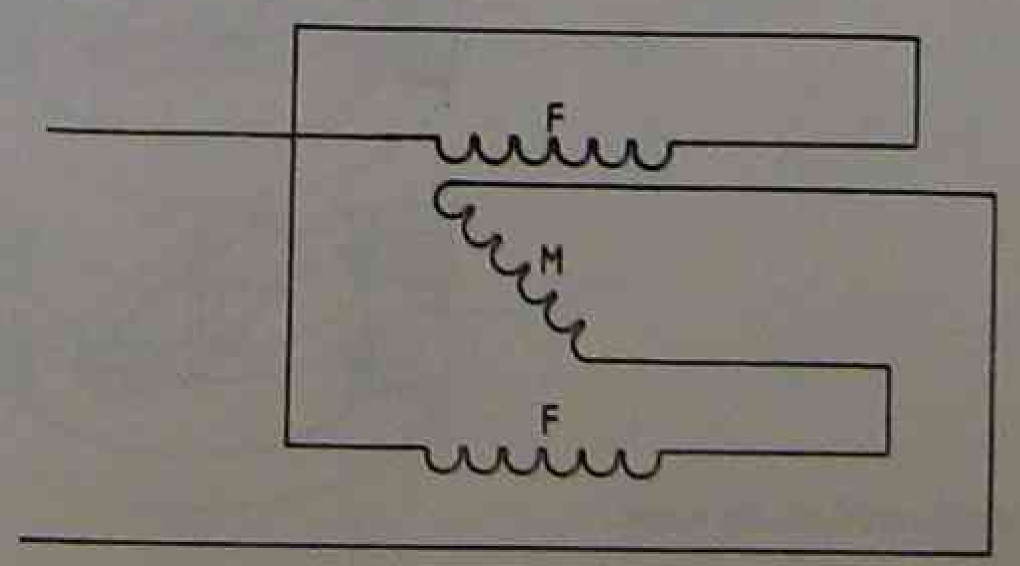


Figure 10.14
Electrodynamic milliammeter-voltmeter

The fixed coils (FF) are in series with a resistor (S) which is provided as a shunt for the moving coil (M).

R is a manganin swamping resistor to provide not only the required voltage drop across the shunt but also temperature compensation.

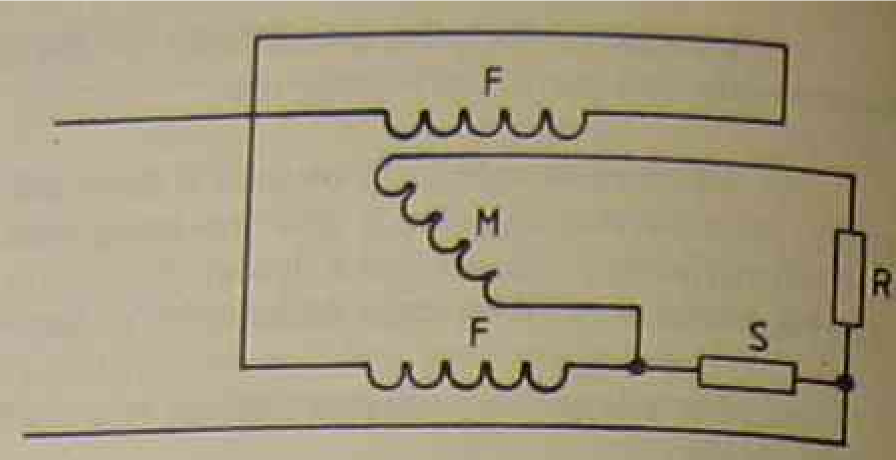


Figure 10.15
Electrodynamic ammeter

The fixed coils (FF) are in series with the load.

The moving coil (M), with a suitable series resistor (R), is connected across the load, or source:-

- Across the load the reading includes the moving-coil circuit power.
- Across the source the reading includes the fixed-coil circuit power.

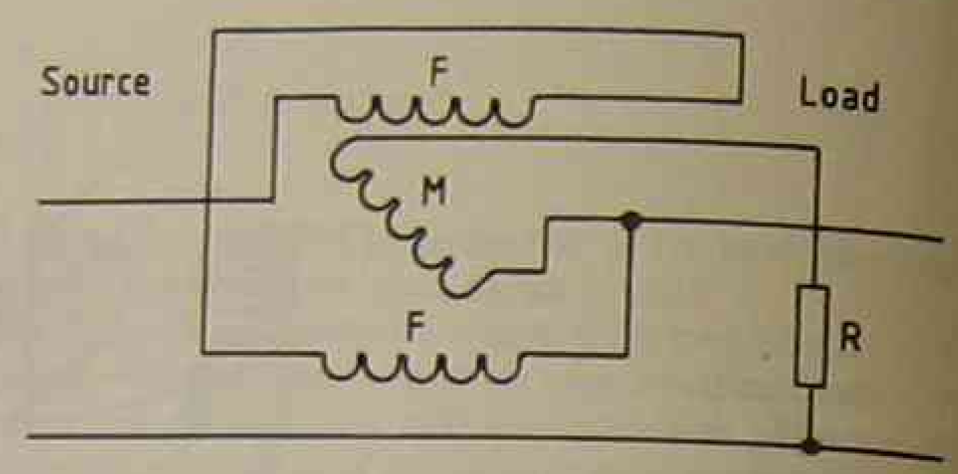


Figure 10.16
Electrodynamic single-element wattmeter

Moving coils (M) are mounted on the same spindle.

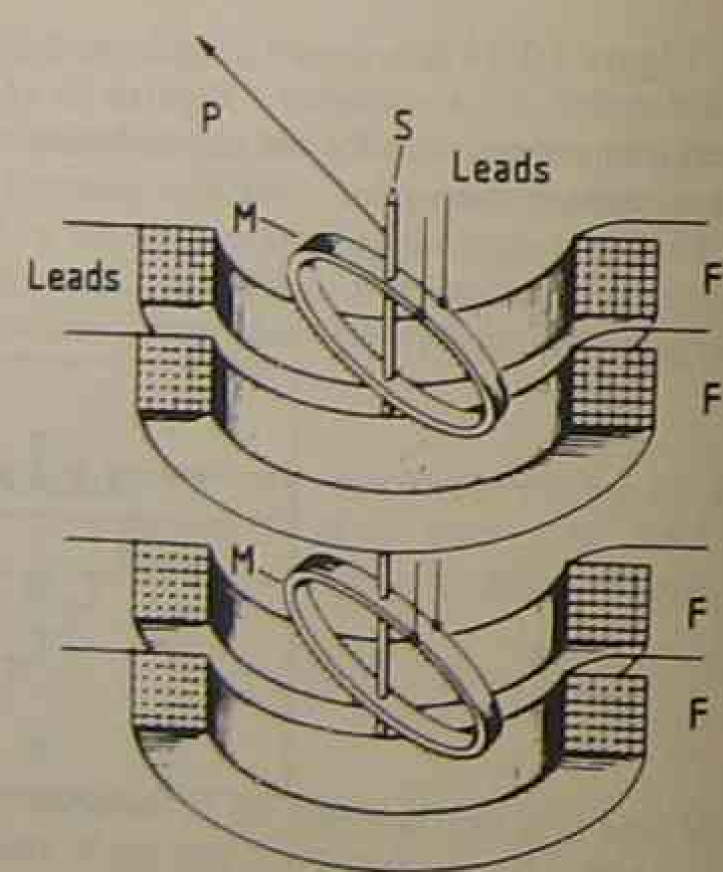


Figure 10.17
Double-element electrodynamic instrument,
coil arrangement used for polyphase measurements.

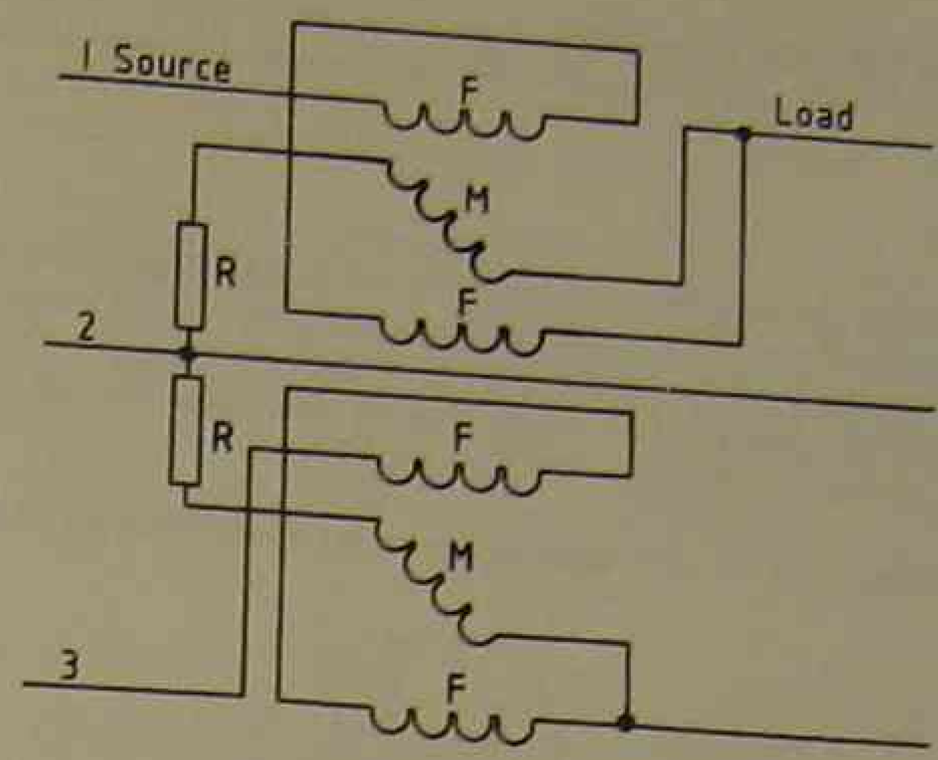


Figure 10.18
Double-element electrodynamic polyphase wattmeter

10.5.3 Characteristics of the electrodynamic instrument

(a) The instrument is not polarised and may be used for the measurement of both direct and alternating current quantities. Due to its inherent accuracy it is commonly used as a transfer instrument from d.c. to a.c. to calibrate other types of instruments. It is frequently used as a secondary standard in the audio and power frequency range.

(b) To obtain the required deflecting torque a comparatively high current through the moving coil is required, resulting in a relatively high power consumption and low current sensitivity. For example, its sensitivity is of the order of 10 to 30 Ω/V as compared to 20 kΩ/V for the permanent-magnet moving-coil instrument.

(c) Its high circuit-loading effect makes it unsuitable for measurements on electronic circuits.

(d) The large coil system gives the instrument a relatively high inductive reactance which varies with frequency, and consequently its application is confined to measurements in the lower frequency range.

(e) The scale graduation spacing is non-linear.

(f) It is relatively expensive.

10.6.1 General

In principle, the induction movement is one in which all direct electrical connection to the moving element is dispensed with, the current being transferred from a fixed external circuit to the moving system, usually in the form of a shaped aluminium disc, by electromagnetic induction. The currents so induced are acted upon by one or more additional magnetic circuits so arranged as to cause a deflecting force.

The standard symbol adopted to designate the induction instrument is as shown in Figure 10.19.

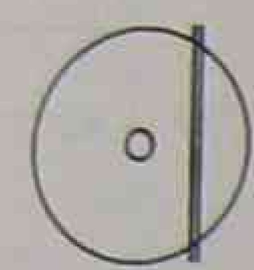


Figure 10.19
Symbol for induction-type instrument

10.6.2 Principle of operation and construction

The induction type of instrument is suitable for the measurement of alternating current quantities only, such as voltage, current and power. It does not have the high degree of accuracy of the electrodynamic and moving-iron types but it has other practical features which make the instrument useful. Figure 10.20 illustrates the constructional details of one type of design – the shaded-pole type of induction ammeter.

A - electromagnet
B - coil
C - permanent magnet for damping
D - induction disc
P - pointer
S - flat spiral control spring
T - staff
U - shading ring

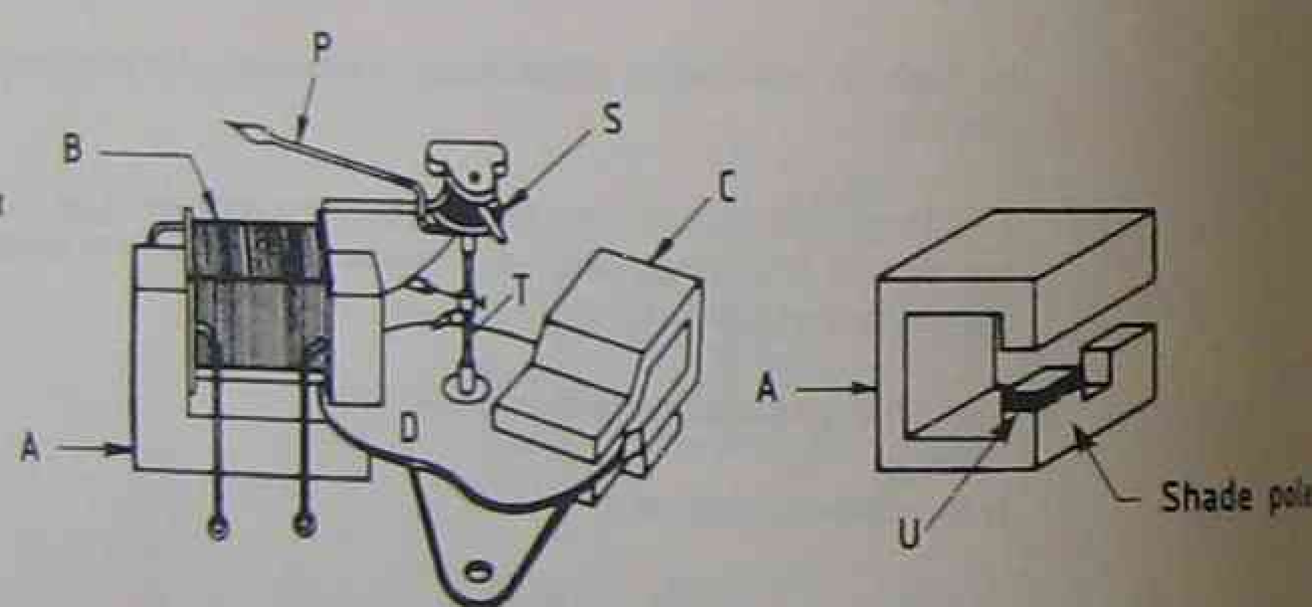


Figure 10.20
Shaded-pole induction-type ammeter

With reference to Figure 10.20 it may be seen that the flat disc is free to revolve in the air gap of the laminated electromagnet. A control spring is attached to the staff, and the pointer indicates the quantity being measured. A shading ring of annealed copper is fitted into the slot and around part of the pole piece of the electromagnet.

When the alternating flux passing down through the shading ring commences to increase, eddy currents induced in the shading ring produce a flux opposing that entering the ring, that is, it opposes the increase in flux. As the alternating flux decreases, the induced current in the shading ring opposes the decrease in flux. This retards the time phase of the flux in the shaded portion of the pole with respect to that in the unshaded portion and results in a sweeping of the flux across the face of the pole cutting the disc and inducing eddy currents in the disc. These currents react with the flux to produce a torque tending to drive the disc in the direction in which the shading ring is displaced from its position of symmetry on the electromagnet pole.

The deflecting torque for ammeters and voltmeters is proportional to the square of the current flowing through the fixed coil, and the scale graduation spacing is therefore inherently non-linear. The control torque is provided by a long, flat, spiral control spring. Since no current flows into the moving system, only one spring is required. Damping is produced by eddy currents being induced in the disc as it moves between the poles of the permanent magnet.

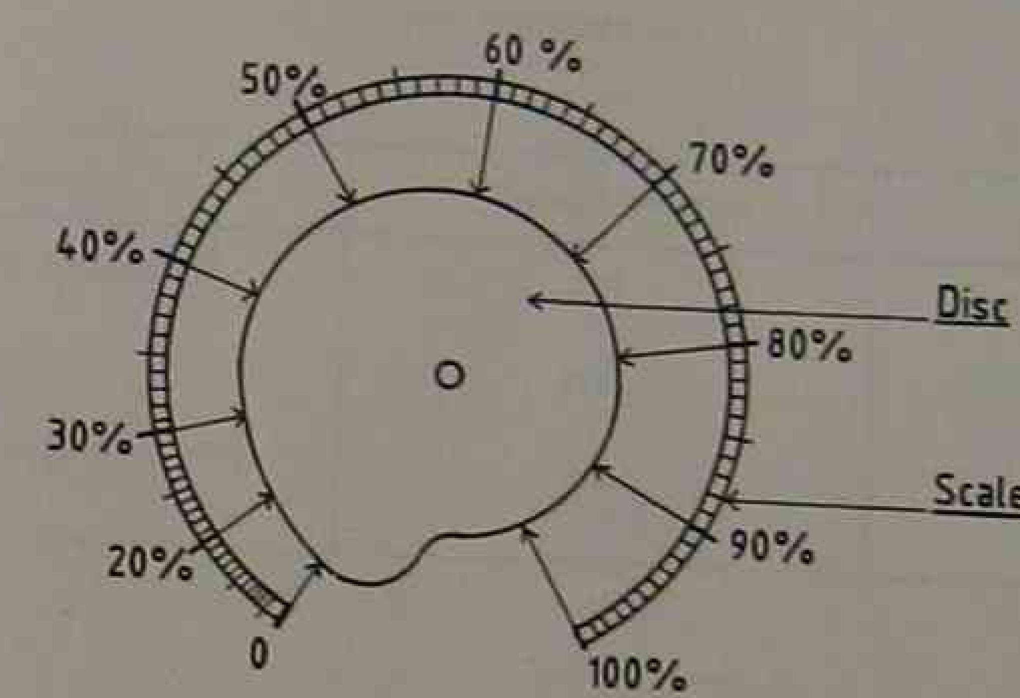


Figure 10.21
Shaped disc of induction ammeter and the resulting scale

10.6.3 Characteristics of the induction instrument

(a) Measures alternating current quantities only.

(b) Unusually long scale subtending an angle of 300° or greater, thus providing clear visibility from a distance.

(c) The scale shape may be modified by varying the radius of the induction disc as shown in Figure 10.20.

