How do they work? 2. Voltmeters

by J Patrick Wilson

Voltmeters are designed to measure electrical potential and three different physical principles have been utilised for this purpose. The first method, *electrostatic*, is the earliest and most direct one and relies on the mechanical force between charged bodies. The second, *thermal* method relies on the heating effects of electrical power either by the mechanical expansion of a wire or by the generation of a thermoelectric potential. The third and most common method relies on the *electromagnetic* effects of electric current controlled by a known resistance and depending upon Ohm's law. As described for ammeters in the previous article there are many possible configurations of magnets and coils to measure this current. Unlike an ammeter, however, an ideal voltmeter consumes as little current as possible in order not to modify the voltage being measured. For this reason the movement or magnetising coils are normally wound with many turns of fine wire in combination with series or swamp resistors for the higher ranges.

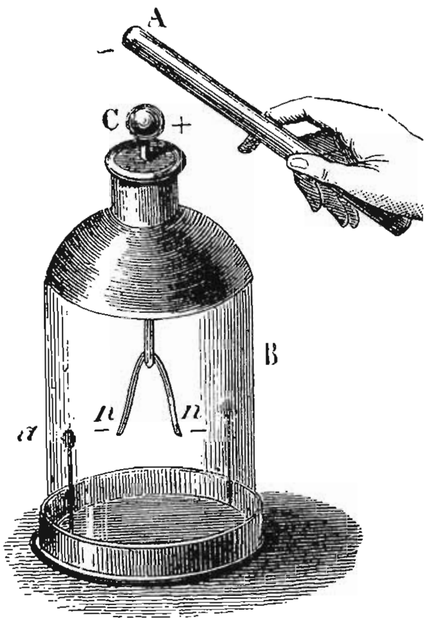

Figure 1. Gold leaf electroscope

Figure 2A. Electrometer (RW Paul)

Figure 2B. Electrometer (RW Paul)

Electrostatic instruments

The attractive effects of rubbed amber were known to the Greeks whose word for amber was *electron* from which our word *electricity* was derived. The first instrument designed to gauge this effect was the gold leaf electroscope (Fig. 1). Two strips of gold leaf hang from a central conductor suspended inside an insulating, and draught excluding, glass bottle. When a voltage is applied to them either directly or, as illustrated, induced by a nearby charged body both leaves become charged with the same polarity and repel each other. Gold leaf is used because it can be beaten much thinner than other conductors making it light and flaccid even though it is a dense metal.

Thomson Absolute Electrometer

The first instrument developed to measure this electrostatic effect rather than merely indicate it was Coulomb's torsion balance of 1785. From 1855 William Thomson (later Lord Kelvin) developed the absolute electrometer in various forms. In the attracted disc version the electrostatic force between a charged disc and an earthed one can be balanced by small weights. The force $F=-\varepsilon_0 AV^2/2x^2$ where the electric constant or permittivity of space, ε_0, is 8.85×10^{-12}, the area of discs, A, the voltage, V, and the separation of the discs, x.

An example made by Robt. W Paul is shown in Fig. 2 (the attracted disc is not visible). The aluminium balance beam can be seen in Fig. 2b suspended by a torsion wire with the earthed attracted disc attached by a rod through the hole in the brass plate. The forked far end of the beam can move vertically between stops and balance observed by a lens visible through the rectangular aperture in the case. Comparison weights can be placed on the small pan at the near end of the beam for calibration.

Fig. 2a shows the charged disc supported on a glass rod and opposing the earthed attracted disc when assembled. This can be adjusted in height by a screw with scale beneath the base plate. The absolute values of potential and charge can be calculated from the area and separation of the plates and the electrostatic force produced. The lead tank is for concentrated sulphuric acid through which air is bubbled to give a dry atmosphere within.

Figure 3. Quadrant electrometer (Dolezalek pattern)

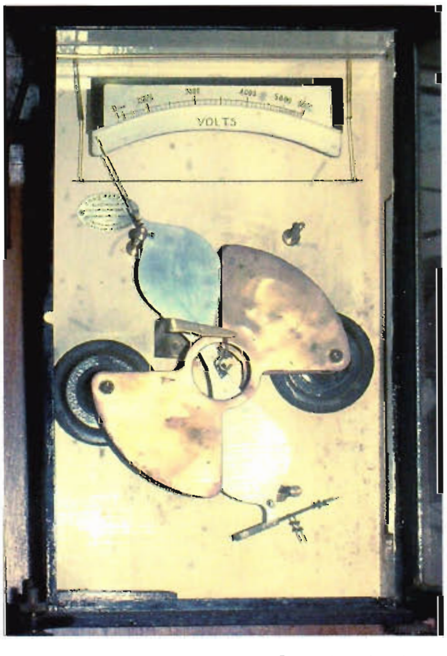

Figure 4. Thomson ES voltmeter (Crich Tram Mus)

The two vertical cylindrical plates are part of a Nicholson revolving doubler, an electrostatic machine for generating a constant potential by rotating an inner pair of cylindrical plates by a knob beneath. The absolute electrometer is limited to a range from about 200V to 5kV, and being a square law device could be used for AC.

Quadrant electrometer

Much greater sensitivity can be achieved with the quadrant electrometer devised by Thomson in 1867, covering the range from 10mV to 400V. An example of the Dolezalek version is shown in Fig. 3. A thin aluminium butterfly with small mirror above is suspended by a fine quartz fibre from a torsion head, and situated within a quartered hollow brass 'cheese' each sector mounted on a separate amber insulator. In its normal sensitive heterostatic, DC only, mode the sectors are cross connected and taken to the two terminals through insulators in the base plate. The butterfly is given a charge of a few hundred volts by a thin conducting fibre when a vertical rod is rotated from the terminal on the top plate. The potential difference between the adjacent sectors rotates the charged butterfly to an angle proportional to the product of the charge and the potential difference and is controlled by torsion.

Because it requires a constant polarising potential the quadrant electrometer is not suitable as a direct reading voltmeter although modern stable electrets would allow that possibility. The alternative less sensitive *idiostatic* mode is selected when the butterfly is connected to one of the pairs of plates when it becomes a square-law device suitable for AC or DC.

Interleaving plates voltmeters

Thomson's first direct reading electrostatic voltmeter dates from 1887 and is a rotated version of the *idiostatic* quadrant electrometer with the sectors connected to the butterfly omitted. Fig. 4 shows a 1907 example, covering 0-6kV. Thomson's instruments were made by Glasgow instrument maker, James White, in which he had a financial interest, becoming Kelvin, Bottomley & Baird in 1900. The butterfly is vertically suspended on knife edges and gravity controlled by nuts on screw threads on the lower wing (an earlier model had a pan for weights to provide the restoring force). Most electrostatic voltmeters have the moving parts connected to the case with the high potential applied to well insulated fixed plates.

To increase sensitivity in order to measure power supply voltages Thomson devised the multicellular version in 1888 (Fig. 5) with a torsion wire suspension and a horizontal circular scale. This was superseded in 1892 (when he became Lord Kelvin) by the 'engine room' version, less reverently known as the 'carriage lamp' voltmeter (Fig. 6, wall mounted with plumb line and levelling screws 15x18x38, 7cm curved reverse scale 260-0V, Pt/Ir torsion wire with worm drive zero adjustment, oil dashpot below, James White, Glasgow, No.1506).

