How do they work? 1: Ammeters

by J Patrick Wilson

This is intended to be the first of a short series on ammeters, voltmeters, ohmmeters, multimeters & wattmeters covering their development throughout the electromechanical era. Their prehistory started in the science lab and with the requirements of telegraphy, but it was during the rise of the electrical power industry in the critical period 1880-1895 that most innovations were introduced. Then with the introduction of electronics, more sensitive meters were required to minimise disturbance to the circuit being measured.

Fig 1: Tangent Galvanometer (Philip Harris & Co Ltd)

Fig 2: William Thomson's Marine Galvanometer (Glasgow University)

Many of the early instruments were beautifully made by craftsmen not merely, I like to think, to assist sales. Later, competition and cost shifted the emphasis from beauty to the need to look modern and up-to-date. It is, however, the ingenuity of their mechanisms that intrigues me most, driven both by technical requirements and the need to circumvent patent infringement. An instrument should if possible look clean and original but, more importantly, work in the way intended although not necessarily to the original specification.

General principles

The general principle of a measuring instrument is to balance one force, that to be measured, against another force, the reference quantity. In common parlance two examples seem to be misnamed: a 'pair of scales' should really be called a 'balance' as it does not usually have a 'scale' whereas a 'spring balance' does use a scale. The latter device introduces the basic principle of most electrical meters in which an electromagnetic force is balanced against a restoring force, most commonly that of a spring, a magnetic field, or gravity, in which ideally that force is proportional to the distance moved, and indicated on a scale calibrated in the units to be measured.

'Weight' is the downward force exerted by gravity on a 'mass' whilst 'mass' is the quantity of material present and has the quality of opposing acceleration. In SI units force (F) is measured in Newtons (N) and mass (m) in kilograms (kg).

The principle of the 'balance' is used in electrical 'bridge' measurements where an unknown resistance, inductance or capacitance is directly compared with a set of standard resistors, inductors or capacitors until a balance, or null, is obtained without the need for a 'scale'. There are of course many types of bridge, which are used when the highest accuracy and precision are required, but these are not the topic of this series.

Resonance and response Time

Because a meter movement plus pointer acts like a mass bouncing on a spring it has a natural frequency of oscillation (usually expressed inversely as period). To obtain a rapid response the mass (or moment of

Fig 3: Astatic Bridge Galvanometer (Siemens & Halske)

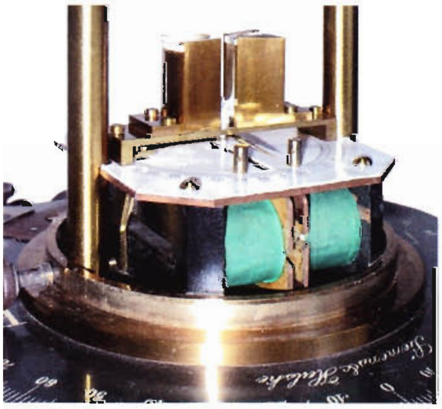


Fig 4a: Astatic Tangent Galvanometer (Nalder Bros)

Fig 4b

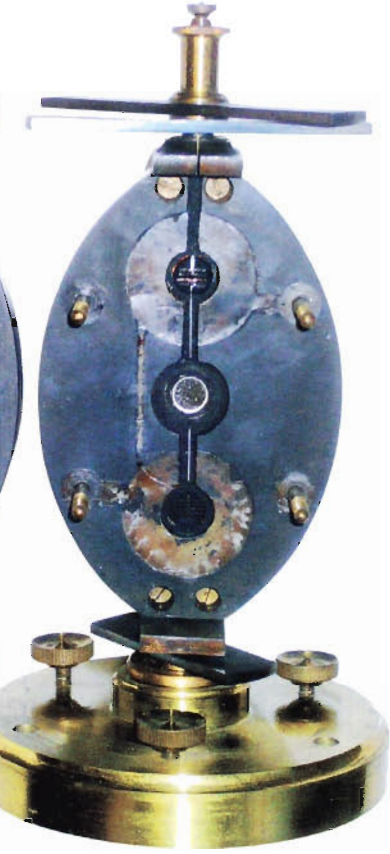


Fig 4c

Fig 4d

inertia when it is a rotary motion) should be as small as possible which is why meter pointers are frequently made from thin aluminium tubing. If, however, the size of the moving magnet or coil is reduced this will tend to reduce the sensitivity of the instrument. Stiffness can also be increased to speed up the response but this again reduces sensitivity. The equation used to calculate the frequency of a tuned circuit $(fo=1/2\pi(LC)^{1/2})$ can be used by substituting *mass* or *moment of inertia* divided by *stiffness* (m/S) for (LC). The response times of galvanometers and pendulums are sometimes given for a swing in one direction rather than the full period $T=1/f_o$.