(d) No electrical connections to the moving system. Current is transferred from the fixed system to the moving system by electromagnetic induction.

(e) Robust construction.

(f) High power consumption.

(g) Susceptible to errors due to variations of temperature, frequency and also voltage for wattmeters.

10.7 THE RECTIFIER TYPE OF INSTRUMENT

10.7.1 Introduction

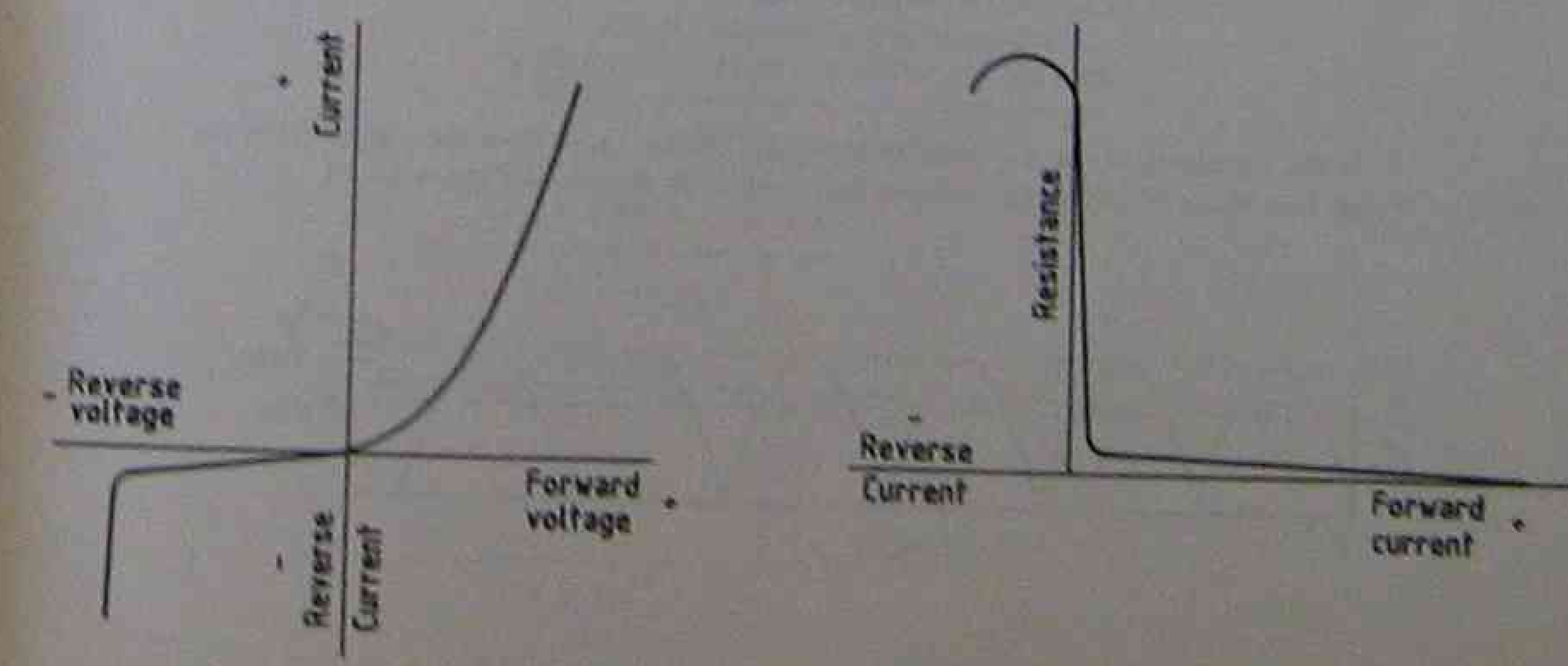
The high circuit-loading characteristic of those instruments normally used for alternating current measurement at power frequencies makes them unsuitable for use on electronic circuits. The obvious choice is the high sensitivity, permanent-magnet moving-coil instrument movement used in conjunction with a rectifier. The rectifier produces a series of positive, unidirectional pulses and the PMMC instrument movement then measures the average value of the instantaneous currents.

10.7.2 Principle of operation and construction

A rectifier unit made up of germanium or silicon diodes is normally used. Typical characteristics of these diodes are given in Table 10.6. Typical solid state rectifier characteristic curves are shown in Figure 10.22.

Table 10.6
Diode characteristics

Characteristic	*Germanium (Ge)*	*Silicon (Si)*
Peak inverse voltage (V)	300	1000
Current (mA)	100	500
Forward voltage drop (V)	0.3	0.7



Voltage-current characteristic *Current-resistance characteristic*

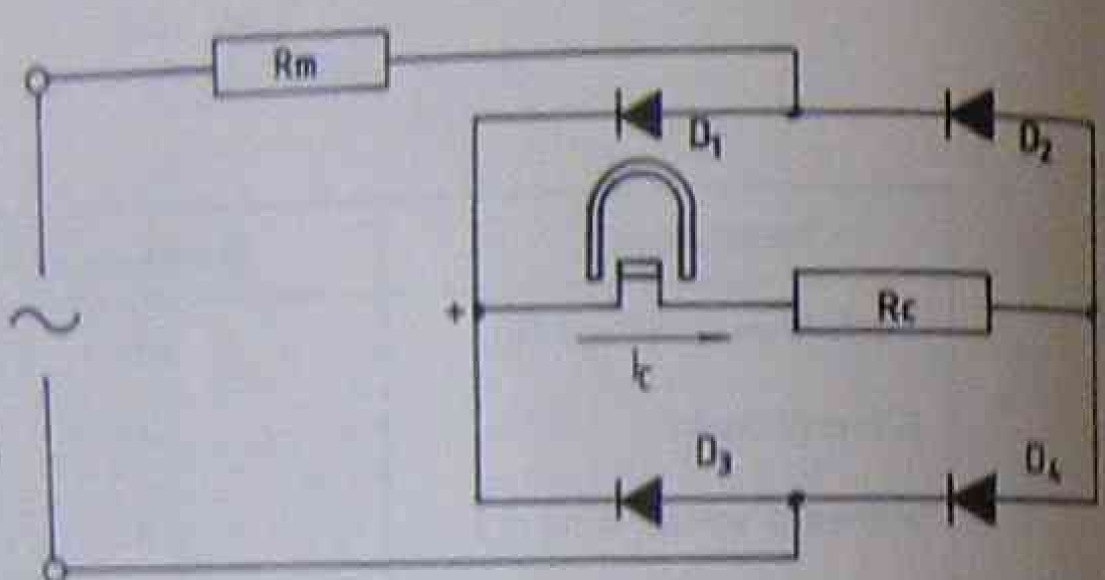
Figure 10.22
Typical diode characteristic curves (not to scale)

The ideal rectifier should have zero forward resistance and infinite reverse resistance. From the current-resistance characteristic curve in Figure 10.22 it can be seen that this is not so. At low values of forward current the rectifier is operating on a critical part of the curve where the steep gradient gives a very high resistance as compared to much lower values of resistance with higher values of current.

When the rectifier is used with the permanent-magnet moving-coil movement to measure a.c. quantities, the current-resistance characteristic of Figure 10.22 imposes the following limitations:

- a decrease in the range of instruments available responding to small values of current, such as microammeters and voltmeters
- the scale shape of low range voltmeters becomes cramped at the lower end of the scale, which frequently results in a separate calibrated scale being provided on the dial for the lowest a.c. voltage range.

The full-wave bridge rectifier circuit is commonly used for the measurement of a.c. quantities, as shown in the circuit of Figure 10.23 which is arranged for voltage measurement.



D - diode
I_c - current through moving coil
R_m - voltage multiplier resistance
R_c - resistance of moving-coil circuit

Figure 10.23
Full wave bridge rectifier circuit

If the waveform of the a.c. source voltage is a sine wave, then the output from the rectifier bridge is a series of pulsating, positive half-cycles, as shown in Figure 10.24.

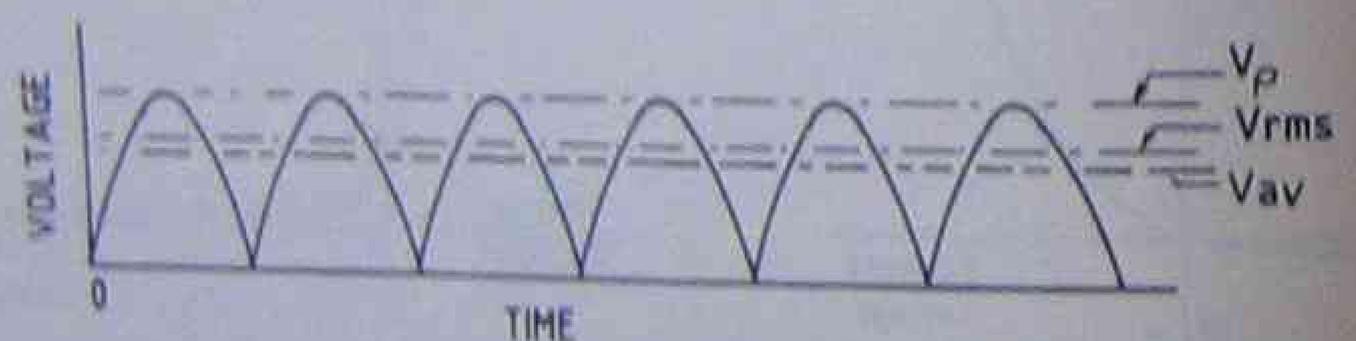


Figure 10.24
Rectified waveform

The PMMC movement, because of its inertia, measures the average value of the pulsating d.c. waveform. To obtain the correct a.c. value the scale must be marked in terms of the rms value. There are proportional relationships between the maximum (or peak), rms and average values. The form factor for an alternating wave is the ratio of the rms value to the average value and for a sine wave equals 1.11

The average values multiplied by 1.11 will give the rms values for the scale graduations. The calculated rms values are marked on the instrument scale at places corresponding to their average values. The form factor of 1.11 applies to a sinusoidal waveform only and a different form factor would be required for non-sinusodial waveforms. Half-wave rectification circuits may also be used in voltmeters for the measurement of a.c. voltage.

Example:

A multimeter instrument movement has an internal resistance (R_c) of 2 kΩ and a sensitivity of 20 000 Ω/V when used as a d.c. voltmeter. A silicon diode, bridge connected, rectifier network is used for a.c. measurements. With the aid of the circuit diagram in Figure 10.23, determine the resistance of the multiplier resistor (R_m) required for a FSD of 100 V rms. Assume the a.c. waveform to be sinusoidal.

Solution:

For FSD, the average current flowing through the PMMC movement is:

$$I_c = \frac{1}{20\,000} = 50\ \mu A$$

$$\text{Peak current } I_p = \frac{50}{0.637} = 78.5\ \mu A.$$

There will be only two diodes conducting at the same time, that is, D1 and D4 or D2 and D3, and (assuming the diodes have infinite reverse resistance) we have:

$$I_p = \frac{\text{Applied peak voltage} - \text{rectifier voltage drop}}{\text{Total circuit resistance}}$$

$$I_p = \frac{(\sqrt{2} \times 100 - 2 \times 0.7)}{(R_c + R_m)}$$

$$R_m = \frac{(141.4 - 1.4)}{I_p} - R_c$$

$$= \frac{140}{78.5 \times 10^{-6}} - 2 \times 10^3$$

$$= 1.781\ M\Omega.$$

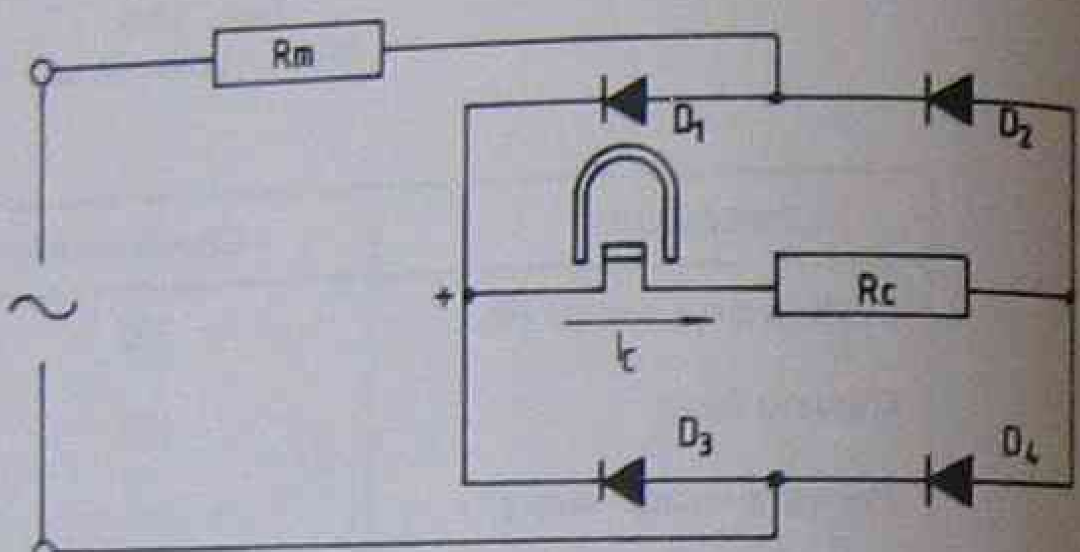
It is of interest to compare the sensitivity of the voltmeter for the d.c. and a.c. ranges.

The ideal rectifier should have zero forward resistance and infinite reverse resistance. From the current-resistance characteristic curve in Figure 10.22 it can be seen that this is not so. At low values of forward current the rectifier is operating on a critical part of the curve where the steep gradient gives a very high resistance as compared to much lower values of resistance with higher values of current.

When the rectifier is used with the permanent-magnet moving-coil movement to measure a.c. quantities, the current-resistance characteristic of Figure 10.22 imposes the following limitations:

- a decrease in the range of instruments available responding to small values of current, such as microammeters and voltmeters
- the scale shape of low range voltmeters becomes cramped at the lower end of the scale, which frequently results in a separate calibrated scale being provided on the dial for the lowest a.c. voltage range.

The full-wave bridge rectifier circuit is commonly used for the measurement of a.c. quantities, as shown in the circuit of Figure 10.23 which is arranged for voltage measurement.



D - diode
I_c - current through moving coil.
R_m - voltage multiplier resistance
R_c - resistance of moving-coil circuit

Figure 10.23
Full wave bridge rectifier circuit

If the waveform of the a.c. source voltage is a sine wave, then the output from the rectifier bridge is a series of pulsating, positive half-cycles, as shown in Figure 10.24.

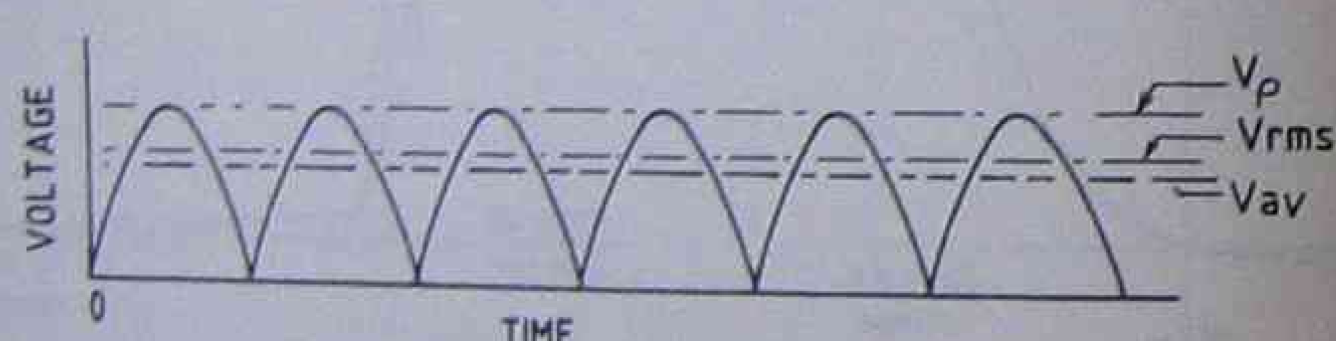


Figure 10.24
Rectified waveform

The PMMC movement, because of its inertia, measures the average value of the pulsating d.c. waveform. To obtain the correct a.c. value the scale must be marked in terms of the rms value. There are proportional relationships between the maximum (or peak), rms and average values. The form factor for an alternating wave is the ratio of the rms value to the average value and for a sine wave equals 1.11

The average values multiplied by 1.11 will give the rms values for the scale graduations. The calculated rms values are marked on the instrument scale at places corresponding to their average values. The form factor of 1.11 applies to a sinusoidal waveform only and a different form factor would be required for non-sinusodial waveforms. Half-wave rectification circuits may also be used in voltmeters for the measurement of a.c. voltage.

Example:

A multimeter instrument movement has an internal resistance (R_c) of 2 kΩ and a sensitivity of 20 000 Ω/V when used as a d.c. voltmeter. A silicon diode, bridge connected, rectifier network is used for a.c. measurements. With the aid of the circuit diagram in Figure 10.23, determine the resistance of the multiplier resistor (R_m) required for a FSD of 100 V rms. Assume the a.c. waveform to be sinusoidal.

Solution:

For FSD, the average current flowing through the PMMC movement is:

$$I_c = \frac{1}{20\ 000} = 50\ \mu A$$

$$\text{Peak current } I_p = \frac{50}{0.637} = 78.5\ \mu A.$$

There will be only two diodes conducting at the same time, that is, D1 and D4 or D2 and D3, and (assuming the diodes have infinite reverse resistance) we have:

$$I_p = \frac{\text{Applied peak voltage} - \text{rectifier voltage drop}}{\text{Total circuit resistance}}$$

$$I_p = \frac{(\sqrt{2} \times 100 - 2 \times 0.7)}{(R_c + R_m)}$$

$$R_m = \frac{(141.4 - 1.4)}{I_p} - R_c$$

$$= \frac{140}{78.5 \times 10^{-6}} - 2 \times 10^3$$

$$= 1.781\ M\Omega.$$

It is of interest to compare the sensitivity of the voltmeter for the d.c. and a.c. ranges.