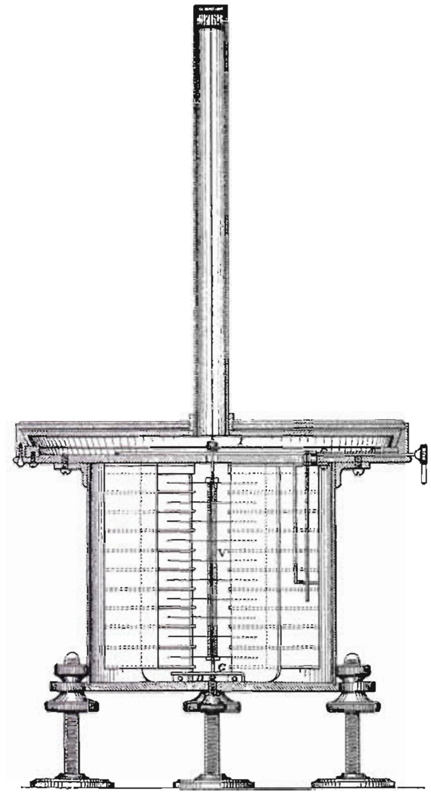

Figure 5. Thomson multicellular voltmeter

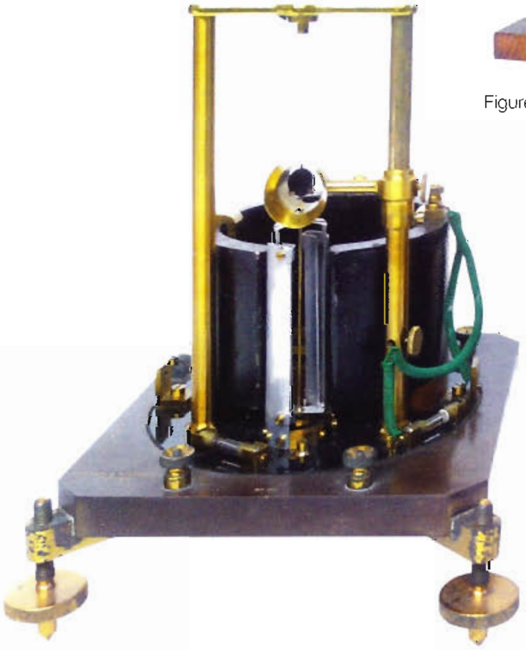

Figure 7. Ayrton & Mather ES voltmeter

There are 15 cells with a total capacitance of 11pF and an accuracy of ±0.5% of fsd. At this capacitance, current consumption is effectively zero. The movement is damped by a disc suspended in a glass vessel below which when filled with liquid paraffin gives critical damping. It is potentially hazardous because the brass case forms one terminal!

A mirror torsion wire instrument by Ayrton & Mather with interleaving cylindrical plates is shown in Fig. 7 (Laboratory bench instrument with levelling screws requiring lamp and scale, 18x18x22). The suspended vanes form part of a single shorted aluminium turn moving between the poles of a magnet to give eddy current damping. Maximum deflection is obtained with about 55V.

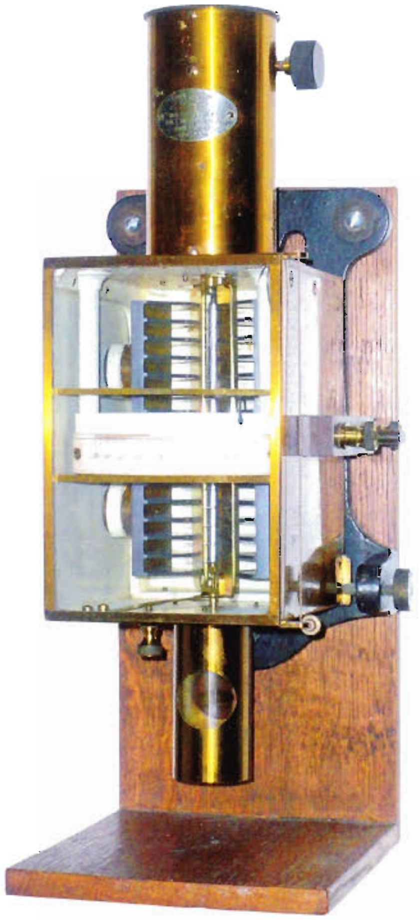

Figure 6. Kelvin engine room voltmeter

Although the maker's name has been erased an identical instrument is illustrated in the Elliott Bros' 1895 catalogue together with some more practical gravity-controlled pointer versions based on similar design features.

Fig. 8 illustrates a wartime design in which the high potential fixed brass plates attract an aluminium vane into the gap with the torque balanced by a hair spring. (Plug-in instrument. d=6.5, 4cm nonlinear scale 0-1500V, AM issue No.629566, 1944, period 1s under damped, 5s settling time, accuracy not assessed).

It will be noticed that many electrostatic voltmeters are similar in design to tuning capacitors and it is an amusing thought that without friction in the bearings, electrostatic

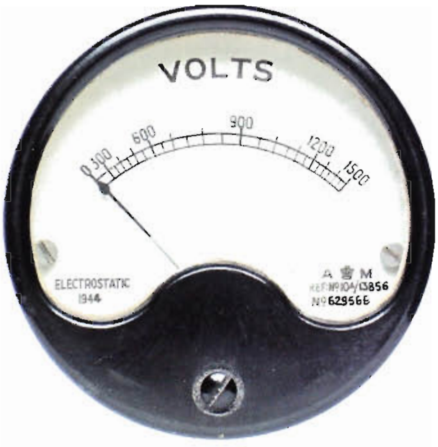

Figure 8. Bakelite ES voltmeter

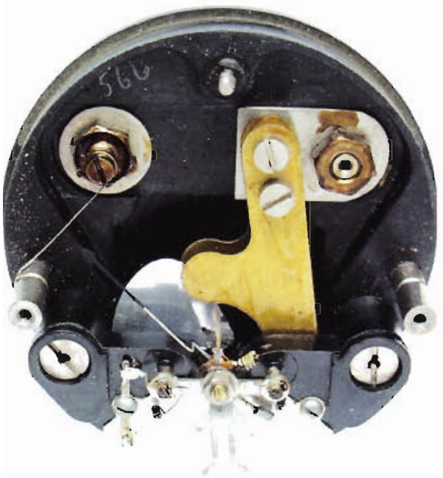

Figure 9. Pye Scalamp ES voltmeter

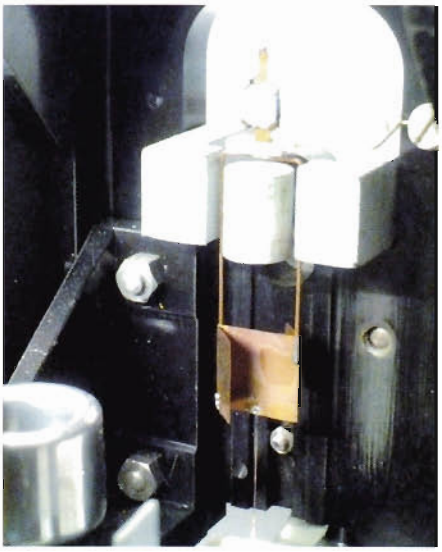

Figure 9B. Pye Scalamp ES voltmeter

forces generated when a station is tuned should in principle rotate it off tune!

Pye Scalamp 18kV voltmeter

(Bench instrument 19x28x18, 14cm nonlinear scale 0-18kV, self-contained mirror instrument requiring 4v or mains supply for lamp, WG Pye & Co. Ltd., Cambridge)

This electrostatic taut suspension instrument (Fig. 9) is designed for a maximum peak voltage of 18kV, thus being restricted to 12.7kV on AC. To avoid corona discharge or spark-over sharp edges and corners are avoided. The live electrode is a polished aluminium ring with rounded edges (Fig. 9b, lower left) fed by a metal rod from the heavily insulated external contact. The attracted element is a rectangle of copper sheet bent into a 'Z' shape suspended from a loop of copper wire forming a single turn in a moving coil magnet assembly to give eddy current damping. Attached above this is a small mirror with the whole movement mounted on taut suspension wires. The electrostatic attraction is greatest on the nearest part of the 'Z' and exerts torsion which is indicated on its calibrated scale by a reflected circle of light with cross hair. A Wimshurst machine set to give 2cm sparks gives fsd but the calibration accuracy has not been checked.