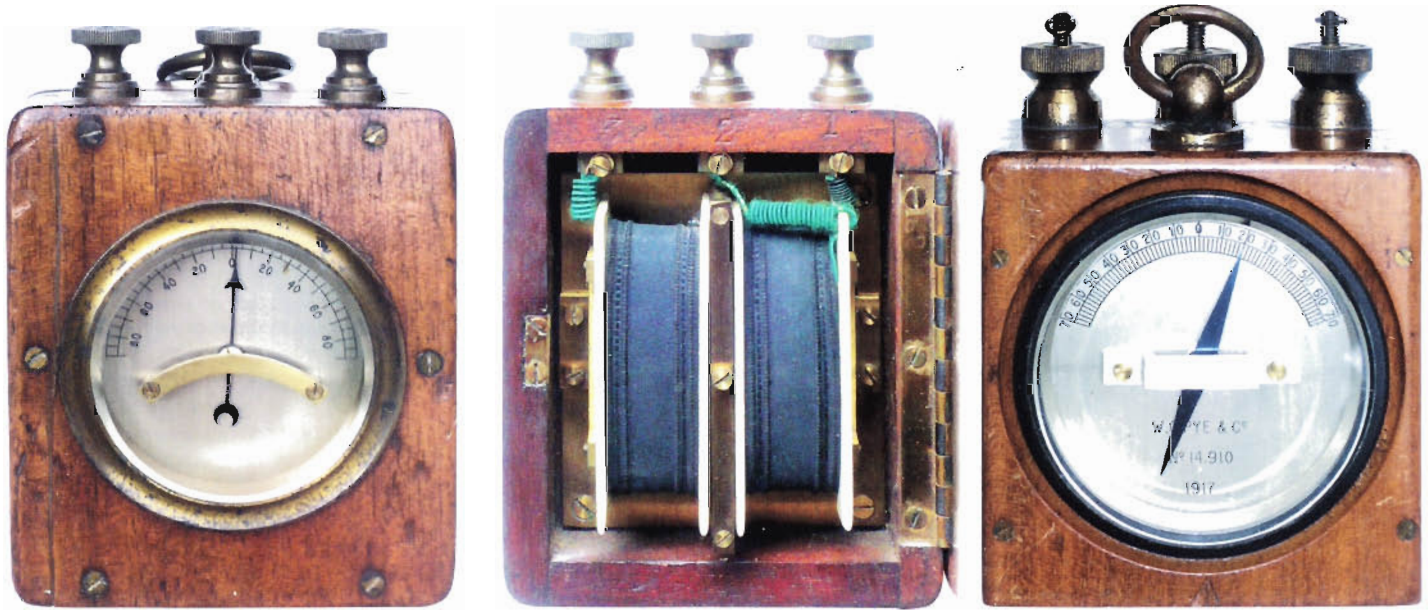
Damping

In obtain a rapid response it is also necessary to have *damping*. Without any, the oscillation would continue indefinitely, whilst with excessive damping the pointer would move sluggishly taking a long time to creep towards its final position. In practice it is desirable to allow some overshoot, keeping slightly below optimal or critical damping to reduce the influence of friction in the bearings. Some instruments use a thin aluminium paddle in a nearly sealed air cell, a dashpot, whilst others use a disk suspended in an oil bath. Eddy current damping is also common, particularly in moving coil instruments, where currents induced within conductors moving in a strong magnetic field incur resistive losses.

Scales

Scales may be linear, square-law, tangent, square-root or arbitrary. Although a linear scale is easiest to calibrate and to read, the important feature is that the scale should be 'open', allowing precise reading, in the region where it is intended to be used most, e.g., around 220-250V for monitoring a mains supply. In general the longer the scale, the better. *Precision* refers to fineness of change that can be detected and read whilst *accuracy* refers to how closely that reading approximates to the true value.

Fig 5: Linesman's Galvos (a&b) unnamed. (c) WG Pye & Co 1917



In better class instruments the scale may be backed by a mirror behind an annular cut-out. When the reflection of the pointer is hidden, the eye is in the right position to avoid parallax error due to the differing planes of scale and pointer.

The term 'direct-reading' implies that the pointer indicates directly the quantity to be measured on a scale calibrated by the manufacturer against a standard reference instrument. Multirange instruments may use a single scale with various *range factors*.