Sensitivity for d c ranges is, as stated, 20 000 Ω/V, and for the a c ranges it is determined as follows:

$$I_{rms} = 0.707 I_p$$
$$= 0.707 \times 78.5$$
$$= 55.5\ \mu A$$
$$V_{rms}\ (FSD) = 100\ V$$

$$\text{Total a c circuit resistance} = \frac{100}{55.5 \times 10^{-6}}$$
$$= 1802 k\Omega$$
$$\text{a c sensitivity} = \frac{1802 \times 10^{3}}{100}$$
$$= 18\ 020\ \Omega/V$$
$$\approx 18\ 000\ \Omega/V, \text{ a reduction of } 10\%.$$

10.7.3 Rectifier ammeters

Ammeters for both d c and a c measurements must have a very low impedance to ensure a low voltage drop, across the terminals, of approximately 75 to 100 mV. The voltage drop across the diodes of a bridge rectifier assembly is typically 1.4 V and 0.6 V for silicon and germanium diodes respectively. Consequently, rectifiers cannot be connected directly to a PMMC movement for alternating current measurements. An internal current transformer is used to give the ammeter a low terminal impedance and a low voltage drop. The secondary voltage of the current transformer is stepped up to operate the diode assembly, and the secondary current is reduced to a suitable low value for use in the PMMC movement. Figure 10.25 shows a typical bridge rectifier arrangement for the measurement of a.c. currents.

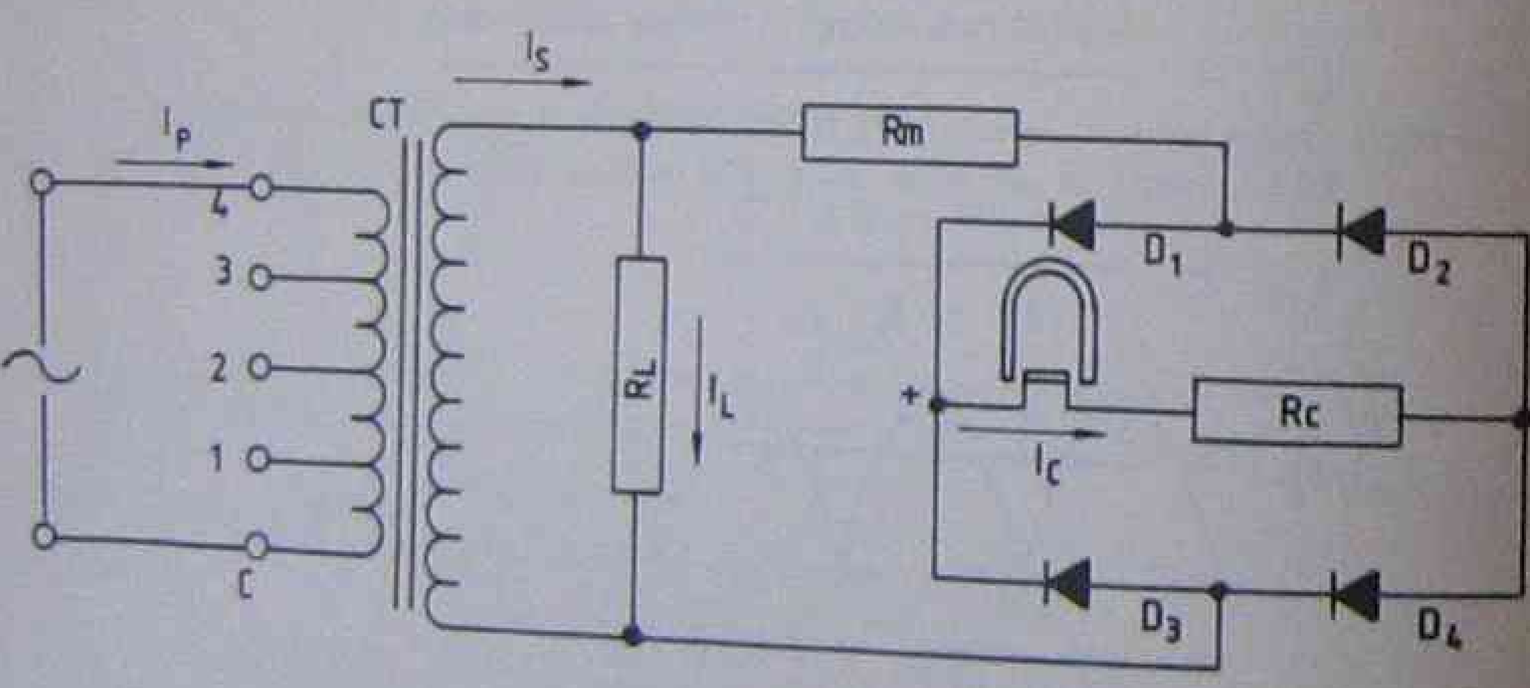


Figure 10.25
Measurement of alternating currents

CT - current transformer
I_L - current through precision resistor
I_p - primary current
I_s - secondary current
R_L - resistor of precise value.

The remaining symbols have the same meaning as in Figure 10.23.

$$\frac{I_p}{I_s} = \frac{N_s}{N_p}$$

where N_s and N_p are the numbers of secondary and primary winding turns. The resistor R_L has a precise resistance value to match the current transformer to the PMMC instrument movement.

The additional primary winding terminals 1,2 and 3 are provided to change the current range by varying the number of turns.

10.7.4 Waveform errors

It is clear from what has been stated earlier that the error introduced into the reading owing to the presence of harmonics in the wave will depend on the extent to which such harmonics will alter the ratio between the rms and average values of the wave, that is, upon the form factor. Errors from plus 5% to minus 10% are possible for a given percentage of harmonic depending on the phase relationship between the harmonic and the fundamental.

The use of rectifier-type instruments for such purposes as the measurement of transformer-magnetising currents or currents of a non-cyclic nature in which the waveform is known to be irregular is inadvisable.

10.8 FREQUENCY METERS

Note: Again, as an indication of the level of assessment of the work covered in Sections 10.8 to 10.13, please refer back to the objectives at the beginning of this unit.

Frequency meters are of four types. These are:

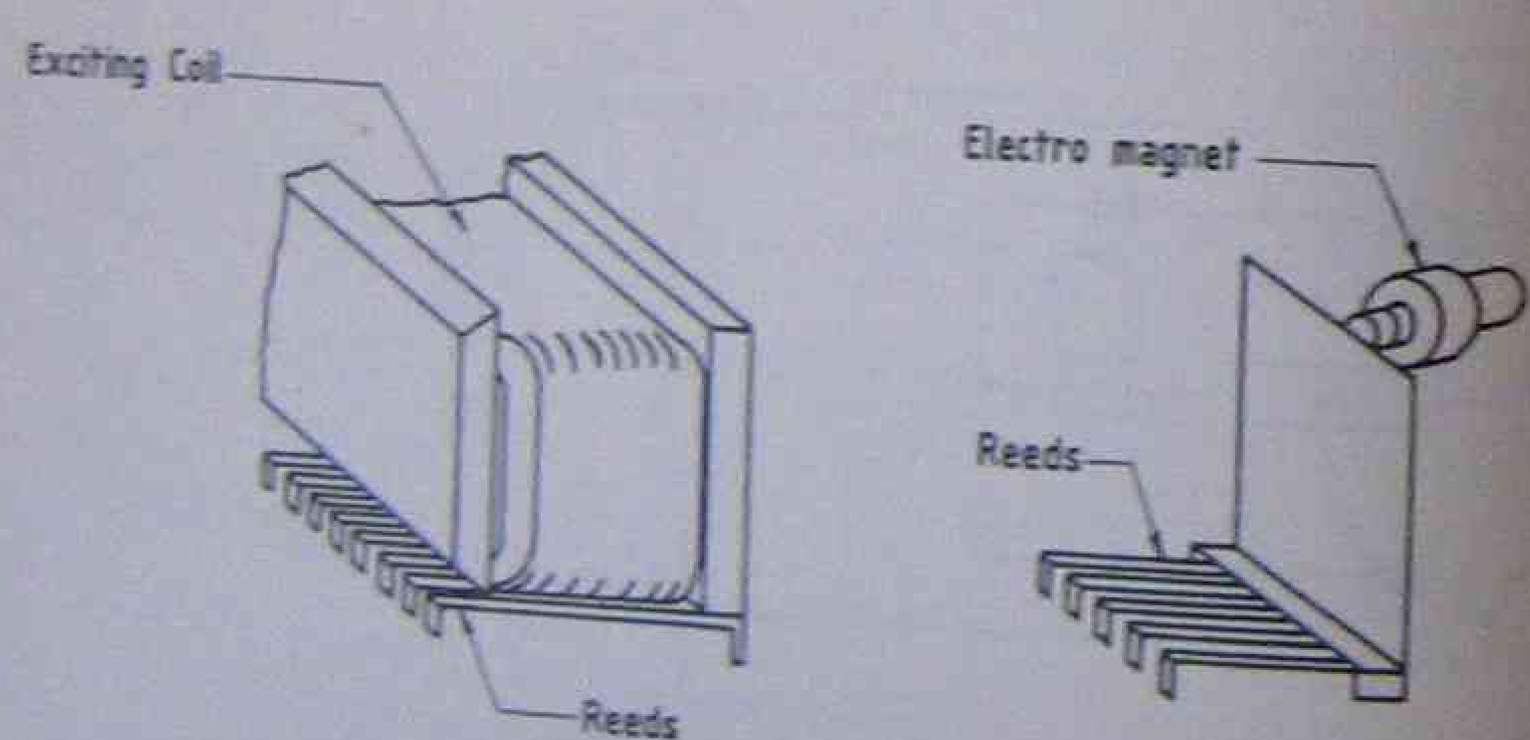
- transducer-driven (refer Section 10.17)
- vibrating-reed type
- moving-coil ratiometer type
- moving-iron ratiometer type.

10.8.1 Vibrating-reed type

This is an instrument in which reeds resonate under the action of a periodic current flowing through fixed coils, which are sometimes combined with a magnet. The reeds may be arranged in one or more rows each comprising a frequency range. The standard symbol adopted to designate the vibrating-reed type of frequency meter is shown in Figure 10.26.

Figure 10.26
Symbol for vibrating-reed frequency meter

The vibrating-reed or tuned-reed type of frequency meter comprises a number of steel reeds, each having a white index on its end, clamped so as to be adjacent to the poles of an electromagnet (see Figure 10.27). The natural frequency of vibration of each reed is different and is precisely tuned by appropriately dimensioning the reeds and controlling their mass.



(a) *Direct type*

(b) *Indirect type*

Figure 10.27
Reed type frequency meters

When the electromagnet is excited from the circuit whose frequency it is desired to measure, the reed, whose natural frequency is the same as the frequency of the circuit, will vibrate with the greatest amplitude. The amplitude is gradually increased with each swing until the energy dissipated in molecular and air friction just equals that imparted to the reed by the electromagnet. A very small alteration in the frequency of say 0.5% alters the amplitude by nearly 50%, as shown in the resonance curve in Figure 10.28. If the frequency of the circuit falls between that of two reeds then both will be set in vibration, but with reduced amplitudes. The amplitude of vibration, which depends on the square of the flux density, is considerably affected by voltage changes.

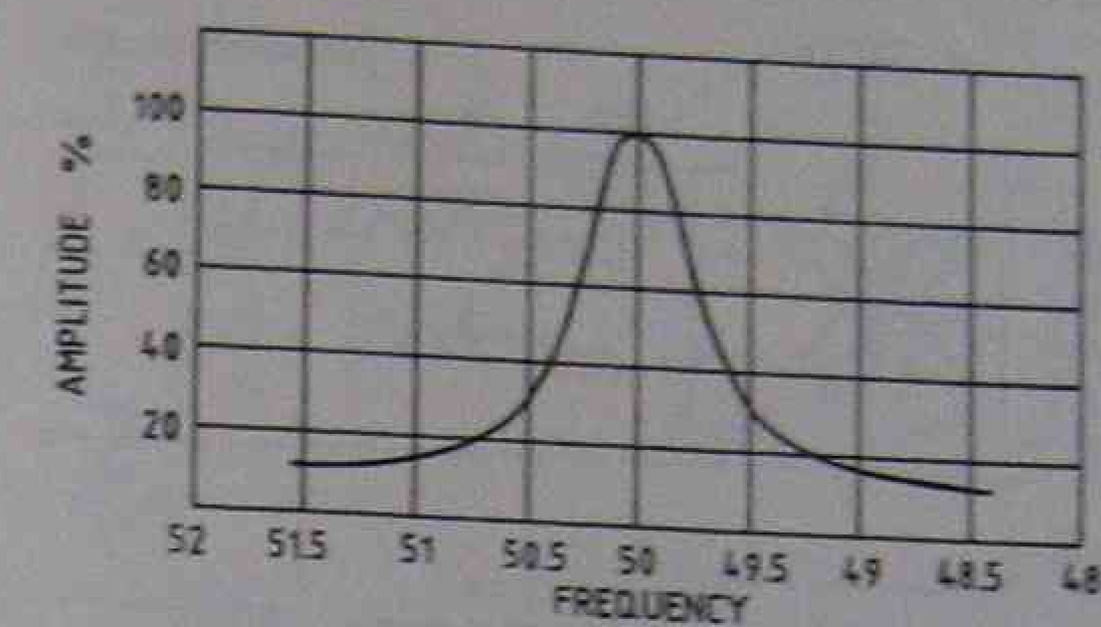


Figure 10.28
Resonance curve showing amplitude of tuned reed

The instrument is of relatively simple rugged construction and maintains its accuracy exceptionally well, provided the steel reeds are not overstressed by large amplitude vibrations which can be controlled by varying the voltage applied to the instrument. If the instrument is connected to a 50 Hz electrical supply for, say, one year, the number of vibrations would be enormous – in excess of 3153 million. However, if well designed, the life of the reeds should be everlasting.

These instruments are not suitable for those applications where it is necessary to control the frequency of supply against time. Fifty hertz synchronous time keeping devices require 50 × 60 × 60 × 24 cycles every 24 hours to keep them in step with time. Vibrating-reed instruments are incapable of performing precisely in this manner. They are robust, relatively inexpensive and ideal for field use such as transportable diesel alternator units and some marine applications.

10.8.2 Deflectional frequency meters

These differ from the reed-type frequency meter in that the movements are deflectional with pointer and scale. Electrical control is employed with these movements, and, with moving-coil systems, coiled minimum-torque ligaments are required to convey current to one or more moving coils.

Most deflectional frequency meters have two deflecting systems and the movement settles to a position in which the two operating torques are balanced. One or both operating torques are made frequency-dependent by the use of appropriate inductive/capacitive circuits.

(a) *Moving-coil frequency meter*

Referring to Figure 10.29, it will be seen that two intersecting moving coils with fixed angular separation are attached to a common shaft. Each coil is supplied through a resonant circuit, one coil 'a' being tuned to a frequency slightly below the scale range and the other, 'b', to a frequency slightly above the upper scale limit. The divided field coil 'd' and 'e', is connected so that it carries the sum of the currents in the resonant circuits.

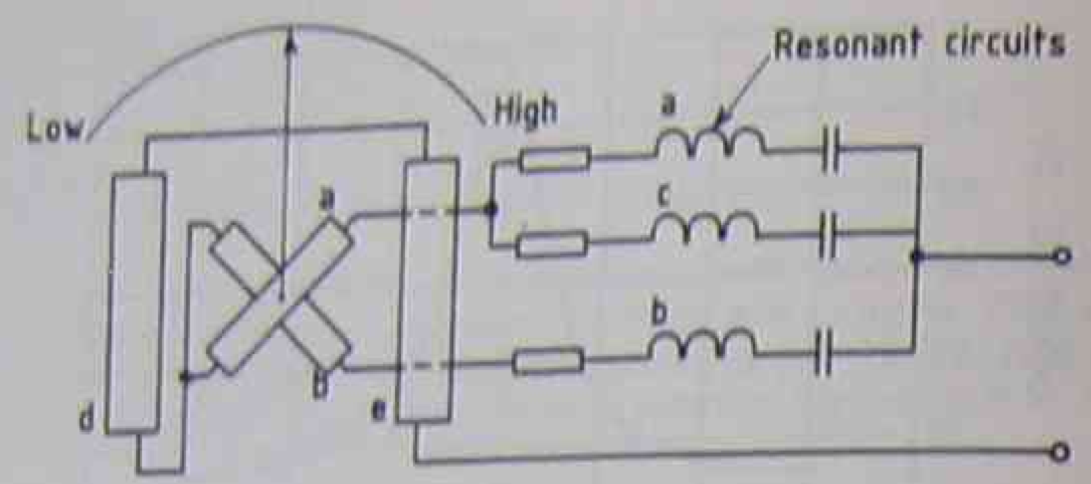


Figure 10.29
Frequency meter with twin moving coils

In operation both moving coils are urged toward a position parallel to the field coils but the torque on each coil is proportional to the cosine of the angle between the planes of the fixed and moving coils. As the torques are in opposition, the movement reaches equilibrium with the coil carrying the more powerful current lying nearer the parallel position.

At frequencies toward the low end of the scale the current of coil 'a' is high and is nearly in phase with the field-coil current, but the current in coil 'b' is low and leads the current in the field coils by a large angle. Thus the coil 'a' sets in a position approximately parallel to the plane of the field coil. For the mid-scale frequency the moving-coil currents are practically equal with nearly equal phase differences, lagging and leading with respect to the field-coil currents. The moving system therefore occupies an approximately symmetrical position.

The third resonant circuit 'c' is tuned to a frequency much lower than the lowest scale reading and serves to keep the pointer off the scale when the supply frequency is low. This is necessary because at very low frequencies the impedances of circuits 'a' and 'b' are again nearly equal. Without circuit 'c' the pointer would give a fictitious mid-scale reading.

(b) *Moving-iron frequency meter*

This frequency meter, shown diagramatically in Figure 10.30, has two closely spaced parallel coils with a composite moving vane pivoted between them. By means of the adjustable reactor L1, the fields of the two coils are made equal for a frequency corresponding to the centre of the scale. At the other frequencies the difference in the currents passed by the series capacitor and series reactor causes the field of one or other coil to predominate, so causing a greater deflection to that coil. The additional reactor L2, shown in series with the paralleled operating circuit, functions as a filter to suppress harmonics. It is made adjustable so that it serves to adapt the instrument to the required working voltage.