Cardew thermal voltmeter

(Horizontal wall mounting, l=107, 300" d=10 circular nonlinear engraved silvered brass scale 0-150V, No.367 on dial, D&G No.5457 inside cover).

Capt. Philip Cardew patented the hot wire voltmeter in 1883 and it came into widespread use in the early power industry. A range of models were produced, the earliest using vertical tubes, but the horizontal one became standard presumably because of better cooling. In the model illustrated (Fig. 10) a 4m length of 0.0025" platinum/silver wire, which expands with temperature, is attached to two insulated brass pillars (Fig.10c), and passes down the tube and round insulated pulleys (Fig.10d) and back to a central ruby pulley between the pillars where it is held in tension by a thin wire passing round a grooved disc to a coil spring taking up the tension. The remote end of the coil spring can be adjusted by an external knob to zero the instrument. On the same spindle as the grooved disc is a toothed wheel engaging with a pinion on an arbor passing through the dial to the pointer. All bearings including the pulleys are jewelled and the pointer arbor has a hairspring to take up any backlash in the magnifying gear.

The pulley table is supported, not by the tube, but by a pair of rods fastened to the movement case. One end of these is brass whilst the other is iron to give temperature compensation for ambient temperature. As the instrument consumes 55W at fsd (430Ω & 350mA) it takes a long time to stabilise and becomes quite hot. Nevertheless it responds rapidly in a dead-beat manner. Unfortunately the original wire was damaged and has been replaced with tungsten which although suitable for demonstration, has a low resistance at room temperature and would fuse if full voltage were applied rapidly. The red fibre disc seen edge-on in Fig.10c supports four radial pieces of fuse wire put into circuit by rotating the disc. In power

Figure 10. Cardew hot wire voltmeter

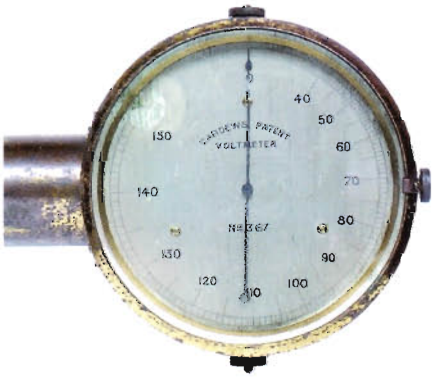

Figure 10B

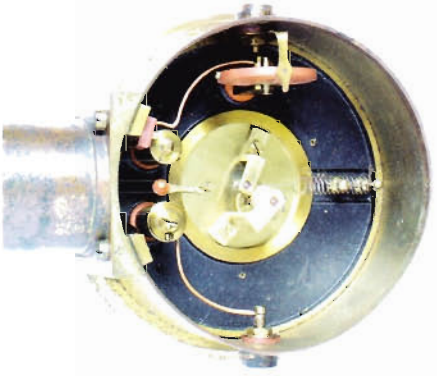

Figure 10C

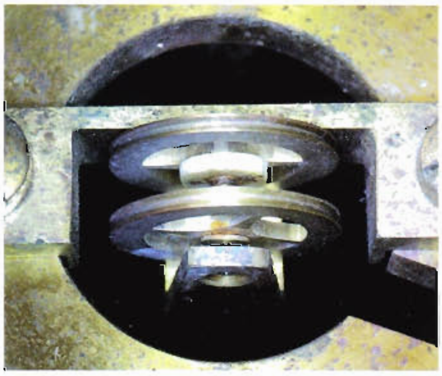

Figure 10D

Figure 11. ECC moving magnet voltmeter

Figure 11B. ECC moving magnet voltmeter

stations it was common to leave meters permanently connected, resetting them each day against a standard instrument. Its low inductance and the small skin effect with fine wire make it suitable for high frequencies.

Electromagnetic instruments: moving magnet types

Most instruments of this type employ a small needle magnetised by a permanent magnet which provides the balancing force as in the tangent galvanometer. In the ECC Voltmeter (Fig. 11, vertical bench instrument, 14x13x5, 10cm nonlinear engraved scale 2.5-0-2.5V on silvered brass dial, Electric Construction Corporation Ltd, London, No.302) its range suggests that it is intended primarily as a cell tester. Its low resistance of 8Ω (0.31A & 0.8W at fsd) would be an advantage in this application, measuring voltage under load, as it is often the increase in internal resistance rather than open circuit voltage that indicates a cell needs replacing or recharging. It clearly follows the design of the Ayrton & Perry Am-meter (described in the previous article) including their 1884 introduction of adjustable magnetic cores within the coils. Short oval iron cores are situated in the outer ends of the coils (Fig. 11b) with square headed adjustable iron screws extending about 5mm further inwards. In addition the pole pieces can be adjusted. Nevertheless, despite Ayrton & Perry's claims for linearity the scale is nonlinear. Probably owing to later tampering the instrument is +2% at ±1v, correct at ±1.5V and -10% at ±2.5V, response time is 0.2s lightly damped. It cannot be used on AC.

By rotating the magnet so that the pointer is at the left end of the scale the near-linear range is extended. Fig. 12 shows an instrument by a small unknown firm which is of simple construction but gives the impression of quality. The case back is turned from a single block of wood into which the terminals are screwed. Into this is let the cast brass movement chassis with protrusions at the rear on which the coil is wound and held in place by sealing wax. The needle is a rectangle of iron above and across the ends of a 'C' magnet which has been stuck into the wooden block. The pointer is a piece of wire wrapped round the arbor and continuing on the other side to a lead counterweight. The cover is made from brass tubing with a soldered turned bezel.

Initially the instrument over-read by about 40% but after placing it at the appropriate angle near the poles of a large powerful magnetron magnet it under read by about