Levelling of movement

It is desirable that an instrument should be able to operate in any position. However, some instruments such as galvanometers and gravity controlled instruments require levelling to perform correctly, and magnetically controlled meters may also require rotating in the earth's field.

Even spring controlled instruments, however, may give different readings in different positions and incorporate adjustable weights to obtain dynamic balance. With the rotation axis and pointer horizontal it is obvious if the pointer is light or heavy. Similarly if the pointer shows an error when vertical, lateral balancing is required, although this may also be caused by a bent pointer.

Tangent galvanometers

Current indication started with Oersted's observation in 1820 that a compass tended to set at right angles to a wire when connected across a battery. Soon after this discovery Schweigger showed that this effect could be magnified by wrapping the wire around the compass as a vertical coil. This forms the basis of the tangent galvanometer.

In a *tangent* galvanometer the compass needle will settle along the *resultant* of a fixed field, due to the earth's magnetism, and the field produced by a current in a vertical coil set at right angles to the earth's field. The resultant angle is independent of the strength of the compass needle, but because the earth's field is weak, it will be greatly influenced by any magnetic material in the neighbourhood. Instruments based on this principle are restricted to DC.

Fig. 1 shows an educational example by Philip Harris & Co Ltd which incorporates three windings of 2, 50 & 500 turns for differing sensitivities and current capacities. The needle, with pointer attached at right angles, aligns itself with the earth's magnetic N and S. The upper part of the instrument then has to be rotated until the coil is parallel with the needle, and the pointer along the axis of the coil. Next the compass case and scale is rotated until the zero degree markings lie below the ends of the pointer. Current then deflects the needle either left or right depending on its direction. The *tangent* of the angle of deflection is proportional to the current flowing, and also to the number of turns in the coil. Thus it is possible to compare currents over a wide range.

The needle swings quite slowly because the balancing 'spring' is 'soft' as the earth's field is fairly weak. The stiffness can be increased either by adding an external magnet above or below the needle to augment the earth's field or by introducing a real spring to apply an additional restoring force.

Marine galvanometer

An early use was identified by William Thomson (later Lord Kelvin) in his marine galvanometer (Fig. 2) used to read telegraph cable code and to test the cable and equipment during the laying of the first Atlantic submarine cable in 1858. To give rapid response the stiffness was increased by suspending the needle at the centre of a taut torsion wire, running the height of the vertical brass tubes, and this keeps the system stable during motion of the ship. To compensate for the reduced sensitivity a coil of many turns, inside the horizontal leather covered tube, was used together with a very long and very light pointer. The latter was a light beam reflected by a small mirror attached to the needle at the centre of the wire. Kelvin later claimed the inspiration for this came from observing the reflection of the sun from his dangling monocle. Kelvin used a close fitting glass case to increase air damping allowing about ±10° rotation of the mirror. The coil is in two halves for access, and the ends of the vertical tube can be rotated by the knurled knobs to twist the wire and zero the reflection.

For laboratory use, where maximum sensitivity is required and speed may be less important, the effects of the earth's field can be reduced by placing an opposing external magnet above or below the instrument.

Astatic galvanometer

(in Siemens & Halske bridge No.1935U)

A different approach to increased sensitivity is the *astatic* galvanometer in which an oppositely magnetised needle is attached to the first one, but outside the coil, where it cancels the effects of the earth's field and,