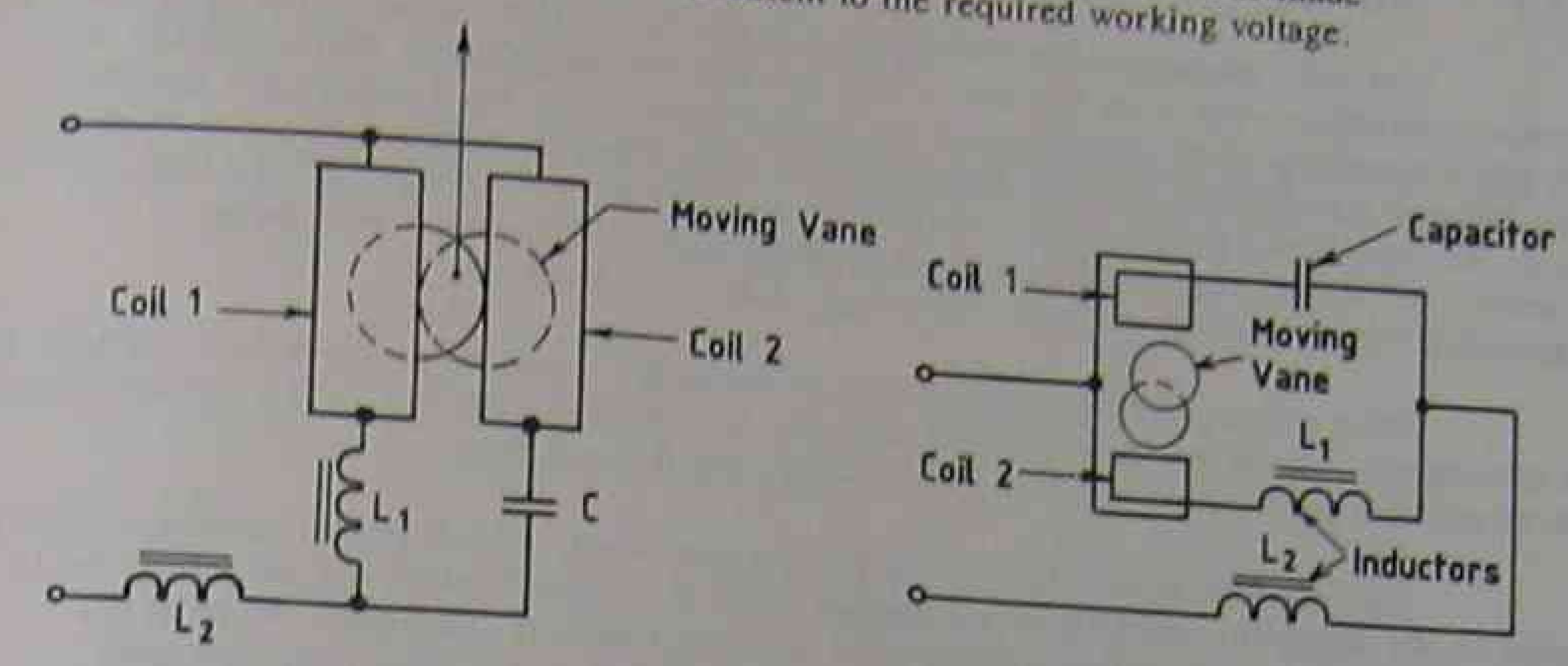


Figure 10.30
Moving-iron frequency meter with composite vane

10.9 POWER-FACTOR METERS

Present day instruments are normally transducer-driven moving coil or digital types (refer Sections 10.17 and 10.18). Earlier types were either moving coil or moving iron, examples of which are described below.

10.9.1 Principle of operation

As with frequency meters the movement of a power-factor meter is free from controlling forces and therefore turns to the position of zero average operating torque. This operation is basically independent of the magnitudes of the current and voltage, but depends upon the phase angle between them; hence the scale may be calibrated in terms of either power factor or phase angle. The operation requires a fixed phase difference between two or more of the exciting currents. For single-phase working a phase splitting circuit is necessary. Polyphase instruments rely on the natural phase differences of the system voltages.

Both moving-coil and moving-iron principles are employed in power-factor meters, but the moving-iron type is the more common since the movement is quite free, and a circular scale can be provided showing lag and lead for two directions of power flow.

Moving-iron indicators have the general disadvantage that a certain amount of error is caused by the hysterises and eddy current effects in the iron. Such errors may be minimised by suitable design of the iron circuit and choice of magnetic materials. Moreover the chief use of power-factor meters is in power circuits where the calibration is for one particular rated frequency. Moving-coil power-factor meters have the disadvantage that ligaments are required to energise the moving system. These exert a little constraint on the movement and also restrict the scale angle to less than 360°. Usually the scale covers less than two quadrants and represents a limited range of lag and lead power factors for only one direction of power flow.

10.9.2 Moving-coil power-factor meters

(a) *Single-phase power-factor meter*

This instrument (see Figure 10.31) has two intersecting coils with a physical displacement between them of 90°. One coil carries a current I_1 amperes in phase with the supply voltage, while the other has an equal current I_2 lagging the supply voltage by 90°. The fixed coil carries the line current.

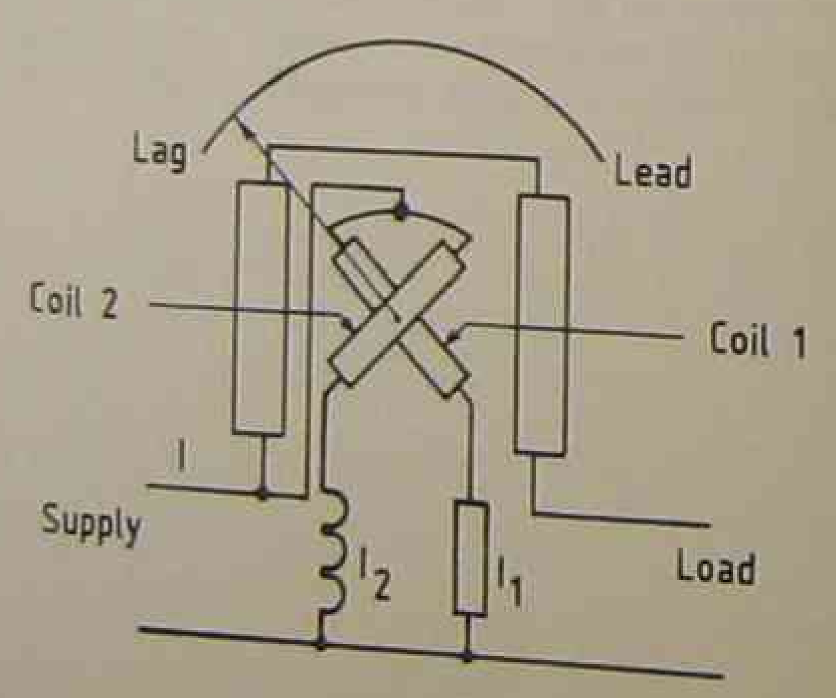


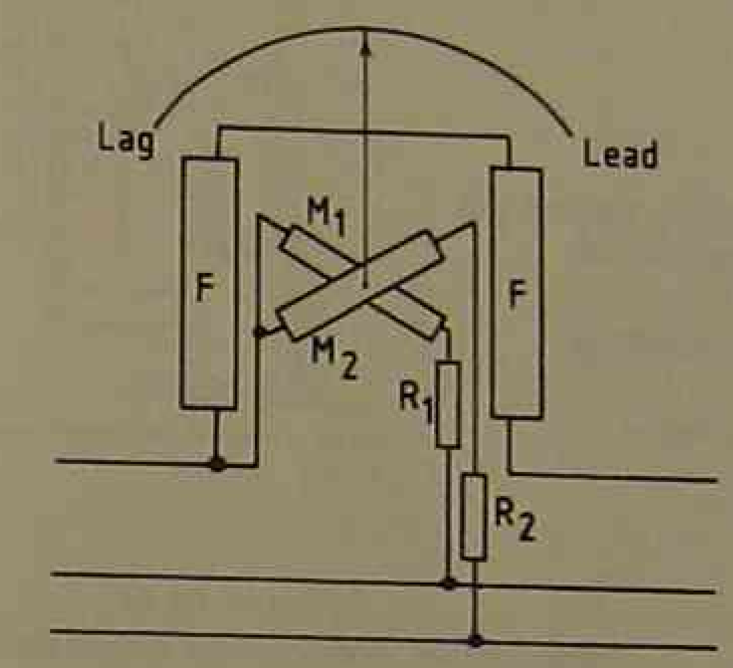
Figure 10.31
Single-phase moving-coil power-factor meter

It will be seen that at unity power factor I_1 is in phase with I, so coil 1 sets itself parallel to the fixed coils. At zero power factor, I_2 is in phase with I so coil 2 sets itself parallel to the fixed coils. The coils therefore set themselves in a position dependent on the power factor of the circuit.

In practice the phase difference between the currents of the moving coils is rather less than 90° and so the angles between the coils are adjusted to suit. The use of a phase splitter makes the instrument susceptible to changes in frequency. The scale markings on the instrument tend to be very open at power factors near unity but close rapidly towards the lower power factors.

(b) *Three-phase moving-coil power-factor meters*

The three-phase power factor meter does not need a phase splitting device. Either two or three moving coils may be used, the two-coil version being shown in Figure 10.32.



F - fixed coil
$M_1 M_2$ - moving coils
$R_1 R_2$ - non-inductive resistors

Figure 10.32
Two-coil three-phase power-factor meter

If the angle between the two coils M_1 and M_2 is made 120° as shown in Figure 10.32 the instrument can be made to indicate three-phase power factor if the system load is balanced. R_1 and R_2 are non-inductive resistors connected in series with each of the moving coils M_1 and M_2. The two series-connected fixed coils F are connected in one line of the three-phase system, and the common terminal of the two moving coils connect to the same line. The other terminals of each of the moving coils connect to each of the other two lines.

The moving system, being free from any control, will set itself in time-phase agreement with the field of the current coils, the position of the pointer indicating the power factor. If the system load is unbalanced, the reading has little significance.

The indication of the three-phase instrument is fundamentally independent of frequency, because the method of deriving the phase displacements between the moving-coil currents depends only on the balance of the three-phase voltages.

10.9.3 Moving-iron power-factor meters

(a) *Single- and three-phase moving-iron power-factor meters*

These may be compared with the moving-coil type if the moving coils are assumed to be replaced by fixed coils surrounding moving vanes, as indicated earlier (refer to Figures 10.33 and 34).

D - damping vane to smooth out movement oscillations
F - fixed field coils
M - magnetising windings
P - pointer
V - moving iron vanes

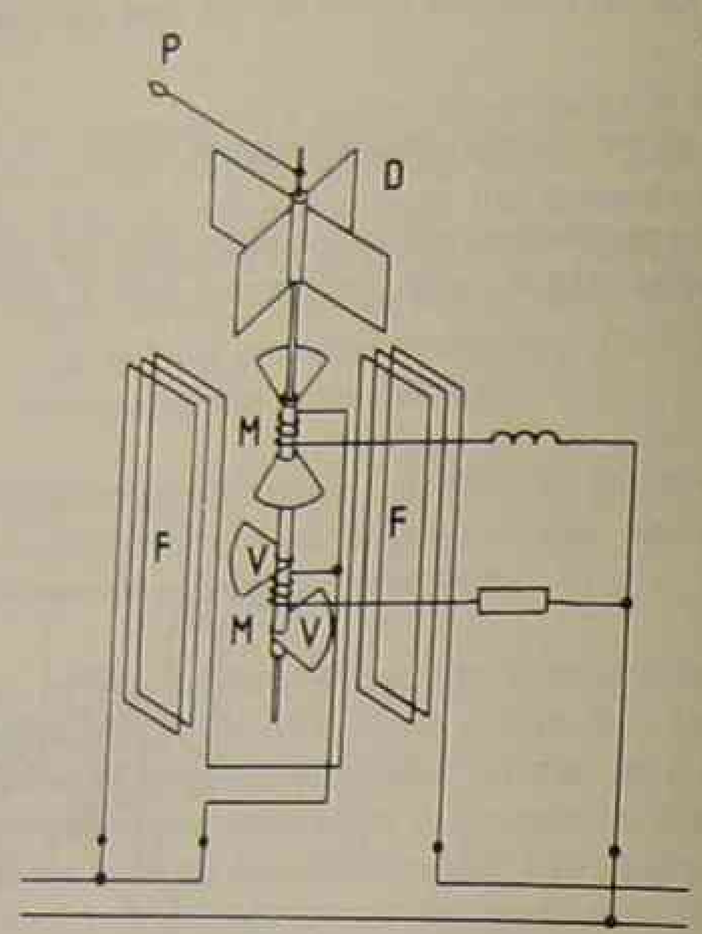


Figure 10.33
Moving-iron single-phase power-factor meter

D - damping vane to smooth out movement oscillations
F - fixed field coils
M - magnetising windings
P - pointer
V - moving iron vanes

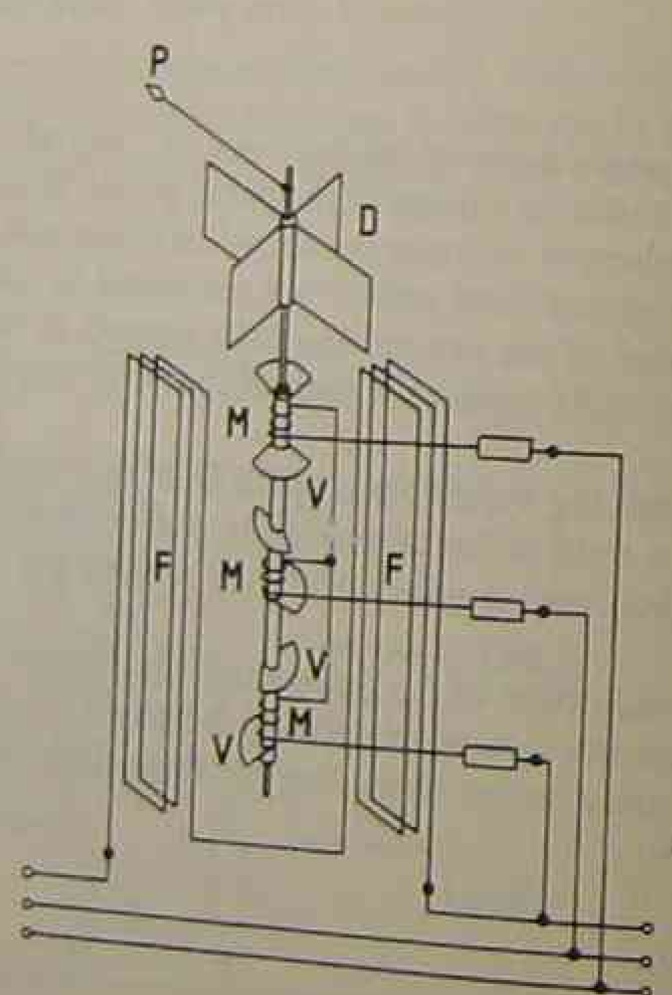


Figure 10.34
Moving-iron three-phase power-factor meter

10.9.4 Alternative measurement of power factor

The power factor of a circuit having constant parameters such as resistance and reactance is most easily read by means of a power-factor meter.

However, with some electricity tariffs, the charges are influenced by power factors or the supply authority, through its service rules, imposes a lower power-factor limit. Because of the fluctuating load and power factor in such cases, it is usual to derive the power factor from the readings of a reactive kilovolt ampere hour meter, in conjunction with a kilowatt hour meter. The value obtained is an average, usually taken over a 15 minute or 30 minute interval. This method will be considered further after kilowatt hour meters have been dealt with.

10.10 SYNCHROSCOPES

10.10.1 General

AS 1042 states that a synchroscope is an instrument to indicate the synchronism of two alternating voltages, as well as the magnitude and sign of the difference between their frequencies when they are not equal, and the magnitude of their phase difference when their frequencies are equal.

10.10.2 Principle of operation and construction

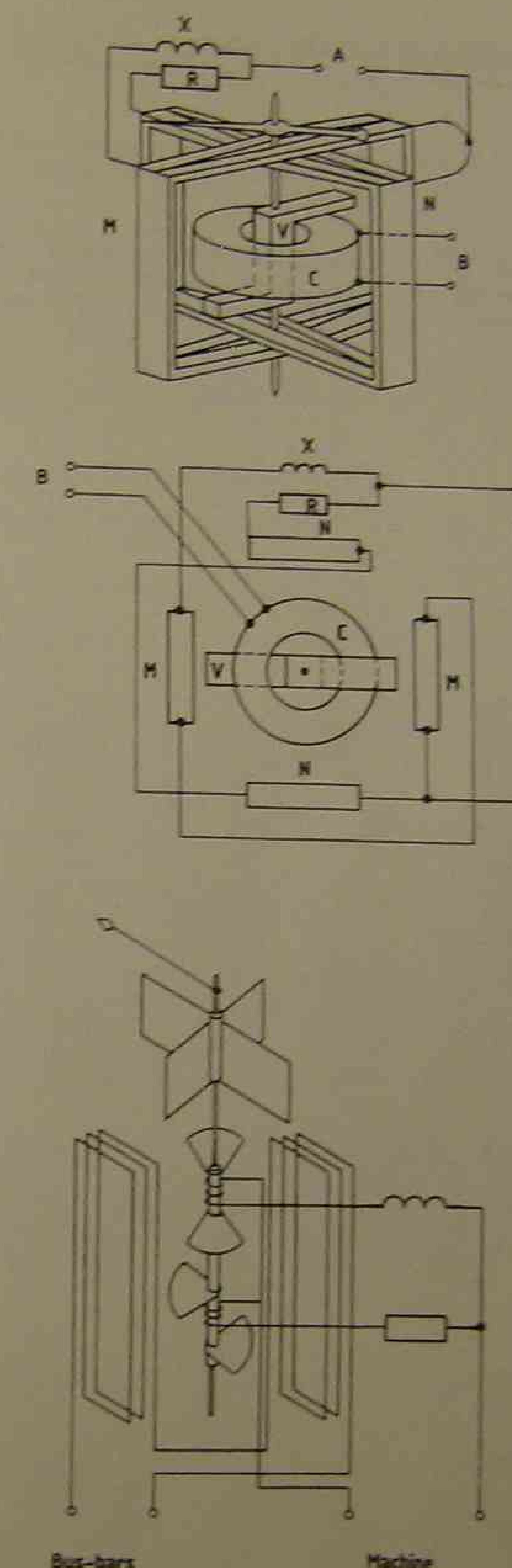
A pointer, known as the index, attached to the rotor of the instrument, moves over the dial face in either a clockwise or counter-clockwise direction depending on whether the incoming supply frequency is fast or slow with respect to the running supply frequency. If it is fast, the index rotates in a clockwise direction at a rate depending on the magnitude of the difference between the two supply frequencies. If it is slow, the index rotates in a counter-clockwise direction.