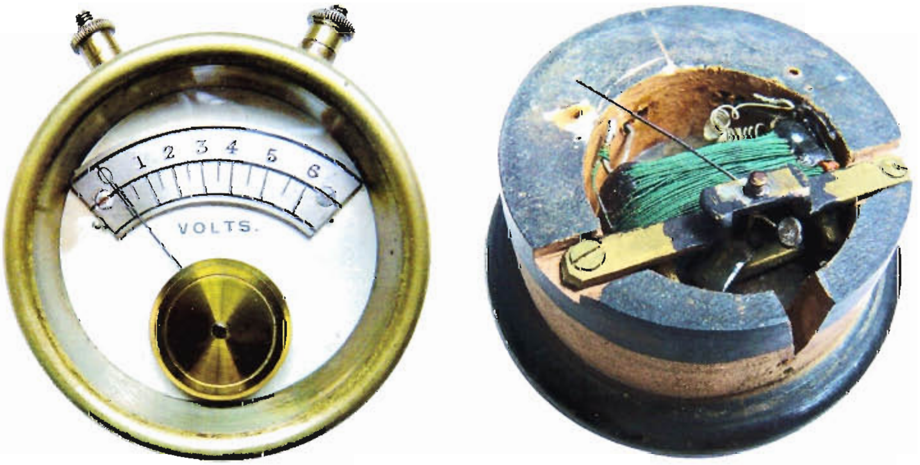

Figure 12. Moving magnet meter

Figure 13. Mass-produced moving magnet

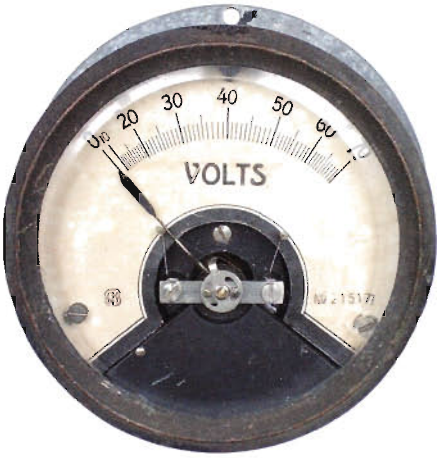

Figure 14. RK moving iron repulsion type

Figure 14b

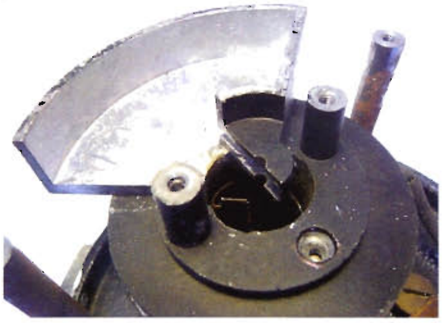

Figure 14c

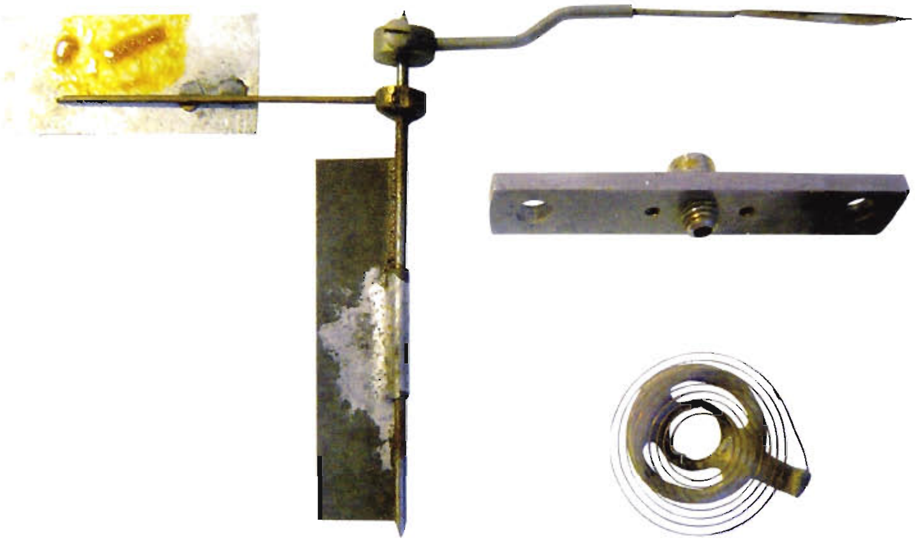

Figure 14d

10% with the pointer off zero. By judicious application of a smaller magnet it proved possible to set both the sensitivity and zero to be correct in the absence of any external magnet. (Domed wooden base 7.5cm diam. 4cm nonlinear engraved silvered brass scale 0-6V, serial no. 182 on back of scale).

Fig. 13 shows a mass-produced voltmeter working on the same principle in which it appears from the + changed to - that a previous user has reversed the polarity of the magnet. (Pocket watch type, d=5.5cm, printed card scale 0-8V & 0-120V, marked 230Ω & 3400Ω [actually 143Ω & 2270Ω], 55mA fsd, S.A.R.E., ±5% both ranges).

Moving-iron repulsion voltmeters

Although in principle both repulsion and attraction moving-iron meters should be useable on AC, the inductance of the coil and hysteresis of the iron mean that the AC and DC calibrations may be different.

Fig. 14 shows an example where the dashpot is visible through the bevelled glass (Wall mounting, d=12, spring controlled, 6.5cm nonlinear scale 0-70V, RK No.21517). The fixed repulsion plate, which becomes magnetised along the axis of the solenoid, can be seen in Fig. 14c together with its tail which holds it in place by spring fit. The moving plate which becomes magnetised along its length in the same sense is seen attached to the pointer assembly together with the aluminium dashpot vane. The instrument over reads by about 10% on AC and 20% on DC (DC resistance 1.33kΩ, 53mA fsd, 3.7W).

Fig. 15 shows a bakelite example by MV (Wall mounting, d=18, 13cm nonlinear mirror backed scale 0-20V, spring controlled, dashpot damped, 50~ moving iron, MV, military nos. on back). Part of the moving and fixed plates can be seen at the bottom of Fig. 15c. (The brownish bent metal to the left may be a piece of transformer lamination added to increase sensitivity). The meter under reads slightly (-1% on AC & DC, 0.31A and 6.2W at fsd, 1s period under damped).

A mass-produced 'watch case' example is shown in Fig. 16. In this the needle is a rod which is repelled by a plate with cylindrical tapered tail as in Fig. 14. (Hand held, d=5.5, crudely printed card scale 0-6V, 24Ω, 250mA & 1.5W fsd, ±5%).

Moving iron attraction voltmeters

Fig. 17 shows a high quality instrument by Evershed & Vignoles in which a black vane normal to the spindle rotates as it is attracted into the horizontal slot within the flattened brown solenoid (Fig. 17b). The dial plate closes off the top of the large dashpot below the pointer and scale. The resistance of the solenoid is supplemented by the four pot resistors. Zero is set by a screw head on the right of the case bearing on a brass spring and rod link to the hair spring. (Horizontal or vertical bench meter 20x21x10, engraved