When the index stops, the frequencies of the two supplies are equal and when the index stops in the vertical, 12 o'clock position, the synchroscope indicates that the frequencies are equal and the voltages are in phase.

The synchroscope is usually a freely rotating moving-iron instrument. In use, the incoming machine is connected to one pair of terminals while the other pair of terminals is connected to the busbars, referred to as the running supply.

The construction may include one or two pairs of moving vanes magnetised by one of the supplies as shown in Figure 10.35(a) and (b). Both types operate in similar fashion. For example Figure 10.35(a) shows a moving-iron synchroscope in which a rotating magnetic field is produced by the coils M and N because of the reactance X and the resistance R. The iron vane V which is free to rotate is mounted in and magnetised by the coil C. The vane will rotate if the frequencies are different, or indicate the phase difference if the frequencies are the same.

The index is at the 12 o'clock position when the two supplies are in synchronism. This position is indicated on the dial by a single black line and is the only position on the dial which indicates synchronism. The scales of synchroscopes are fully exposed, and arrowheads on their dials clearly indicate whether the incoming supply is 'fast' or 'slow' with respect to the running supply.



(a)

(b)

Figure 10.35
Moving iron synchroscope

10.11 CHARACTERISTICS OF INSTRUMENTS

AS 1042 – 1973 Appendix C includes a table summarising the characteristics of typical instruments of various types, which may be useful for the selection of a suitable instrument for a given application.

The table lists the various types of instruments which may be used as ammeters, voltmeters, wattmeters, varmeters, power factor meters, frequency meters and synchroscopes, and provides details of typical ranges, scale shape, accuracy, wave-form effect and burden.

10.12 SINGLE-PHASE A.C. ENERGY METER

10.12.1 Introduction

Commonly called the watt-hour meter, the basic concept of the energy meter has not changed. However, technological progress has gradually contributed to a refinement in design resulting in an extremely reliable meter having a superior performance. Modern meters have much greater stability and consistency as well as a wider current range, while their insulation level and resistance to outside influences have increased to such an extent that they are now virtually unaffected by environmental conditions, short circuits and lightning surges. A considerable reduction in the mass of the disc assembly and the introduction of a permanent-magnet bearing has substantially reduced the effects of friction resulting in a longer maintenance free life.

10.12.2 Principle of operation and construction

The essential parts of a kilowatt-hour meter are:

- a main supporting frame or grid
- a voltage coil
- a current coil
- a rotor or disc
- top and bottom bearings to support the disc, leaving it free to rotate
- brake permanent magnets to maintain the disc speed proportional to power
- adjustments for heavy and light loads
- a register to count and sum the disc revolutions and, by suitable gearing, register the energy consumed
- a dustproof base and cover to afford protection for the meter components.

Modern meters have rigid light-weight, stress-relieved, diecast aluminium alloy mainframes which accommodate in special cavities the two, sintered, alnico brake permanent magnets. The magnets have a very high coercive force and, consequently, resist to a very high degree the effects of temperature change and the demagnetising influence of the alternating, magnetic fields produced by voltage and current surges. They are diecast in the frame for precise location on either side of the disc and give constant damping strength unaffected by age. The mainframe is drilled to hold all components in exact alignment, and the bearing and register mounts are precision machined.

To assist in understanding the principle of operation of the watt-hour meter, Figure 10.36 shows the magnetic fluxes produced by (a) the voltage electromagnet and (b) the current electromagnet, and how these fluxes would interact with the disc (note that Figure 10.36 includes the flux paths through flux return plates which link the voltage and current eletromagnets. For clarity, these plates are omitted on other diagrams).

(a) *Voltage-coil flux* (b) *Current-coil flux*

Figure 10.36
Flux distribution (instantaneous directions)

Eddy currents and magnetic fields, the polarity and direction of which are constantly changing, are induced in the disc. This has the effect of a field sweeping across the disc, inducing it to follow.

Figures 10.37 and 10.38 are simple line diagrams to illustrate the arrangement of components and some of the adjustments of an energy meter, and an energy demand meter, respectively.

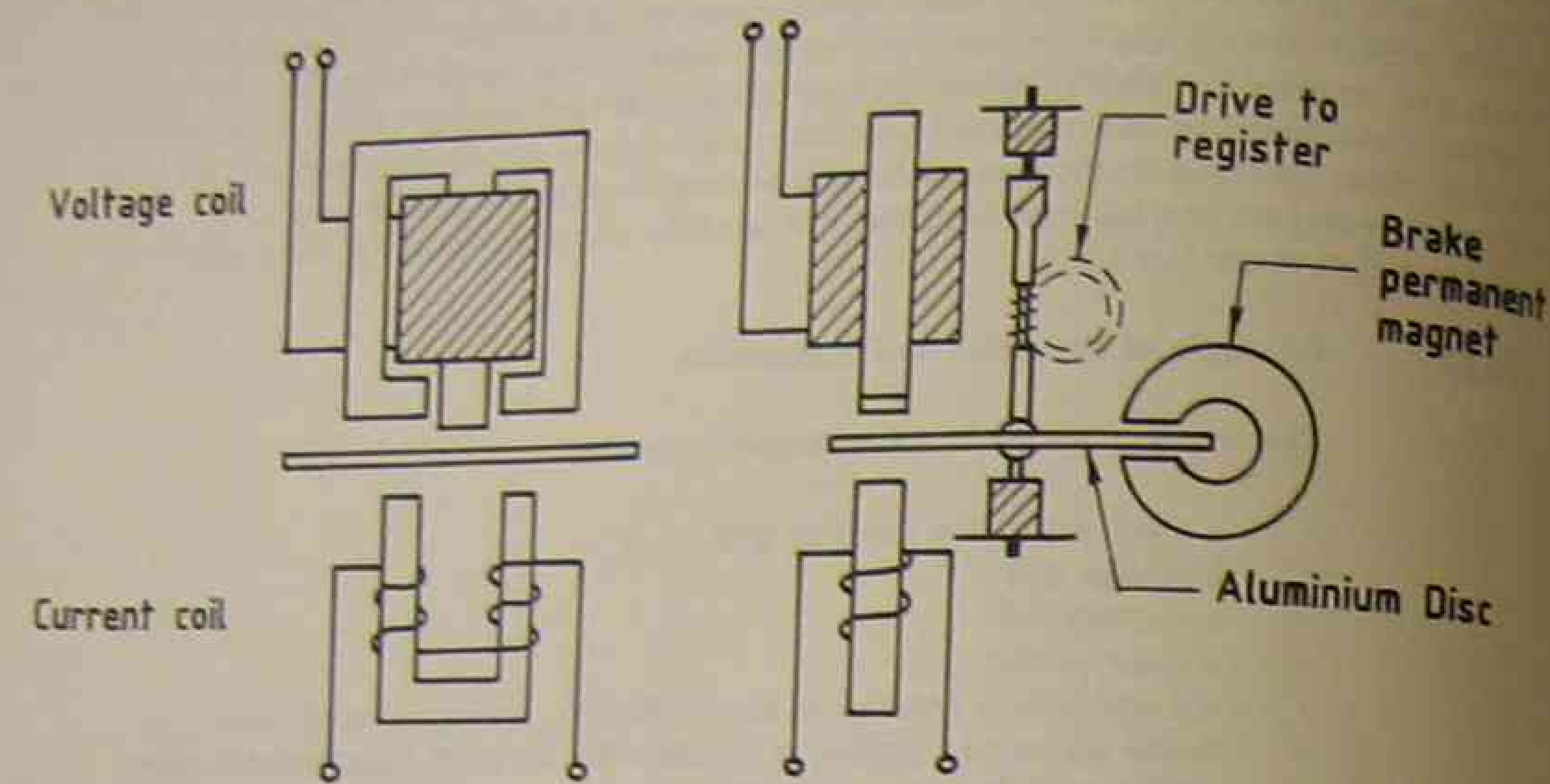


Figure 10.37
Single-phase induction-type watt-hour meter

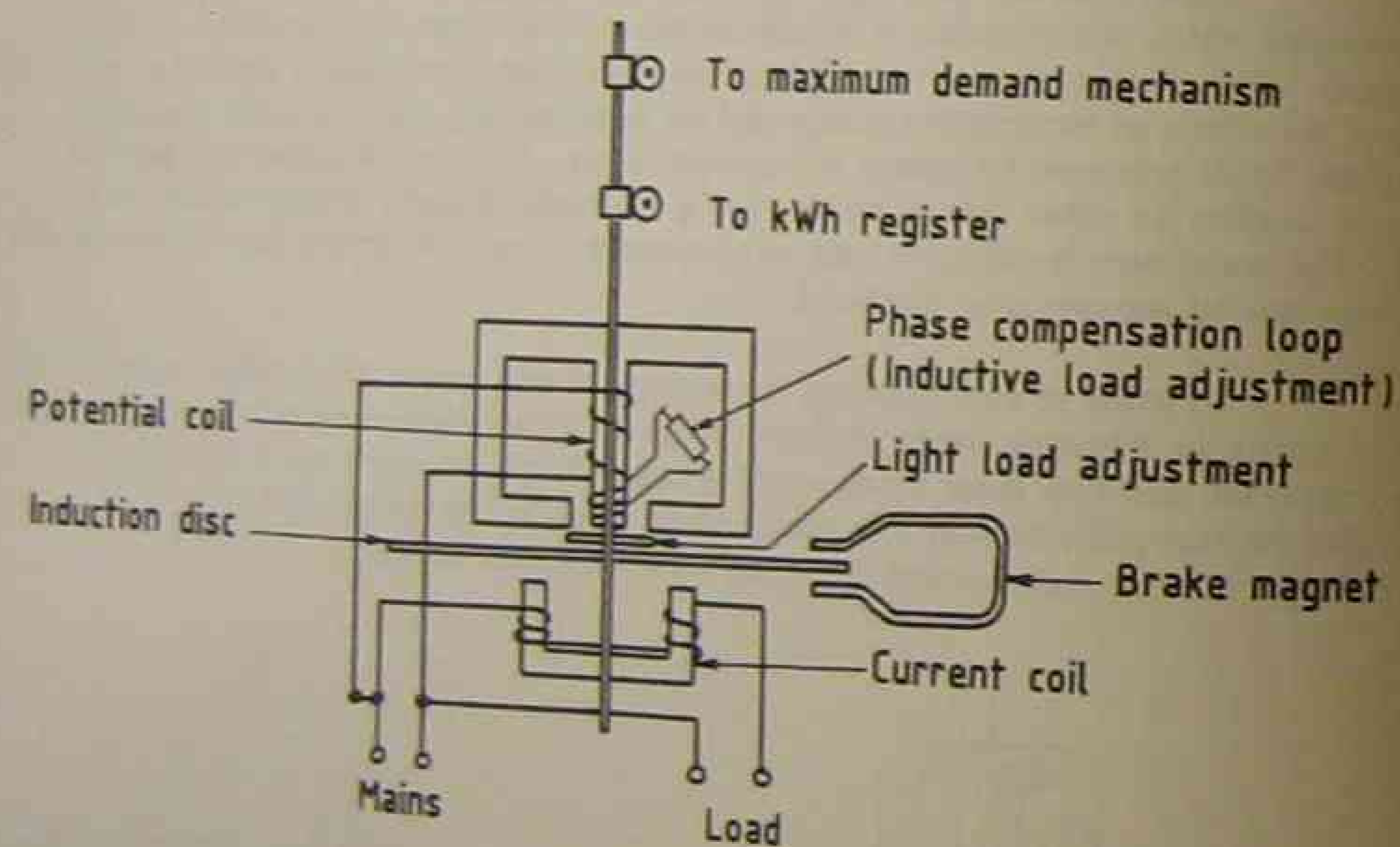


Figure 10.38
Energy demand meter showing the energy mechanism

The voltage coil is wound with a large number of turns of small diameter insulated copper wire — typically 4200 turns, 0.2 mm diameter and at 240V, 50Hz would draw a current of approximately 40 mA. The coil is wound on the centre leg of a former of high quality electrical steel laminations which has two short air gaps in the magnetic circuit, as shown at C in Figure 10.36. The air gaps cause a high reluctance path to be introduced to the magnetic circuit of the coil and to force about 17 to 20% of the total flux through the disc, which is in close proximity to the coil. The highly inductive coil causes the coil current, and hence the flux produced, to lag the applied voltage by about 83° to 85°.

The current coil consists of a few turns of relatively heavy gauge insulated copper conductor wound on a U-shaped laminated electrical steel former so as to produce two magnetic poles of opposite polarity at any instant. For a meter having a current range of 15 to 100 A it would typically have six turns of 6 mm diameter wire. The coil is only very slightly inductive and so it has negligible influence on the load current.

Because the current passing through the current coil is the load current, the flux produced by the coil is proportional to the ampere turns of the coil, rather than the power in the circuit. However, it is necessary for the meter disc to turn at a speed proportional to the power. Therefore it is so arranged that, whilst the flux produced by the current coil is proportional in strength to the current passing through it, the angle or phase difference between it and the voltage coil flux follows the circuit power factor. An analysis of the phasor diagrams in Figure 10.39 show that the angle between the fluxes alters with a change of power factor.

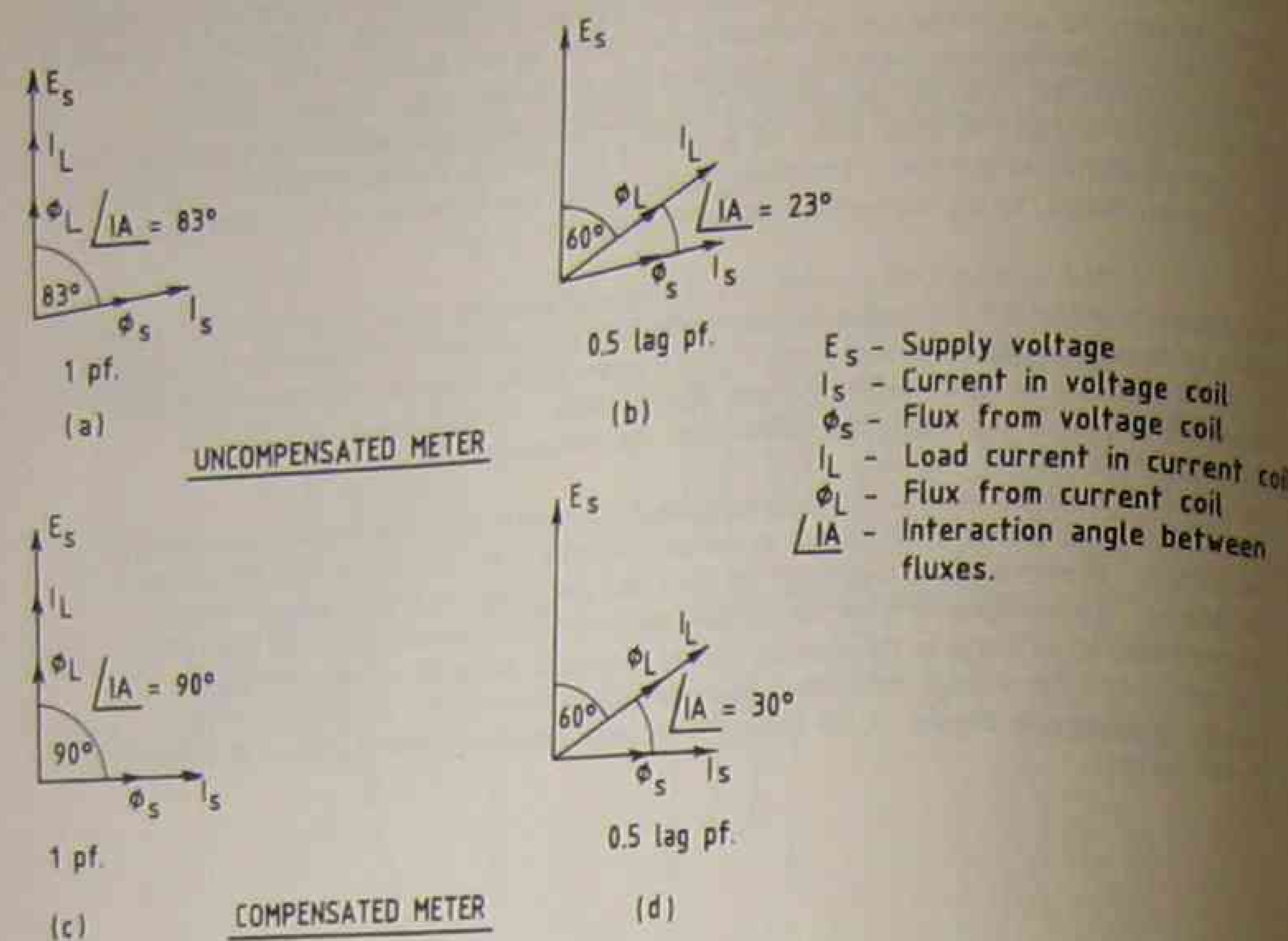


Figure 10.39
Phasor diagrams showing effect of compensation

A large proportion of the current electromagnet flux, probably 80%, passes directly from pole tip to pole tip of the current-coil magnetic circuit, without passing through the disc. The remaining 20% will find a path from one current electromagnet pole through the air gap — disc — air gap — voltage-coil pole tip — air gap — disc — air gap to the opposite current electromagnet pole. The air gap length in which the disc rotates is of the order of 4.76 mm.

The maximum torque on the disc occurs when the angle between the voltage electromagnet flux and current electromagnet flux, known as the interaction angle, symbol , is 90°. Since the interaction angle is of the order of 83°, maximum torque is not developed. It is helpful to examine the effect of this condition with the following example.

Assuming a resistive load of 10 A at 240 V, the true power is
$EI \cos\phi = 240 \times 10 \times 1 = 2400$ W.