Figure 15. MV moving iron repulsion type

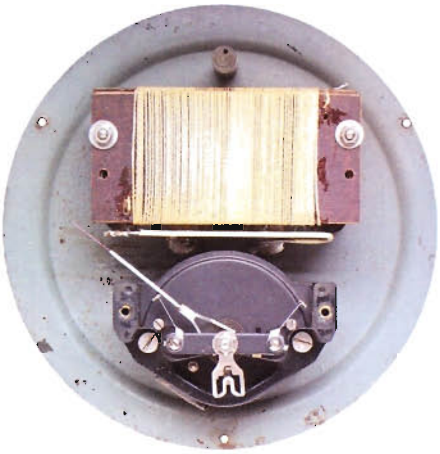

Figure 15b

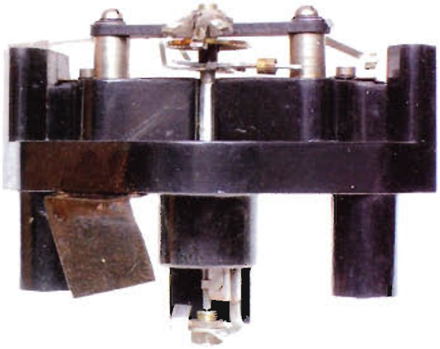

Figure 15c

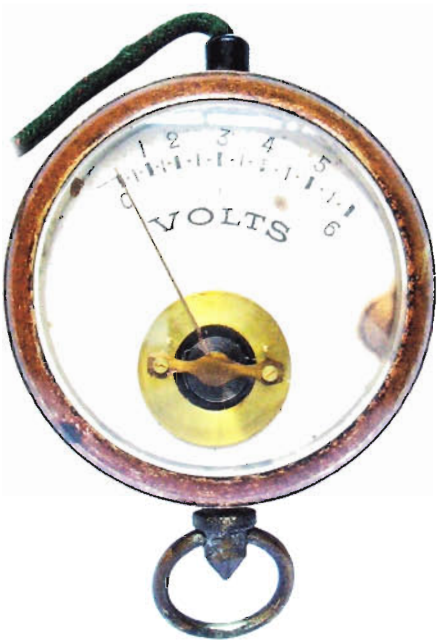

Figure 16. 'Watch case' repulsion type

Figure 17. SEV moving iron attraction type

Figure 18. Fleming & Gimingham electrodynamic type

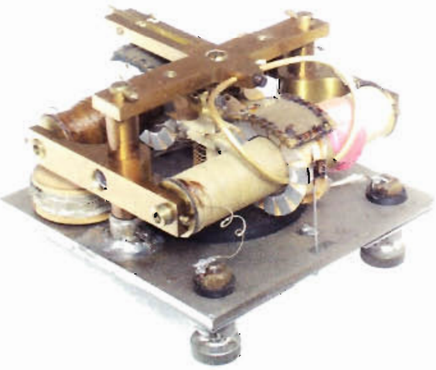

Figure 18b

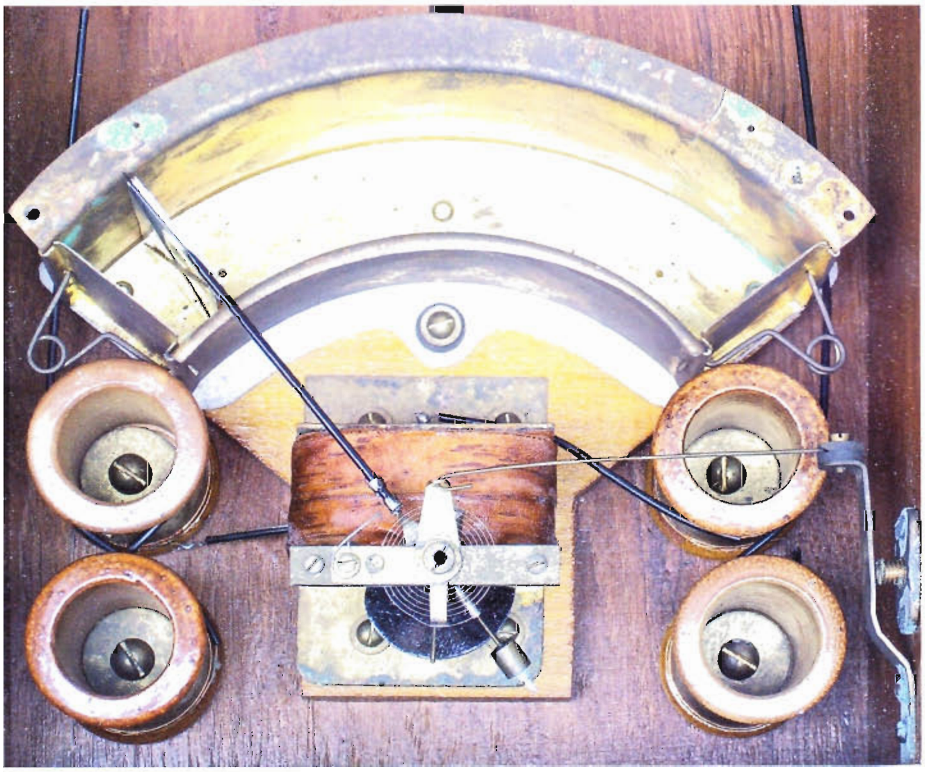

Figure 17b

Figure 18c

silvered brass 13cm nonlinear scale 0-250V, SEV No.44088). Between 150 and 250V the meter is fairly accurate (+0.5±0.5% AC & DC, 6.97kΩ, 36mA fsd).

Electrodynamic voltmeters

The electrodynamic principle can be used in ammeters, voltmeters and wattmeters and as it does not need magnetic material, is free of the problems of hyteresis and loss of magnetism. The penalty is lower sensitivity and greater possible influence of the earth's field. Nevertheless it is suitable for stable standard instruments. With improved magnetic materials these are now incorporated in some designs. In all cases, because the torque is a product of the current passing through the static and moving coils, it is a square law device for voltage or current and linear for power. The inductance of the coils does not produce significant error at power frequencies.

Fig. 18 shows a beautifully made meter by Fleming & Gimingham in a neat and compact case, which would have had no competition in terms of accuracy and portability when introduced. Fleming was a consultant for, and Gimingham works manager of, the Edison-Swan Co. and they gave a very detailed description of this meter in *J Telegraph Eng, 24th Nov. 1887* (which also includes discussion of the Cardew voltmeter). The instrument was also supplied as a wattmeter. It is in effect a Kelvin current balance turned on its side. Because the moving coils are wound oppositely, the torques exerted by the earth's field will cancel rendering the instrument astatic. (In my previous article I erroneously stated that the moving coils of the Kelvin current balance were wound in the same direction!).

The Fleming & Gimingham instrument consists of two moving coils mounted at the ends of an ivory beam supported by an inverted hardened steel cup on an iridium tipped point. When the lid is screwed down a rod and lever lifts the coils on a

Figure 19. Elliott sub-Standard electrodynamic voltmeter

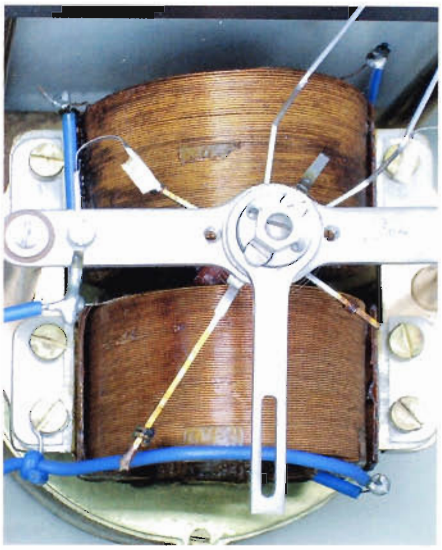

Figure 19b

Figure 21. Early Weston voltmeter

Figure 20. Cambridge electrodynamic voltmeter

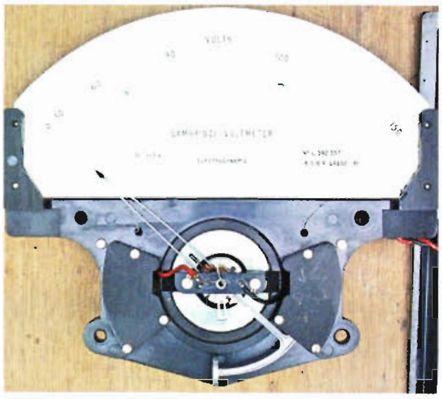

Figure 20b

Figure 22. Weston microammeter

Figure 20c

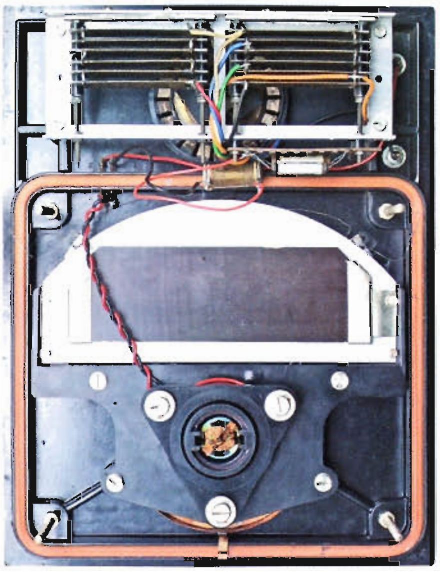

Figure 20d

pair of cloth-lined cradles firmly against the fixed coils (seen inverted in Fig. 18b). The balance pointer can be seen attached to the coil passing through a rectangular aperture in the nickel plated top plate. The helical controlling spring suspended from the rotating dial assembly is just visible in the centre. Although the fixed coils look like simple solenoids their two halves are wound in opposite directions. This results in the N poles being in the middle and the S poles at the four ends, giving radial fields at their centres with the flux passing through the moveable coils.

Initially the instrument has to be levelled so that the balance index moves freely within its aperture using the wooden wedge provided. The mica scale pointer is rotated until the balance index is at zero, the knob loosened, scale pointer set to zero, and tightened. When energised the moving coil assembly rotates and then balance is restored by rotating the dial, which then indicates the voltage.

The small ebonite headed plug below the scale can be removed to add an additional resistor, seen on the left of Fig. 18b between fixed coil and top plate, to double the range. All windings are of German silver giving a temperature coefficient of 0.273% per 10°C. Although the instrument has suffered attention over the years it is within 0.2% for AC or DC on the 110V range (935W, 118mA, 13W at fsd) and 0.5% low on the 220V range.

Another electrodynamometer is the Elliott Bros. Portable Precision Voltmeter (Fig. 19, bench use, 14cm mirror backed nonlinear scale, 0-75/150/300V ranges,

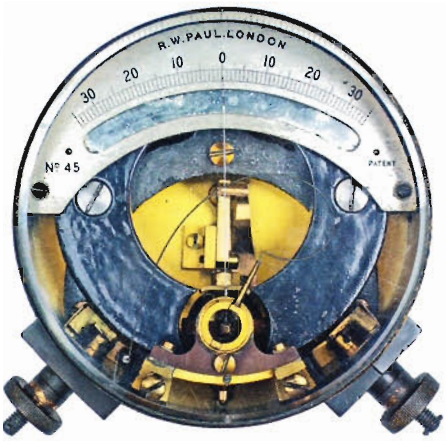

Figure 23. Unipivot moving coil

spirit levels and levelling screws, Elliott Bros. (London) Ltd,, No.A52673, Sub-Standard grade certificate dated 17.10.49). The spring controlled moving coil rotates between 50° and 120° from the axis of the fixed coils (Fig. 19b). The three copper coils are wired in series with resistors giving total resistances of 1.56, 3.12 and 6.24kΩ respectively for the three ranges (48mA fsd, 3.6W on 75V range). The instrument under reads by 0.1% between '25' and '75' on the scale for all ranges. No temperature coefficient is quoted. As the moving coil is quite large and unshielded by magnets the earth's field could be significant on DC. The movement is therefore enclosed in a shielding box and no influence could be detected.

A dynamometer voltmeter in which the magnetic circuit has been improved by the use of magnetic materials can be seen in Fig. 20. (Bench use, 16cm mirror backed square-law scale, 150V x 0.2, 0.5, 1, 2 & 5 (30, 75, 150, 300 & 750V), 50Ω/V, Cambridge Instrument Co. Ltd., No.L.392357, Precision grade ±0.5% of fsd, ±0.5% frequency 20-1000Hz, temperature correction -0.2%/10°). This is similar to a moving coil instrument in which the central core has been replaced by stack of circular laminations slotted and wound as an electromagnet and surrounded by a ring of laminations completing the magnetic circuit. Thus it becomes a multiplicative device in which the torque is proportional to the product of the currents flowing in the electromagnet and in the moving coil.

It appears from Fig. 20b&c that the pivots must be within the moving coil and the external laminations can be seen within the black plastic frame. The dashpot damping is split with the left end of the scale served by the right dashpot and vice versa. On test the instrument was found to over read by about 1% with no obvious way of adjusting the sensitivity. At 20mA fsd (0.6W on 30V range) it is more sensitive than the iron-free Elliott meter above.

Moving coil voltmeters

In the moving coil meter the magnetic flux flows inwards across one annular gap and outwards on the other side so that the currents in the coil, upwards on one side, downwards on the other, both exert a clockwise torque which is balanced by the hairsprings leading the current in and out.

Figure 23b

Edward Weston, an Englishman who set up in business in Newark, New Jersey, USA, introduced many advances to accurate measurement including a standard cell as well as new alloys for resistance materials, magnets and hair springs. He found that by cyclically remagnetisation and final magnetisation to two thirds maximum, magnets remained stable. It is remarkable that the majority of his innovations remained virtually unchanged for the remainder of the pre-digital age.

In my experience some moving coil instruments do seem to lose sensitivity over the years. This may be due either to poor design and manufacture or to mistreatment by the user such as dropping or touching the magnet with a screwdriver. As the magnetic gap normally has an adjustable shunt, it is only possible to comment on stability if the instrument is certified and remains sealed. Two early Weston meters in the Science Museum were retested a century after production and found to be correct. The only moving coil instruments in my collection fulfilling these criteria are the Weston microammeter (see opposite page) and the Elliott 150/300V voltmeter (+0.3%, on the upper limit specified). Thus clearly Weston was justified in his claims for stability. Fig. 21 shows an early Weston 150/300V voltmeter from a private collection. The upper right knob is pressed for test. Although Weston had set up a subsidiary in this country their movements continued to be made in New Jersey until 1937 when Sangamo took over the company, becoming Sangamo-Weston in 1938 with local manufacture.

Into the electronics Age

Early voltmeters were mostly for the power industry and 50mA at fsd would be quite common and perfectly satisfactory. With the introduction of valve circuitry, however, more sensitive movements became desirable for voltage, current and resistance measurement. Fig. 22 shows a 1937, 150mA fsd (36.9Ω and 0.83μW) microammeter, made in the USA but calibrated at the Weston Laboratory, Surbiton. As the instrument is still sealed and correct to 0.1% there is no photograph of the movement.

Figure 23c

The temperature dependency of resistance of the copper moving coil is not a major problem for voltmeters because it is normally swamped by the series resistance necessary to set the range. Nevertheless there are slight changes in current sensitivity with temperature due to the magnet, elasticity of the hair springs and dimensional changes. From the certificate in the lid of this meter (Fig. 22) it amounts to +0.12% for a 10°C rise.

Swamp resistors

There are many types of resistor used in voltmeters depending on voltage range, order of accuracy required, and cost. In general traditional carbon resistors are unsuitable because they have a large negative temperature coefficient (dependent upon value), and are unstable with age, humidity and soldering. Furthermore they do not obey Ohm's law exactly. The cracked carbon resistor, however, is much more stable and used in later models of AVO and many other instruments. They have a negative temperature coefficient (-0.06 to -0.25 %/10°). In my experience these resistors do remain stable. With more sensitive movements these became a necessity because 1MΩ is about the practical limit for wirewound resistors. More recently metal oxide and metal film resistors have become available with even better characteristics and can also be used in printed circuits.

Wirewound resistors come in two types, the more familiar being power types as used in mains droppers. Alloys such as nichrome are designed to work at high temperatures and can be used as heaters but do not need or indeed have particularly low temperature coefficients. The second type are instrument grade resistors where accuracy and stability are important. These are generally produced specifically for the application, e.g., in a multirange instrument all the shunt or swamp resistors may be wound on a common former. Eureka or constantan is generally used for voltage ranges where thermoelectric potentials would not be significant. Manganin is used for high grade shunts and for standard resistors and bridges but requires hard soldering.