The meter torque produced by the interaction of the voltage and current electromagnet fluxes depends upon EI times the sine of the angle between the fluxes. From Figure 10.56(a) the angle = 83°, that is, the meter torque is proportional to: $240 \times 10 \times \sin 83° = 2382$ W.

The torque produced is equivalent to a power of 2382 W or 0.72% less than the true power. An error of this magnitude could be compensated for by decreasing the braking effect of the permanent magnets to allow the meter to revolve at the speed appropriate to the circuit power. However, the error increases with loads having a power factor less than unity.

Figure 10.39(b) is the phasor diagram of a 10 A, 0.5 lagging power-factor load connected to a 240 V supply. The voltage flux remains the same, the current flux lags by 60°, and the interaction angle between the fluxes is 23°.

True power = $240 \times 10 \times 0.5 = 1200$ W.

The meter torque is proportional to $240 \times 10 \times \sin 23° = 937.7$ W giving a loss of 21.9%, which is beyond the range of adjustment of the meter.

The problem has been created by the fluxes not having an interaction angle of 90° at unity power factor. Correction for inductive loads is essential and is carried out as described in the next section.

(d) If the disc was absolutely free from any braking force of the adjustable, damping, permanent magnets it would rotate faster and faster when torque was applied, until it raced at high speed and would give no indication whatsoever of the true energy in kilowatt hours. The purpose of the damping magnets is to present the disc from racing and to make the speed of the disc proportional to the power supplied to the meter. The interaction of the permanent-magnet flux and the rotating aluminium disc — generator action — is to induce eddy currents in the disc which exert a retarding force on the disc proportional to its speed.

For any driving force exerted by the electromagnet causing the disc to rotate, there is some definite speed at which the retarding force caused by the permanent magnets exactly equals it. This may be summed briefly up as follows:

(e)
- the electromagnet exerts a driving force proportional to the power in the circuit
- the damping magnets exert a retarding force proportional to the speed of rotation
- the resultant motion is a speed proportional to the power.

Since the speed is proportional to the power, it follows that each revolution of the disc represents a definite amount of energy known as the meter constant. For a typical energy meter, the meter constant is 400 r/kWh or, when expressed as watt hours per revolution, 2.5 Wh/r. No error is permitted in the meter constant.

10.12.3 Meter adjustments

(a) *Inductive load correction*

(f) A quad band or phase-compensation loop is fitted to the lower end of the middle limb of the voltage-coil magnetic circuit, as shown in Figure 10.38. If the resistance of the band or loop is adjusted to the correct value, it modifies the voltage electromagnet flux to lag the supply voltage by exactly 90°. Refer Figure 10.39(c) and (d).

The meter torque is now proportional to the true value of power. This adjustment is factory preset but is accessible if required.

(b) *Full load adjustment*

This is invariably made by means of a device operating on the brake magnets and shunting flux from the disc in varying degrees. Usually the adjusters are of the micrometer screw type, nylon locked and adjustable from the meter front. Linear adjustment is approximately 1% per turn.

(c) *Overload droop*

Early type meters were rated at either 5 or 10 A and the load-performance curve was as shown in Figure 10.40. If the load on the meter was increased above this rated current by even a small amount, the meter accuracy was adversely affected. This error was due to unwanted self-breaking effects, the degrees of which were dependent on the levels of the voltage and current coil fluxes and the disc speed.

'Saturation bridges' may be inserted in the voltage and current coil magnetic circuits to minimise these effects and help keep the meter speed proportional to circuit power. This allows a modern meter to retain its accuracy up to 600 – 800% of its rated current, as illustrated by Figure 10.41.

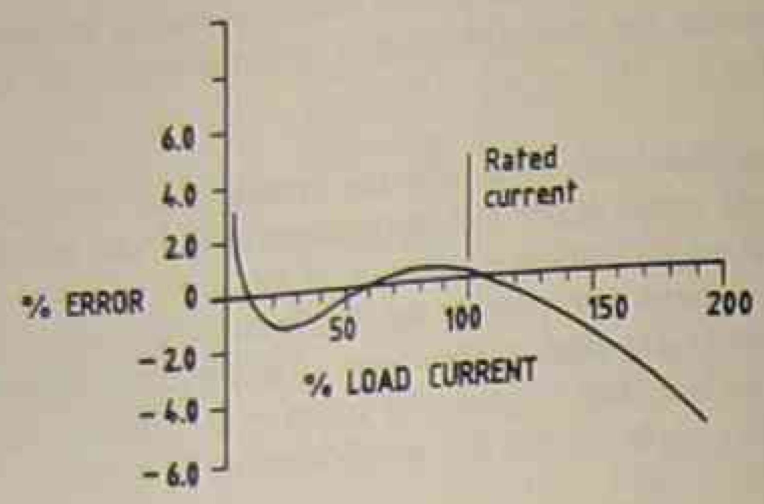


Figure 10.40
Load curve of early type meter

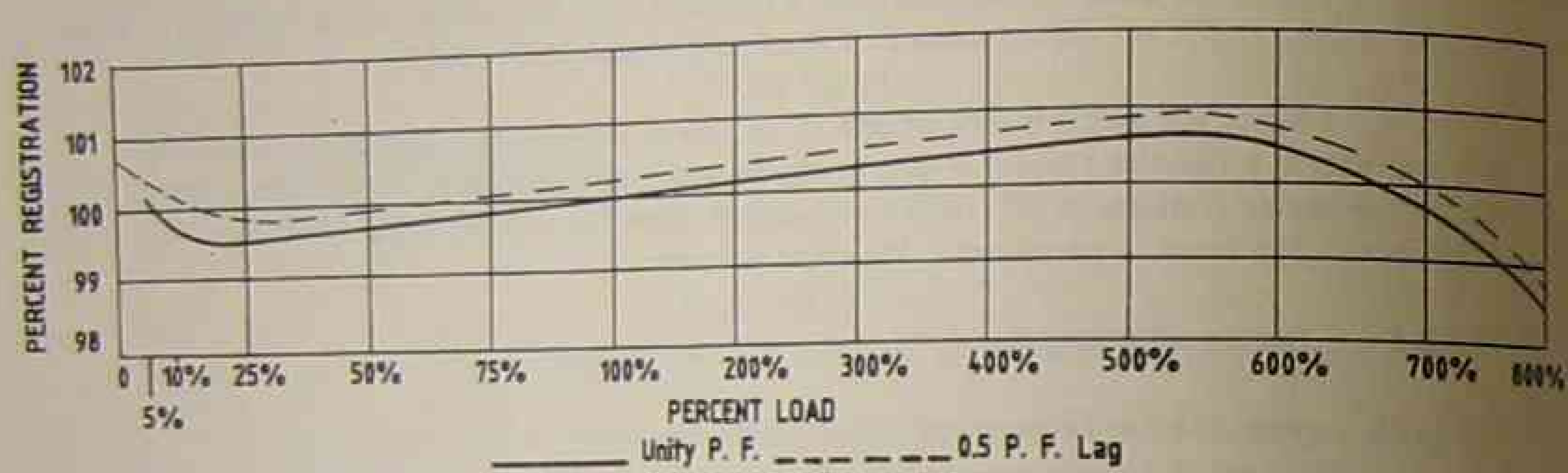


Figure 10.41
Characteristic curve of Email type M2 single-phase energy meter

Source: Email Limited

(d) *Light-load corrections*

A comparison of the load curve of the modern meter (Figure 10.41) with the curve of an early type meter (Figure 10.40) shows a marked improvement at light load. This has been achieved by a combination of improvements to meter construction including the use of modern alloys in the construction of electromagnets, the use of lightweight materials and precise gear meshing for registers, lightweight disc assemblies and magnetic suspension systems.

Figure 10.42 shows the arrangement of a meter bearing design known as the 'Magnethrust' bearing. It employs two small ring-shaped, barium ferrite magnets moulded in steel, flux return cups and magnetised to repel each other. One magnet is located in the top of the lower bearing mount and the other on the bottom end of the rotor shaft. The movement floats in an axial position determined by the mass of the moving system and the force of repulsion between the two magnets.

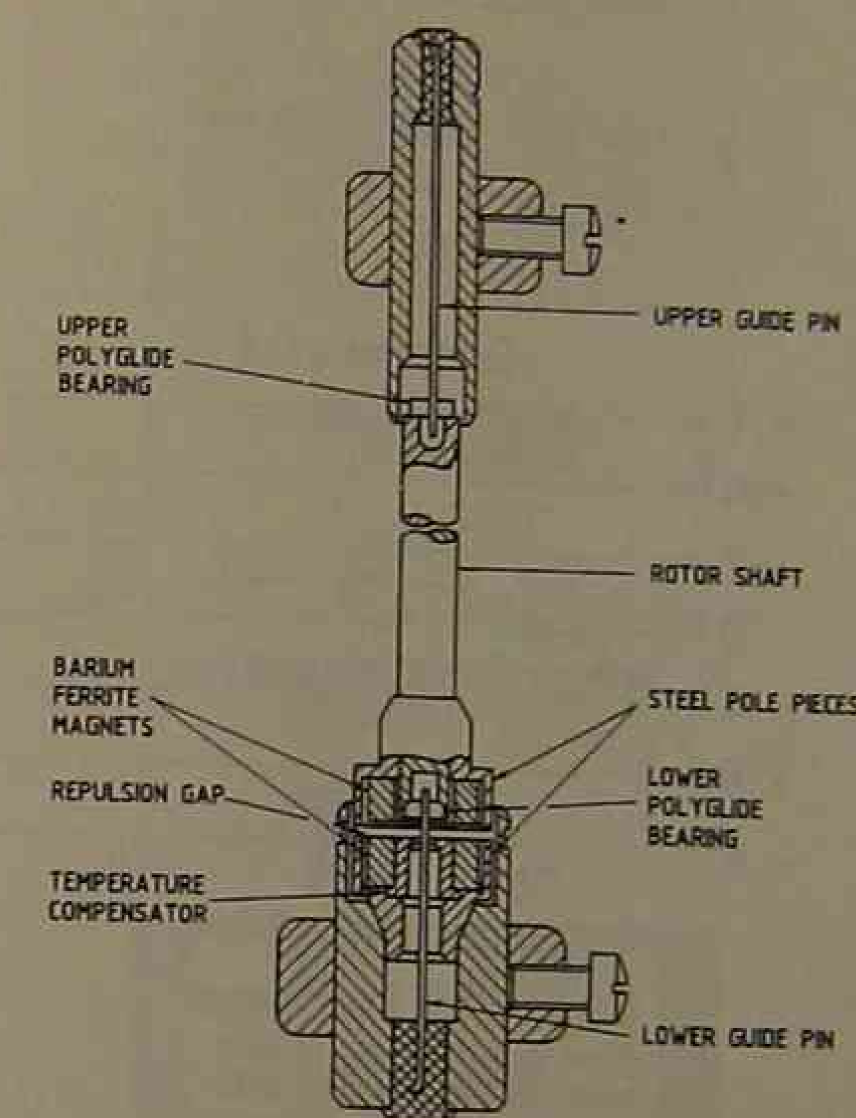


Figure 10.42
Sectional view of a magnetic-thrust bearing

Source: Email Limited

Despite these improvements, losses due to friction do occur and a light load adjustment has to be provided. This consists, usually, of a copper plate which is placed in the voltage-coil leakage flux path, either above or below the disc, in such a way that it is cut by the voltage flux. Whilst the light load plate is in a position of symmetry (that is, directly under the voltage-coil pole), it has no effect on the meter except to cause a small lag in the voltage flux. However, if moved to one side, it has a shaded pole effect because part of the leakage flux from the voltage coil passes through the plate and part bypasses it. This causes one part of the flux to be out of phase with the other, and, by arranging to move the plate in the correct direction, a torque is produced by the two out-of-phase components of flux, which either assists or detracts from the meter disc performance. Figures 10.43 and 10.44 illustrate this feature.

As the effect on the meter performance created by the light-load plate is due to the voltage flux passing through the plate, and as voltage flux is independent of load, then it can be seen that the light load adjustment is not load dependent.

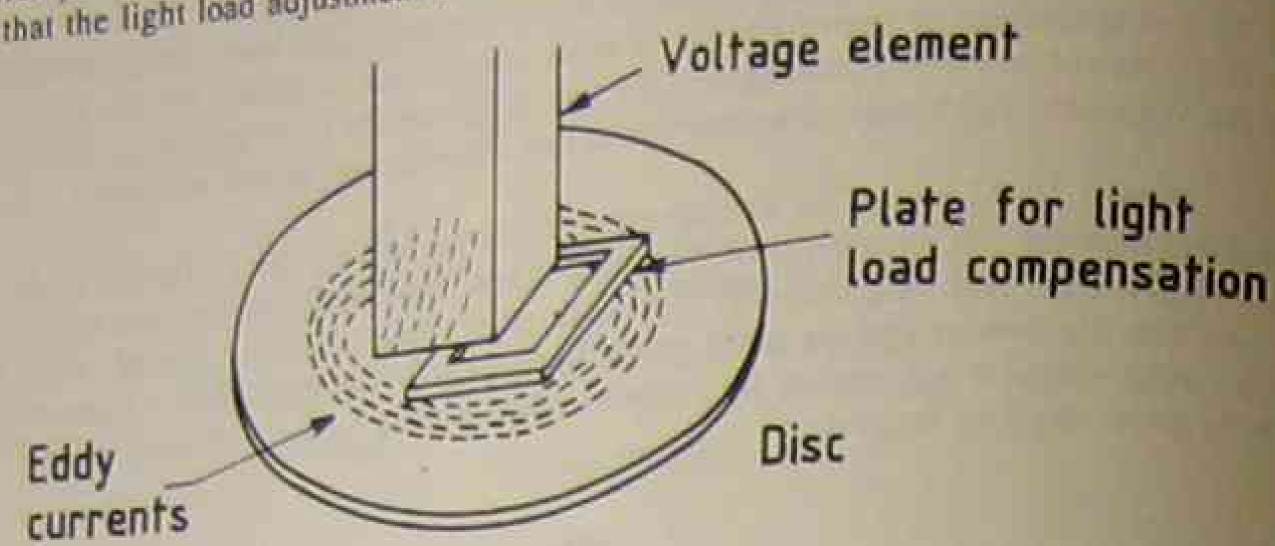


Figure 10.43
Light-load compensation plate

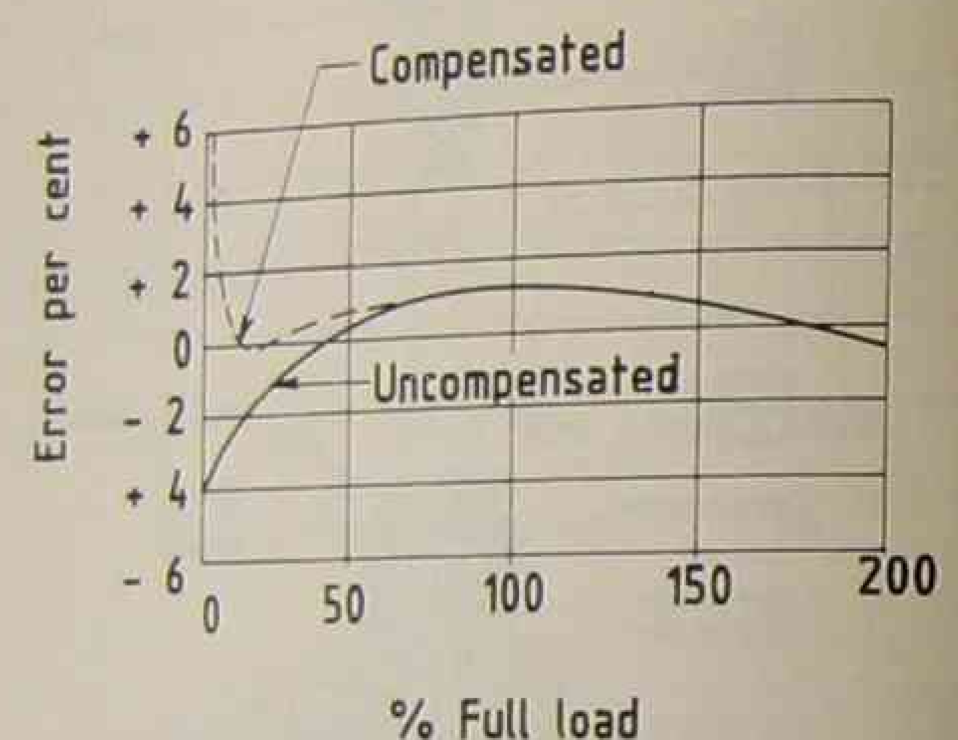


Figure 10.44
Effect of light-load compensation

(e) *Creep*

Certain problems may arise by over-correction in the light-load plate (that is, moving it too far in a given direction) and the meter can be made to run without load applied to it. This is known as creep, which can also be created in a number of other ways such as a lack of symmetry in the gap between current and voltage coils, shorted turns in the current coil, excessive vibration from external sources which can reduce friction, fields from equipment in close proximity to the meter, or incorrect adjustment of the quadrature loop resulting in the plate not being symmetrical above the centre line. To prevent creeping of the disc, some form of 'stop' is provided, normally by placing two small holes in the disc diammetrically opposite each other. These have the effect of dividing the eddy currents created in the disc as the creep hole passes under the voltage-coil pole. This division of the eddy currents results in a small retarding effect on the disc which is usually sufficient to arrest the creeping. Other methods have been employed to prevent the disc from creeping but the above is the most common.

10.12.4 Register

The register is simply that part of a meter which integrates the revolutions of the moving disc and, by the use of suitable gearing, provides a visible display in terms of electrical energy. The gear train is designed to give accurate registration down to 1/10th (or in the case of current-transformer meters, 1/100th, or even smaller) of a kilowatt hour. The gear ratios up to the first pointer or dial are dependent on the revolutions per kilowatt hour of the particular meter, but from thereon each ratio will be 1:10. To ensure the maximum reliability under field conditions metal gearing performs best.

Figure 10.45 shows a range of typical meter dials together with a meter nameplate.

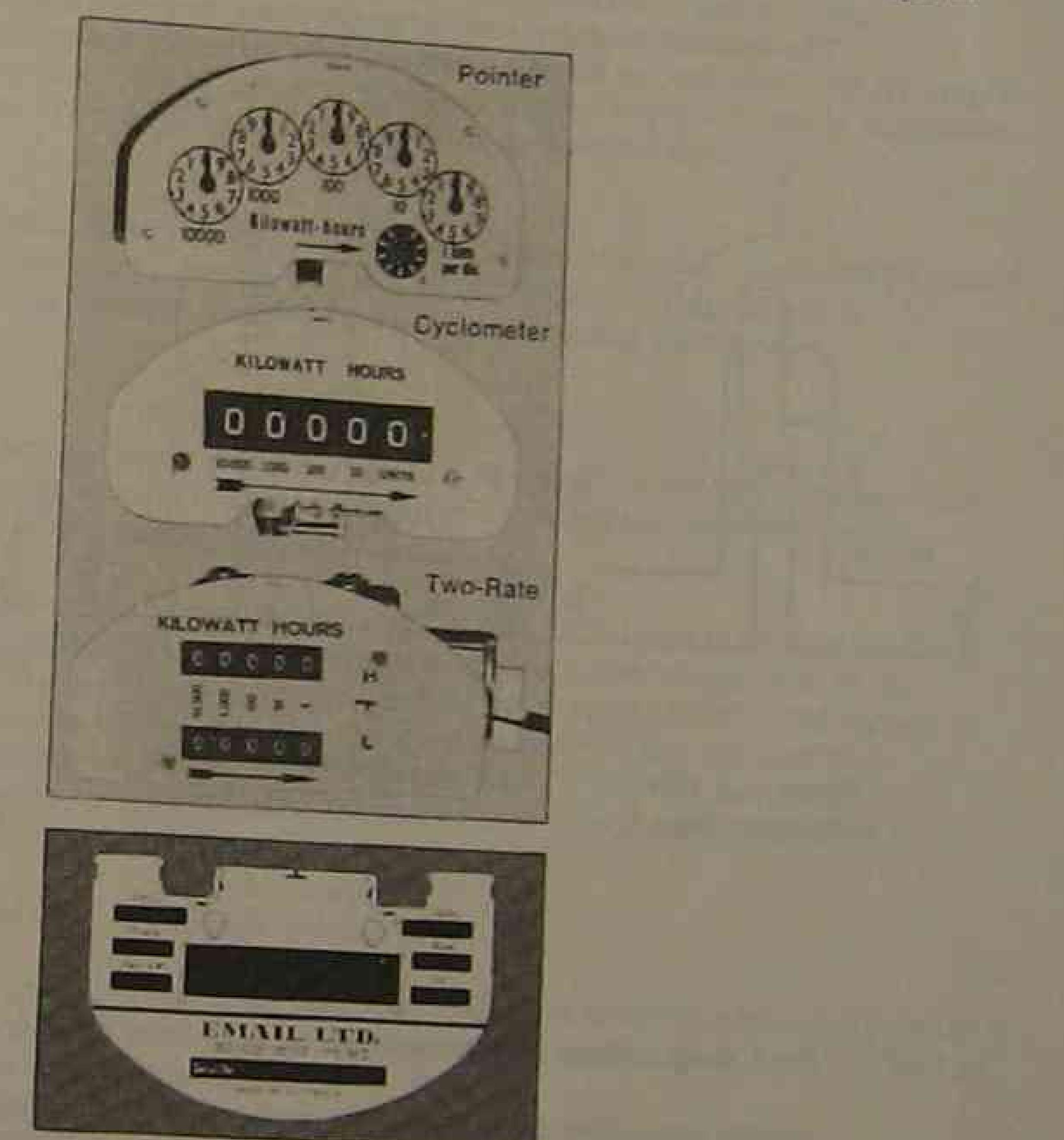


Figure 10.45
Typical meter dials and nameplate

Source: Email Limited

10.12.5 Rotor

The modern meter, such as the Email type M2, has a rotor disc of solid, high purity and high conductivity aluminium, surface stippled and temperature stress relieved to ensure a good state of dynamic balance and true running at high disc speeds. Two small, anti-creep holes are incorporated into the rotor along with two larger holes to facilitate precision photo-electric testing. The rotor speed at the basic current of 10 A is 16 r/min.

The meter constant gives the number of revolutions of the disc for 1 kWh of energy. For the M2 meter it is 400 r/kWh.

10.12.6 Connection diagrams

The terminal arrangements for single-phase, two-wire watt-hour meters are shown in Figure 10.46. Note that, for the three terminal base meter, the neutral link has been dispensed with.

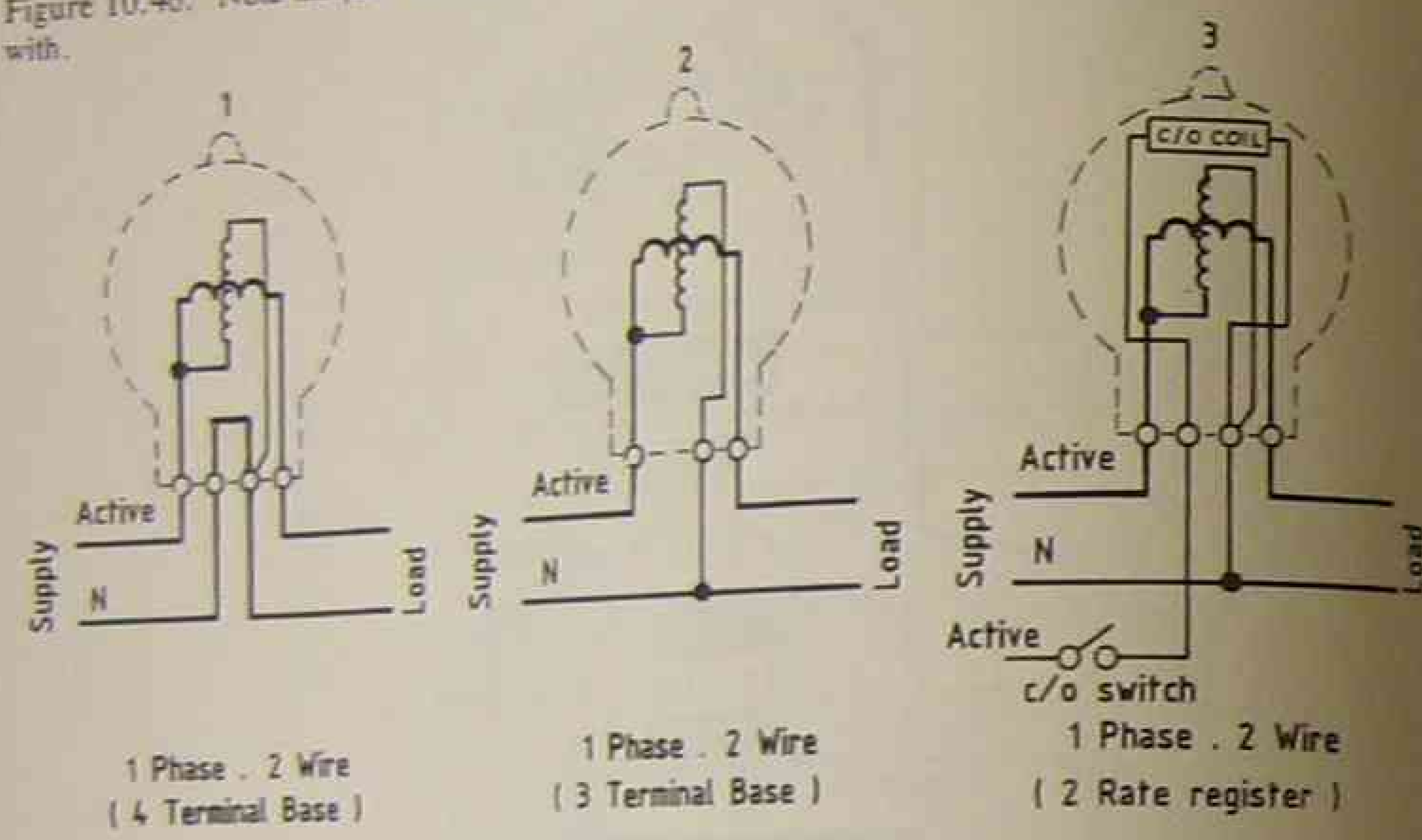


Figure 10.46
Connection diagrams

10.12.7 Two- or dual-rate energy meters

Supply authorities make use of two-rate tariffs to encourage consumers, on economic grounds, to take supply at times other than those hours when demand is high. A two-rate tariff is available having two different prices for energy consumed at different times of the day.

Standard single-phase and polyphase energy meters are used in conjunction with a self-contained register mechanism that changes over from one tariff rate to the other at prearranged times initiated by a time switch, a ripple-frequency control signal, or by a photocell. The signal energises a solenoid which, when energised or de-energised, changes the mechanical drive to the register from either one of two output shafts by a differential mechanism similar to that of a motor-vehicle transmission system.

Figures 10.45 and 10.46 show a dial and connection diagram for a single-phase, two-wire two-rate energy meter. Two sets of cyclometer read-out registers show independent readings of the energy consumed on each of the two separate tariff rates.

The advantages of the two rate register are:

- conservation of space which would be otherwise occupied by two meters
- transfer of the mechanical drive from one read-out to another dispenses with the need for complicated electrical switching
- standard meter housing is retained to reduce installation cost.

10.12.8 Plug-in metering

Australian supply authorities are progressively changing to the plug-in system of connecting meters. Installation wiring can be completed by the contractor, and the supply authority needs only to plug in the meters when the installation has been approved.

Installation costs are reduced and plug-in meters require less space than is needed for the older type of meters. This is of particular importance in multiple meter installations.

The plug-in system also provides a ready means of disconnection, which can be done by an unskilled operator since there is no contact with live circuit parts. A bridging tool is available to enable meters to be changed in the field without interrupting supply.

10.12.9 Meter testing

Kilowatt-hour energy meters may be tested in a laboratory, a special meter test room, or in the field. Tests are made by comparing the reading of a rotating standard with one or more revolutions of the disc of the meter under test.

To reduce the rating and size of the loading resistors, it is usual to employ what is called a phantom load when testing meters. Full voltage is applied to the voltage coils of the meter and rotating standard, but a reduced voltage is used on the current circuit. The voltage used is of the order of 8 V and is sufficient to pass the rated current through the meter current coil, the rotating standard current coil, and the resistors. In this way the power dissipated in the testing resistors for a 10 A meter is reduced from approximately 2.4 kW if full voltage is used, to 80 W for the 8 V circuit.

(a) *Laboratory testing*

New meters and meters which have been overhauled are tested in a laboratory where a stabilized voltage supply is available, and the meter can be tested at various loads from 5% of basic current to the maximum permissible current.

Facilities are available for testing at both unity power factor and 0.5 power factor lagging. The 0.5 power factor which represents a 60° phase angle is obtained by utilising the phase displacements in a three-phase circuit. As shown in Figure 10.47, the voltage coil is energised from the red phase to neutral. The current coil is energised from the same lines for unity power factor loading but from the yellow to neutral lines, reversed, for 0.5 power factor lagging. The yellow phase is displaced 120° from the red phase and by reversing this an angle of (180° − 120°) or 60° is obtained. It is usual in these tests to check the meter at 90%, 100% and 110% of normal voltage.

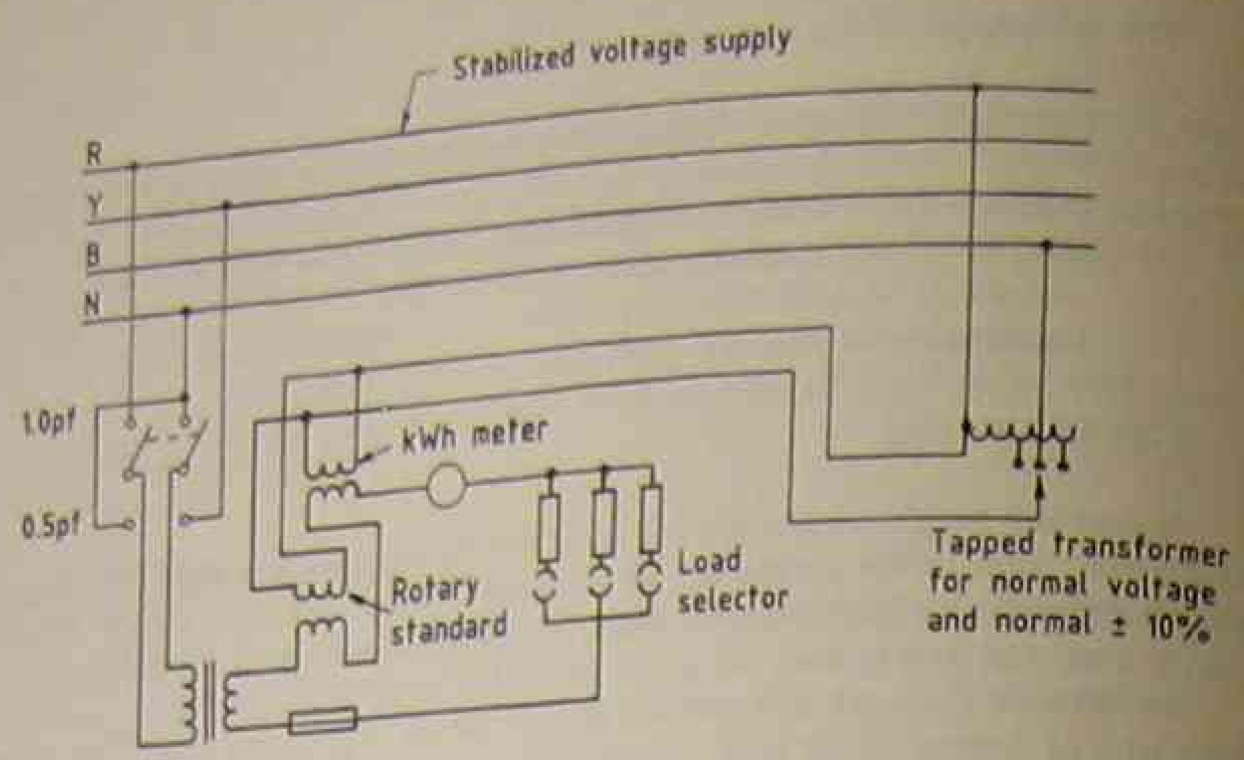


Figure 10.47
Laboratory test circuit for single-phase energy meters

(b) *Field testing*

When there is any doubt about the accuracy of a meter, either by the consumer or the supply authority, field testing is reverted to. The field tests are usually:

- a check for creeping of the disc
- a light load test of 10% at unity power factor
- a full load test at unity power factor.

A standard field test set is used, as shown diagramatically in Figure 10.48, comprising a transformer to supply the phantom load, a suitable load, and a rotary standard. The active connection to the consumer's load is removed at the meter and cable 'C' is connected in its place. The active and neutral for the test set are connected as shown by means of clips. The check is then made by comparing the reading of the rotary standard with one or more revolutions of the disc of the meter under test.

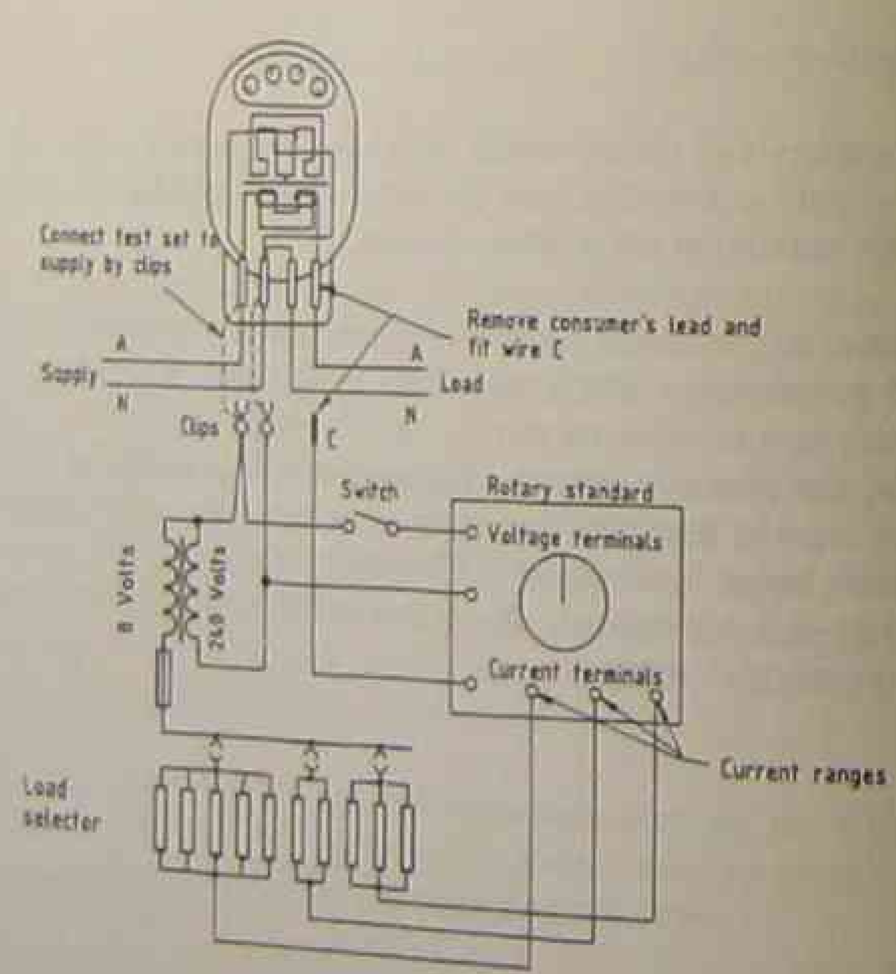


Figure 10.48
Field testing equipment for single-phase energy meters

WORK TO BE FORWARDED FOR COMMENT

Marks		
8	1.	What is meant by: (a) effective range (b) fiducial value (c) resolution (d) accuracy class.
8	2.	State four applications for electrical instruments and indicate an appropriate order of accuracy for each.
6	3.	What are the advantages of the core magnet design for permanent-magnet moving-coil instruments?
10	4.	Briefly describe, with the air of simple sketches, what is meant by: (a) taut-band suspension (b) spring-loaded jewel assembly.
12	5.	Describe carefully with the aid of a neat, freehand sketch the construction and operation of a single-phase power-factor meter.
16	6.	Give brief answers to the following questions relating to the a.c. single-phase energy meter. (a) List six essential parts. (b) (i) What is its fundamental principle of operation of the meter movement? (ii) Name another item of electrical equipment which uses the same principle (c) The meter indicates kilowatt hours, not kilowatts. How is this achieved? (d) What is the essential condition in such a meter with regard to the disc speed? (e) What factors control the disc speed? (f) What is the purpose of the phase compensation loop
12	7.	Explain with the aid of a circuit diagram the method of testing a single-phase energy meter at a consumer's premises. PAGE 60.
10	8.	(a) Define demand as it applies to the electrical metering industry. Page 61 (b) What is (i) the unit of demand and what is meant by (ii) maximum demand and (iii) the demand time interval? PAGE 61.
8	9.	What is a transducer? Describe how transducers are classified. Page 71.
10	10.	Describe briefly, the principle of operation of the digital instrument and how it may be adapted to measure both electrical and physical quantities.