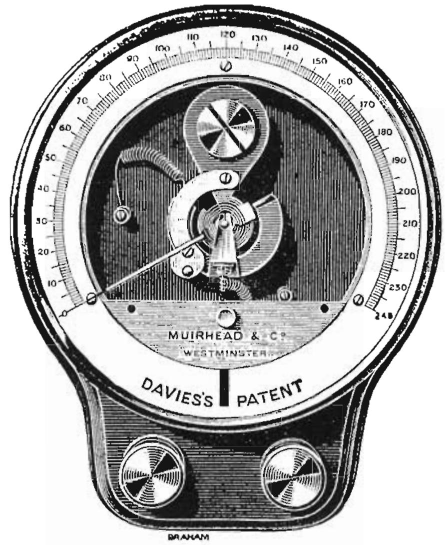

Figure 24. Benjamin Davis 240° moving coil

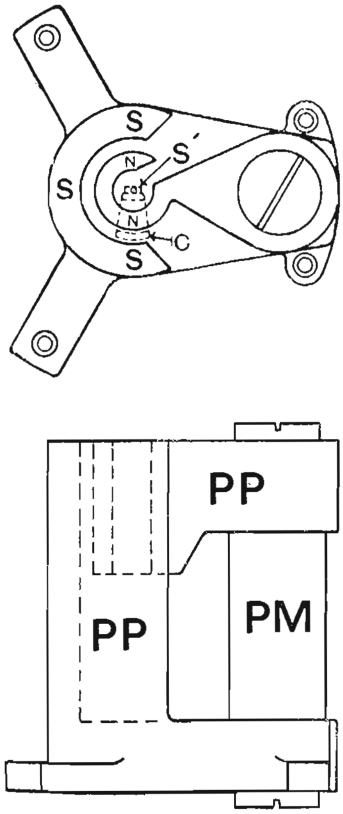

Figure 24b

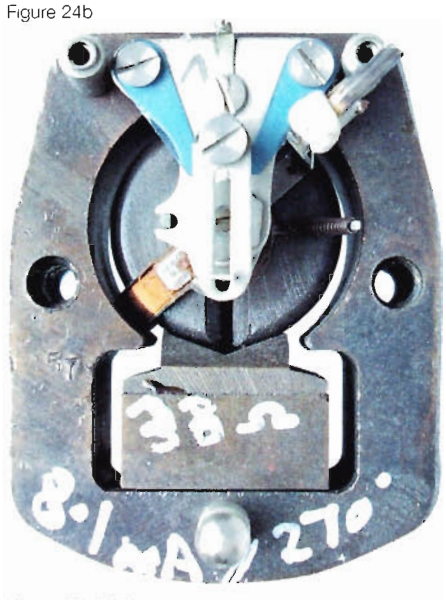

Figure 25. 270° moving coil movement

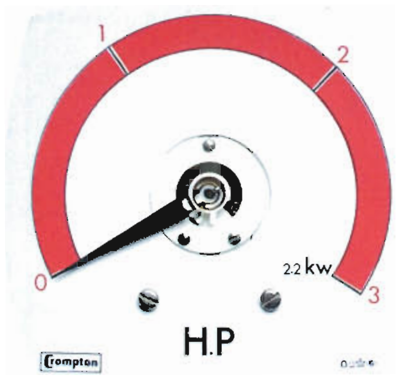

Figure 26. Crompton 240° taut suspension moving coil

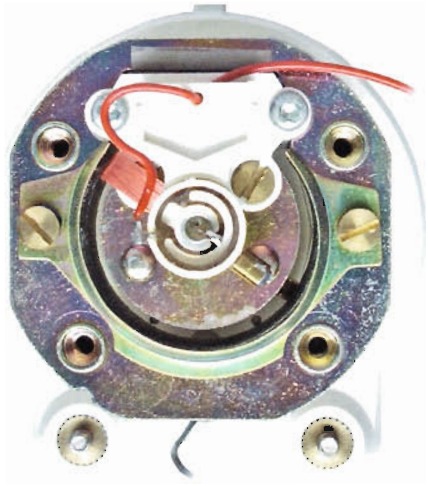

Figure 26b

Figure 27. Sangamo Weston voltmeter

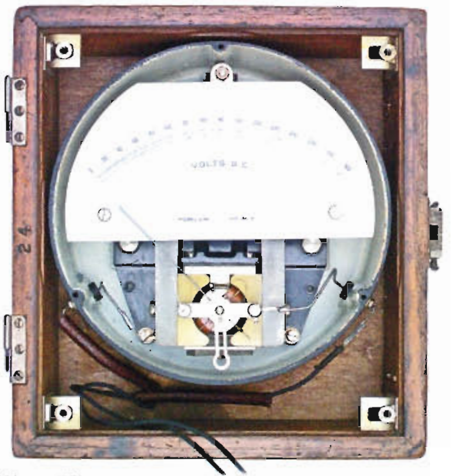

Figure 27b

Variations on the moving coil

In 1903 the Robt. W Paul Co. patented a new form of moving coil movement using a single pivot point at the centre of a spherical soft iron core which is also the centre of gravity. The advantages claimed are lower friction and self balancing, making the reading independent of levelling. This allowed the use of very light springing and consequent high sensitivity. These were continued after Paul joined with The Cambridge Scientific Instrument Co. in 1919.

Fig. 23 shows an early 35-0-35μA galvanometer (No. 45, d=10.5cm) with a mirror backed engraved silvered brass dial. Fig. 23c shows a 0-12/120mV millivoltmeter for either bench use or wall mounting (18x17x7, 14cm mirror backed scale, 50/500Ω, 240μA fsd and 2.9μW on 12mV range). Unfortunately neither movement now moves as freely as it should.

In 1895 Oliver Lodge's research assistant, Benjamin Davies, devised a long scale version of the moving coil in which the pointer covered up to 270°. Fig. 24 shows a 240° version by Muirhead. In these, the moving coil rotates on an axis along one side of the coil (Fig.24b) with the central core being a shell attached to the N pole of the vertical magnet (PM). The outer pole piece is attached to the S pole. The inner pole piece has to be slotted to allow assembly of the coil.

The Record 'Cirscale' movement is similar except that the outer S polepiece embracing the movement is replaced by two endplates above and below the coil. Thus instead of the outer limb of the coil cutting a radial flux it is the radial end limbs of the coil cutting a vertical flux and allowing 300° of rotation.

Improvements in permanent magnets allow a more compact structure (Fig. 25, where the magnet block is marked with the coil resistance '38Ω'). One pole contacts the outer polepiece, embracing the movement, and the other pole, the inner cylindrical polepiece. The stub of the missing pointer is at the upper right. This produces a full 270° deflection at 8.1mA (2.5mW).

Fig. 26 shows a Crompton power meter (0-3HP or 0-2.2kW) with a 240° scale using a taut suspension instead of pivots and hair springs. The structure is otherwise very similar to the previous instrument except that the pole pieces are laminated. This suggests that the permanent magnet, concealed by the white plastic, could be replaced by an electromagnet giving an electrodynamic version. The instrument is part of a 3-phase power meter in which a direct current proportional to the power is derived by internal electronic circuitry from three voltage and two current terminals via external transformers. There would be similar blue and yellow scaled meters for the other phases. The movement is linear with 1mA fsd and 265Ω resistance (0.265mW).

Some high quality moving coil voltmeters

Fig. 27 shows a Sangamo Weston Ltd. Model E45 (No.184E, 13cm mirror backed scale 0-150/300V, 20x21.5x12, 15/30kΩ, 10mA/V). This instrument over reads by 0.2% at half scale and above.