Page 73.

2813X DISTRIBUTION AND UTILISATION

APPENDIX TO UNIT 18

TRIAL EXAMINATION QUESTIONS

The following questions relating to Units 10 to 18 have appeared in past examinations and are included here for your guidance and practice. If you have any difficulty approaching or working through any of them, use a pink 'Query Form' to ask External Studies College for advice on how to proceed. Where applicable, answers are given.

Note: Your practice answers should not be returned to the College for marking; they are for exercise only.

1. (a) To achieve a viable distribution system, economic consideration has to be given to the components that help to provide its overall reliability. Indicate factors that system planners may include in their consideration of this aspect and make brief comment on the contribution of these factors.

   (b) In relation to load determination of low voltage network, what is meant by 'after diversity maximum demand' (A.D.M.D.)?

   Provision is being made for the establishment of an underground all electric housing estate. What value of A.D.M.D. would you recommend?

   (c) On occasions it is required to lay supply cables or erect overhead lines on private property.

   Indicate *three* conditions that could be included in the cable easement acquisition documents that would ensure protection of the Supply Authority's equipment.

   (d) In the preparation of specifications for large supply and erect projects, it is necessary to include items relating to the general condition of the contract.

   Nominate *three* (3) general condition items and indicate how they are of benefit to the purchaser.

2. (a) A 40 kW 3-phase 415 V induction motor whose torque characteristics are such that 220% of full load torque is available at starting and with increase in speed the torque reduces linearly to 150% at 1200 r/min and continues to fall to zero torque at 1500 r/min. The load torque is constant at 75%. Auto-transformer equipment connected on the 80% tap starts the motor and load whose combined momemt of inertia is 3 kg m^2 .

   Determine the motor's load speed and the accelerating time if the changeover occurs at 1200 r/min. (Answer: 1320 rpm, 3.4 s)

   (b) If the above motor was to be started D.O.L., what starting current restriction would be applied by the Supply Authority?

   (c) Indicate the type of protection that can be used to prevent over-heating of the motor when one phase of a 3-phase supply is lost.

3. (a) Determine the most economical size of a self ventilated motor required to drive a cyclic process machine in which the load rises from 40 kW to 180 kW in 20 seconds, with the increase directly proportional to time. The load then remains constant at 180 kW and remains at this value for 10 seconds before repeating the cycle. (Answer: 145 kW)

(b) A three-phase induction motor with normal applied voltage develops 1.5 times full load torque. What must be the percentage of normal applied voltage to obtain 0.8 full load torque at starting? (Answer: 73%)

$0.8 = 1.5\left[\frac{E}{100}\right]^2$

(c) Indicate the type of induction motor which would be used on the following drives:

(i) hoisting operation of a crane

(ii) punching or shear press

(iii) a large compressor where constant speed is normally required. A small decrease in speed is allowed during overload

(iv) a line shaft in a dusty location.

Good speed control

4. (a) A general office 30 m long, 10 m wide with 4.3 m ceiling is required to have an illumination of 200 lux. The twin 40 watt tubes have a light output of 60 lumens/watt per tube. Determine the number of luminaires required. Assume the following factors:

(i) utilisation factor of 0.4

(ii) maintenance factor of 0.7

(iii) working plane height of 1.0 m

(iv) centre of light source 0.3 m from ceiling. (Answer: 45)

$40 \times 60 \times 2$

$E = \frac{FCMN}{A}$ $\quad 200 = \frac{1 \times 0.4 \times 0.7 \times N}{30 \times 10}$

$E = \frac{I}{d^2}$

(b) Calculate the illumination on the floor at a point immediately below the centre luminaire lit by three identical luminaires spaced 30 m apart, mounted 5 m above the floor, if the lamp intensity is 600 candelas in all directions. (Answer: 24.7 lux)

(c) List principal aims of expressway lighting design. Make reference to the type of lantern used and how an even distribution of light on the road surface is obtained.

5. (a) The obtainment of high efficiency with diesel-electric traction requires that the load characteristic of both diesel engine and dc generator are matched over the full load range. Describe how the generator characteristics are adjusted to obtain this result.

(b) What type of electric motor is used for electric traction work? Explain the reasons for this choice?

(c) Indicate a method of starting motors on an electric locomotive to ensure a reasonable speed transition is obtained during the starting period.

(d) Name *five* (5) acceptance tests that would be undertaken as part of the negotiations in the purchase of a large power transformer.

Copper Loss
Iron Loss

Initial cost
Interest payments
Salvage
Useful life

6. (a) Supply authorities require notification of electrical work undertaken on consumer premises. What regulation gives approval of this action?

(b) Comment on the inclusion of a demand charge in the formulation of a tariff for industrial customers.

(c) A motor generator set is to be connected to the Supply Authority's low voltage three-phase four wire system. Briefly describe the operation of a synchroscope for the above application and indicate the appropriate line connections.

(d) Indicate the load equipment that develops third harmonic currents and the action necessary to off-set the effects of these harmonic currents.

7. An 11 000/433 volt substation is to be established to provide underground supply to a new all-electric housing estate. There are 110 residences within the substation's supply area.

(a) Assuming an average diversified demand of 3.5 kW per customer at a power factor of 0.8, what size of transformer would you recommend? (Answer: 500 kVA)

(b) Draw a typical daily load curve for the above distribution centre and comment on the conditions that lead to the creation of a maximum demand. What methods are available for the improvement in load factor?

(c) To provide information related to the 'Application for supply', supply authorities publish *Consumer Service and Installation Rules*. Nominate two matters contained in these Rules.

Point of supply – Metering
Service fuse

8. (a) Describe the main constructional features and indicate the life expectancy of the following lamps:

(i) Quartz Iodine

(ii) Colour corrected high pressure mercury vapour.

(b) Indicate how the accuracy of a kilowatt hour meter is checked in the field and describe the standard meter adjustments available for correction of any deficiencies in accuracy.

(c) Discuss relative merits of electrification as opposed to diesel-electric traction.

(d) List the main factors that would have to be considered in the selection of a suitable site for the establishment of 120 MVA 66/11 kV substation. Assume the 66 kV supply is overhead and the outgoing 11 kV cables are underground.

$P = \sqrt{3} V I \cos\theta$ Jose 2173783

9. (a) A 400 kW, 2 930 rpm, 2.2 kV three-phase motor has an efficiency of 93% and full load power factor of 0.9 lag.

When started direct on line the machine draws 5.5 per unit rated current at 0.2 lag power factor and develops 1.2 per unit rated torque.

Starting current is limited to 500 amps by means of an auto-transformer starter which has been extensively damaged on fault.

When ordering a replacement starter what % tap would you specify? $500 = 5.5 \times 125 \times \left[\frac{E}{100}\right]^2$ $E = 85\%$

As a temporary measure it is intended to install primary resistance starting to the same current limitation.

Determine the value of resistance required and the difference in starting torque which results from the temporary arrangement.

(Answer: 85% tap, approximately 1.45Ω, reduction of approximately 300 Nm)

$\frac{P \times 60}{2\pi N} = T$

10. (a) Performance tests on a motor with a directly coupled load showed that the accelerating time from start to operating speed of 1400 rpm was 15 seconds.

From the motor data sheet it is known that the moment of inertia of the rotor is 0.2 kgm^2 and that the motor's torque speed characteristic may be considered to rise linearly from 250 Nm at start to 300 Nm at 1150 rpm, then fall linearly to operating speed.

The torque required by the sum of load and stray torques was constant at 100 Nm during the tests.

Determine:

(i) the moment of inertia of the load
(ii) the maximum instantaneous output of the motor during test.
(Answer: Approximately 16 kgm^2, 36 kW)

$T = \frac{P \times 60}{2\pi N}$

$300 = \frac{P \times 60}{2 \times \pi \times 1150}$

$P = 36.13\ kW$

10.13 DEMAND METERS

10.13.1 General

There is a group of electricity tariffs which takes into consideration the energy consumed, the maximum kilowatt or kilovolt-ampere demand and in some cases the time-of-use (T-O-U). Tariffs are dealt with in Unit 16 and T-O-U metering is discussed later in this section.

In the past, maximum demand charges have been based on either kW or kVA values. The current preference is for kW demand and, where applicable, the kVA demand is being phased out.

Considerable progress has been made in the design of meters for the measurement of maximum demand. However, since there are a good many of the older types of meters still in service, these are described first, followed by an introduction to the modern generation of MD metering equipment.

10.13.2 Demand meter types

Generally, demand meters may be divided into two classes:

- *Lagged demand meters*

  These are so arranged that the indications respond only gradually to the load. In this type of meter the indications are asymptotic to the value that would be obtained if the quantity under measurement was applied for an infinite time. Thermal storage meters are of this class and are said to give a logarithmic average.

- *Integrated demand meters*

  These integrate the desired quantity over a definite time giving data for an arithmetical average.

(a) *Maximum kVA demand meter*

Figure 10.49 illustrates a lagged-type meter which is actually a thermal ammeter calibrated for kVA by assuming a constant voltage.

The movement consists of two bi-metallic coils 'a' and 'b' with their spirals wound in opposite directions and heaters 'cc' connected in series. The actuating coil 'a' is fixed at its centre to a spindle. The compensating coil 'b' has an indicating pointer 'd' attached to its centre which forms a sleeve bearing on the spindle. The outer ends of the coils are joined together by a yoke 'e'. When load current passes through the heating elements, the heat developed is transmitted to the actuating coil causing it to close up. The resulting movement is transmitted through the yoke and compensating coil to the pointer. This causes the pointer to move across the scale carrying forward a second pointer, known as the demand or slave pointer, which remains held at its maximum reading where it is held by a light frictional device until reset by hand.

Any change in ambient temperature rotates the free outer ends of the two coils through the same angle without causing any movement of the pointer, thus rendering the instrument free from any inherent temperature errors. The time lag is determined by the dimensions of the insulating material enclosing the heating elements and may be 15, 20 or 30 minutes.

Under constant load conditions and starting from zero, the deflection rises according to a logarithmic law (similar to that of the current in an inductive circuit when a constant voltage is applied) and theoretically attains the final value only after infinite time. The characteristic logarithmic curves of Figure 10.50 are typical of such curves and were obtained on the same meter with different load currents. On a fluctuating load it is evident that the deflection depends on the integrated effect of previous load currents.

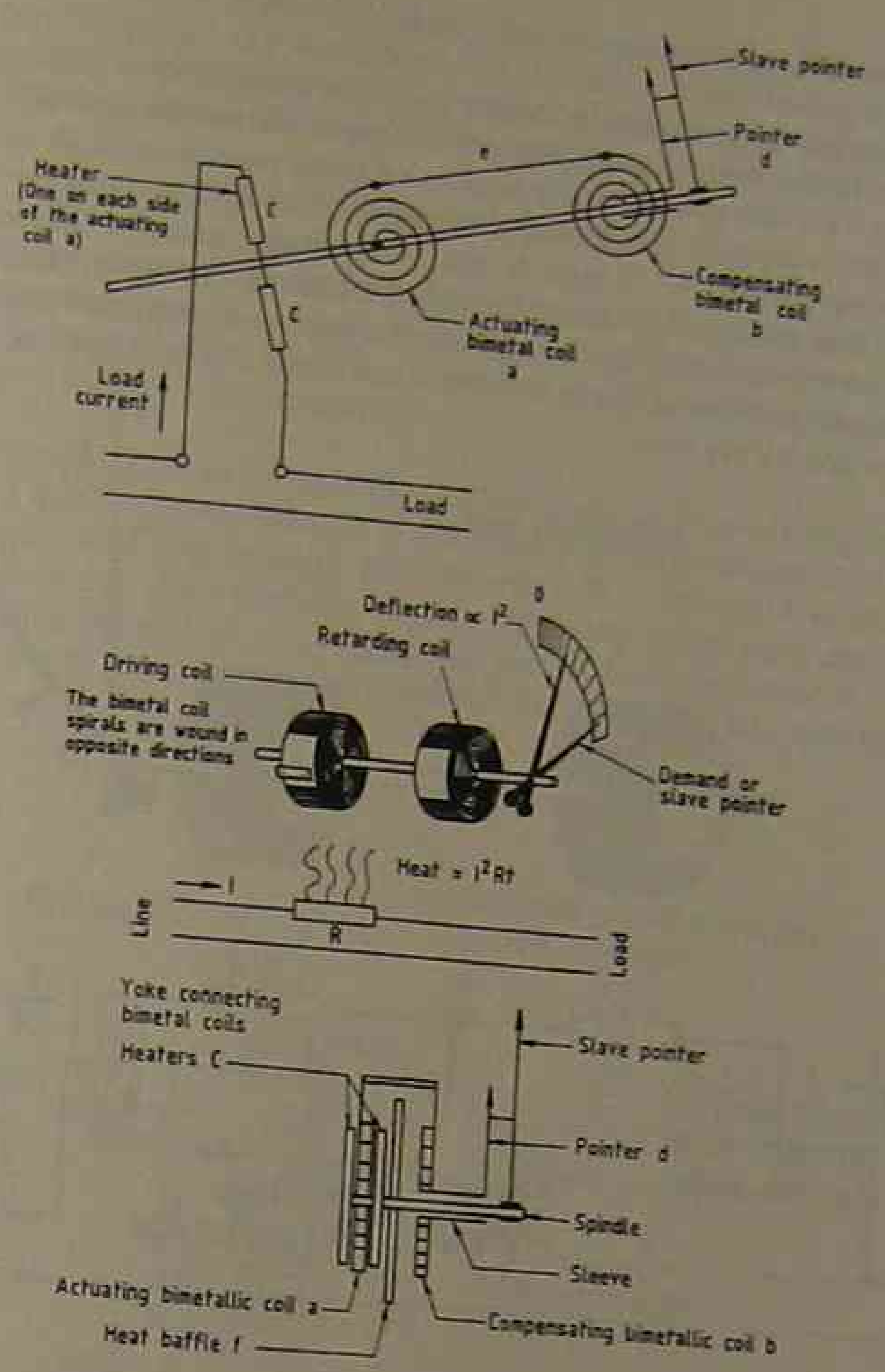


Figure 10.49
Thermal maximum kVA demand meter

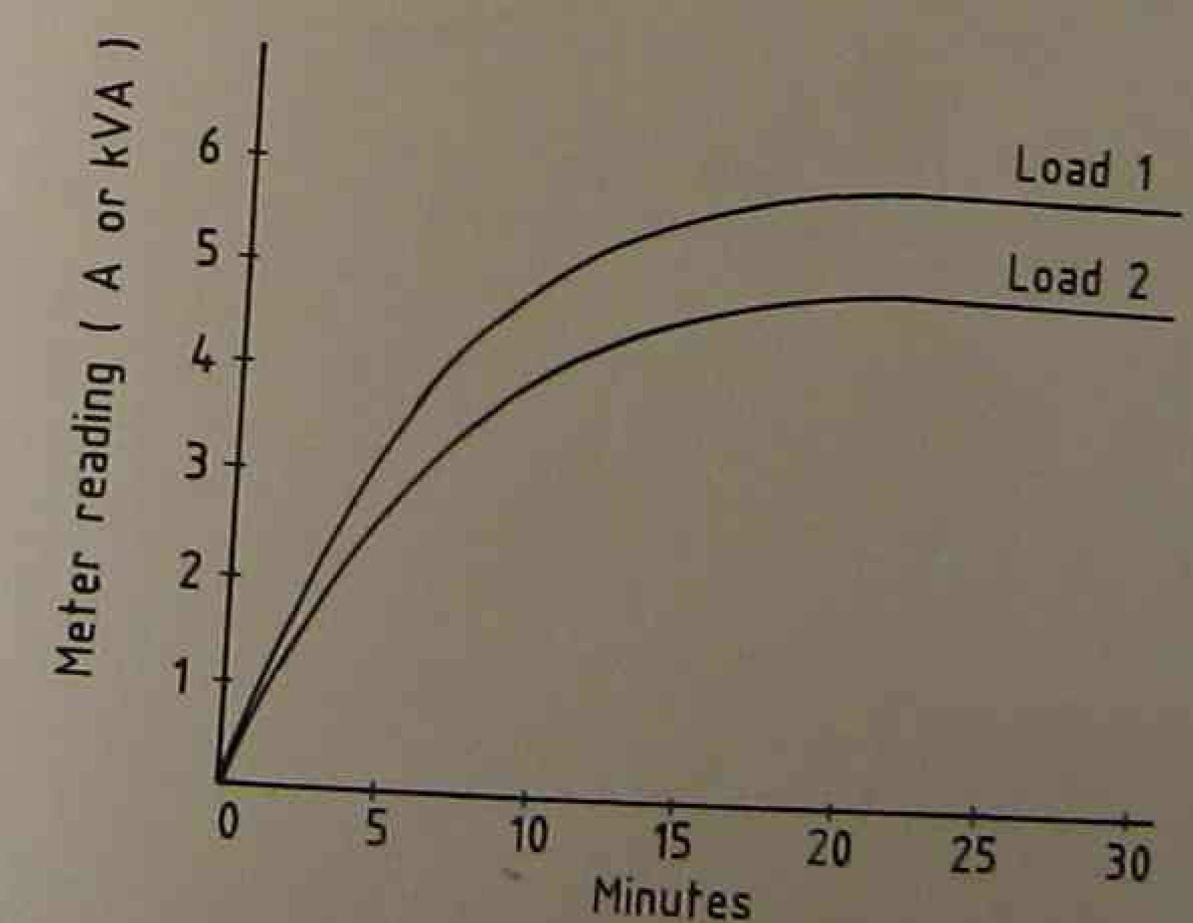


Figure 10.50
Demand-meter characteristic curves