Figure 28. GEC iron clad voltmeter

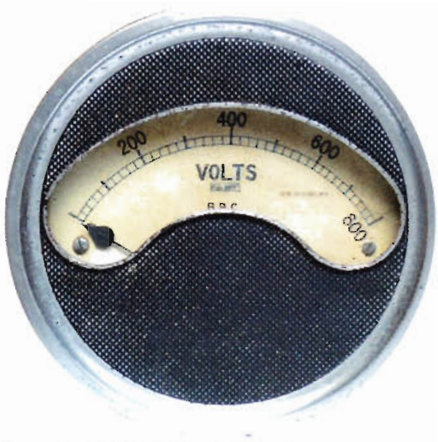

Figure 29. Elliott BBC Droitwich meter

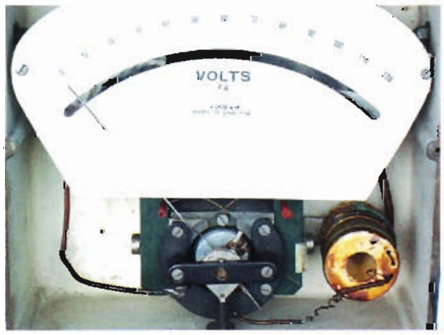

Figure 28b

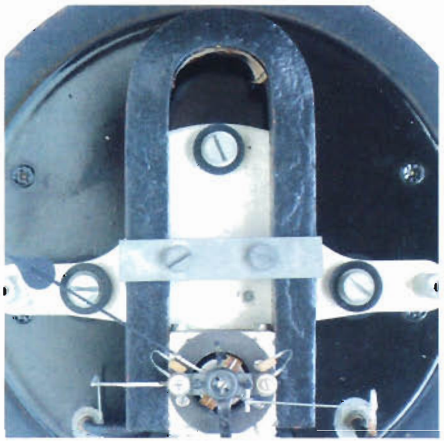

Figure 29b

Fig. 28 shows a GEC 120V iron clad meter for use in magnetic environments with 13cm mirror backed scale (No.11310VP, 18x20x8, 18.4kΩ, 6.52mA/V). It over reads by 1 to 1.5% across the scale.

Fig. 29 is one of a pair of meters made by Elliott Bros. for the BBC transmitter at Droitwich, this one being 0-800V (No.1104810, d=20cm, 21Ω movement) the other being 0-40A. As the internal swamp resistor has been rewound for a lower voltage it is not possible to comment on accuracy although as fsd is 8.08mA it may have lost 1% of sensitivity.

Fig. 30 shows an Elliott Bros. Portable Standard Voltmeter (No.D226301, 21x19x11, 12cm mirror backed scale 0-150/300V, 6.7mA/V). This instrument is still sealed so the inside is not shown. It is certified accurate to 0.3% of fsd for International volts. It over reads by almost this amount and may just exceed 0.3% in absolute volts (which are about 0.034% smaller).

Fig. 31 is another Sangamo Weston DC Voltmeter (Model S83, No. AH15910, 1958) suspended on sorbo-rubber blocks within a rugged military case (26x27x16). It has a 12.5cm mirror backed scale 0-400V, 1mA fsd, certified Precision Grade BS89. The temperature coefficient (-0.1%/10ΩC) is opposite to that of the 1937 Weston meter (Fig. 22). The meter was obtained, apparently unissued, on the surplus market only a few years after certification and has since remained in storage. It was found to under read by 1% but was easily corrected with the magnetic shunt.

Figure 30. Elliott Portable Standard Voltmeter

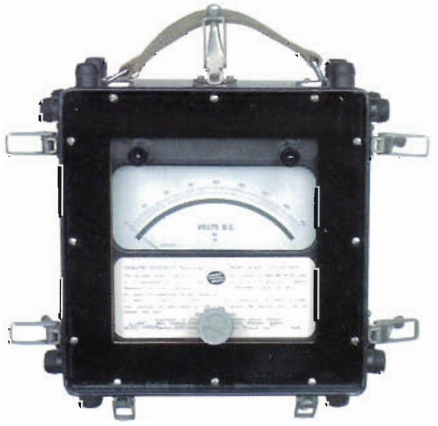

Figure 31. Sangamo Weston in rugged case

Figure 31b

Figure 32. Ernest Turner AC voltmeter

Figure 32b

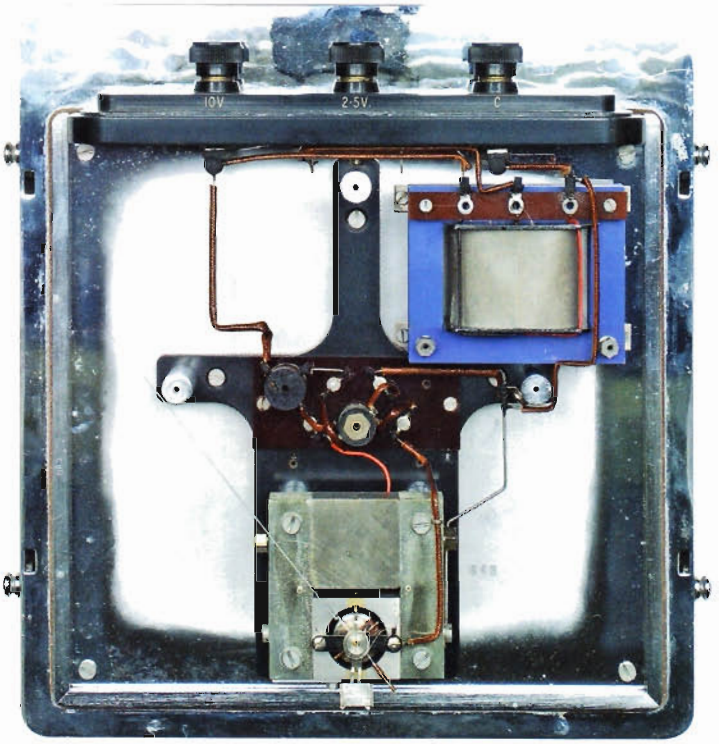

Figure 32c

Turner AC rectifier voltmeter
(Horizontal bench meter, 26x27x16, with 20cm mirror backed scales 0-2.5V and 0-10V, 50~ AC, Ernest Turner Electrical Instruments Ltd, High Wycombe, Bucks, Model 102 Pr, No.1893149)

This is a stylish design (Fig. 32) of the period (1960s?) aiming to look modern and scientific with rounded corners, textured grey enamel, polished chrome and black perspex, and matt teak cover, the effect somewhat spoiled by the carrying handle. Perhaps the nicest feature, however, is the use of vernier scales in which the minor divisions are crossed by faint (faded?) diagonal lines so that on the inner, 10V scale, the crossing points divide the 0.2V divisions into quarters (0.05V) whilst on the 2.5V scale the 0.05V divisions into fifths (0.01V). Reading the 2.5V scale would, however, have been made easier if it had been marked 0, 0.2, 0.4, 0.6, etc, instead of 0, 0.25, 0.50, 0.75, etc. In spite of this great precision the instrument was found to under read by 2% with its magnetic shunt already at minimum. The movement itself is a very neat and compact design (Fig. 32c) with the shaped pole pieces separated by brazed inserts and machined as one block.

Rectifier instruments are normally designed and marked for sinusoidal rms (root mean square) although the deflection actually depends on the arithmetic average of all deviations taken as positive, which is 10% lower. For other waveforms this ratio would be different, e.g. for square waves the rms and average are identical. The other shortcoming of such instruments is the small forward voltage drop across the rectifier, resulting in the compression of markings near zero. In multimeters where the same scale is used for AC and DC this is sometimes ameliorated by tapping off a small proportion of the voltage of the battery (used in the resistance ranges) to apply an offset to the pointer. A half wave rectifier cannot be used because damaging reverse voltages would occur on higher ranges. When an instrument transformer is used, the meter can be fed from a higher voltage winding, where this offset becomes negligible, at the cost of higher current consumption.

This is done in the Turner meter (Fig. 32c) where the 10V terminals are directly connected to the single swamp, bridge rectifier and movement, and a transformer is used to step up the 2.5V range to 10V, with the secondary winding permanently in circuit.