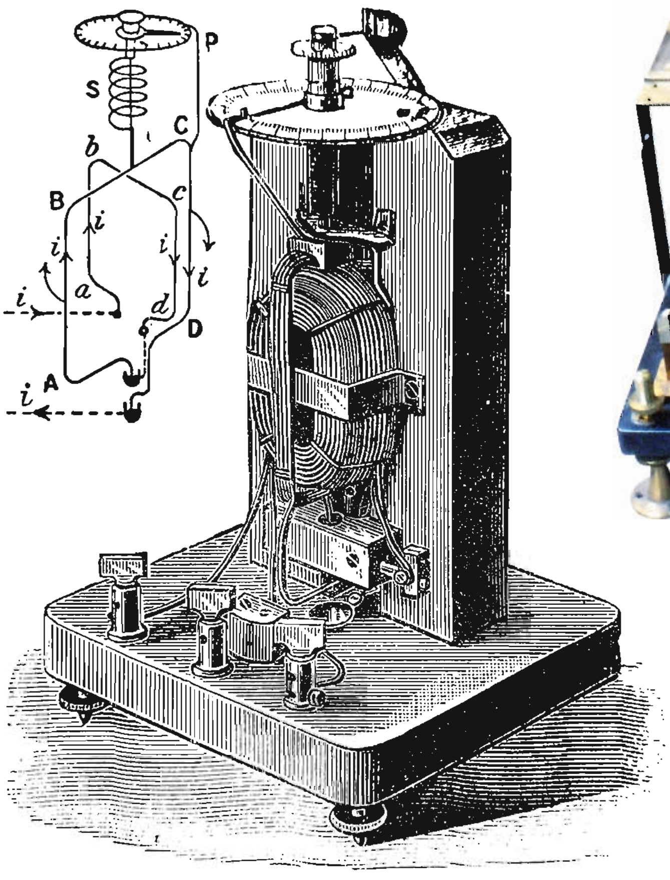
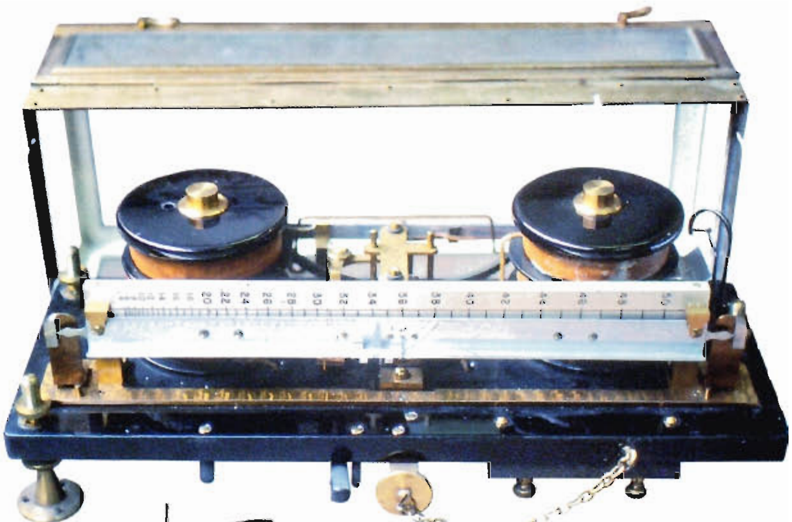


Fig 6: Siemens Electrodynamometer



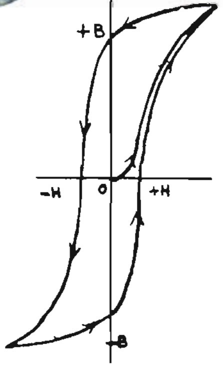


Fig 7 (above): Kelvin Current Balance (Glasgow University)
Fig 8 (left): B-H magnetisation curve

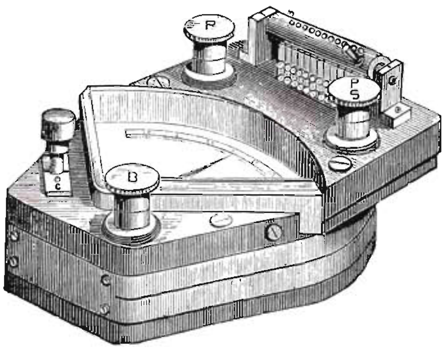


Fig 9a: Ayrton & Perry's first Am-meter

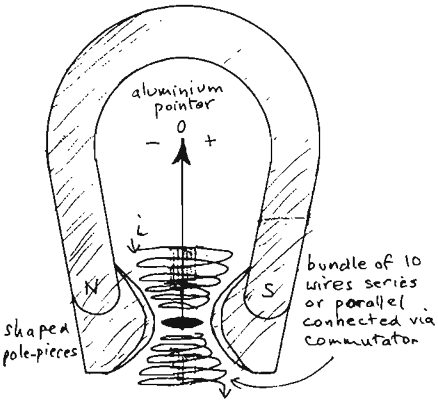


Fig 9b

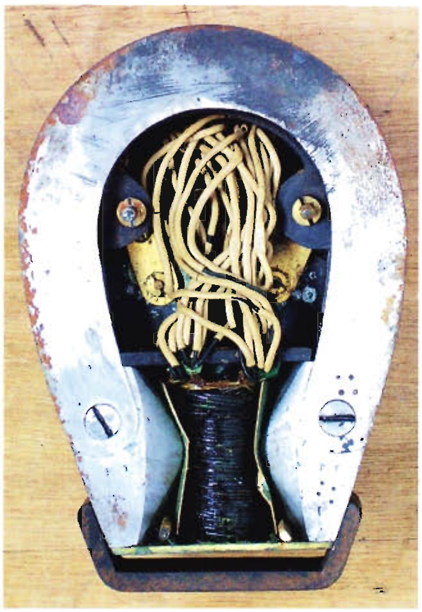


Fig 9c

Fig 9d

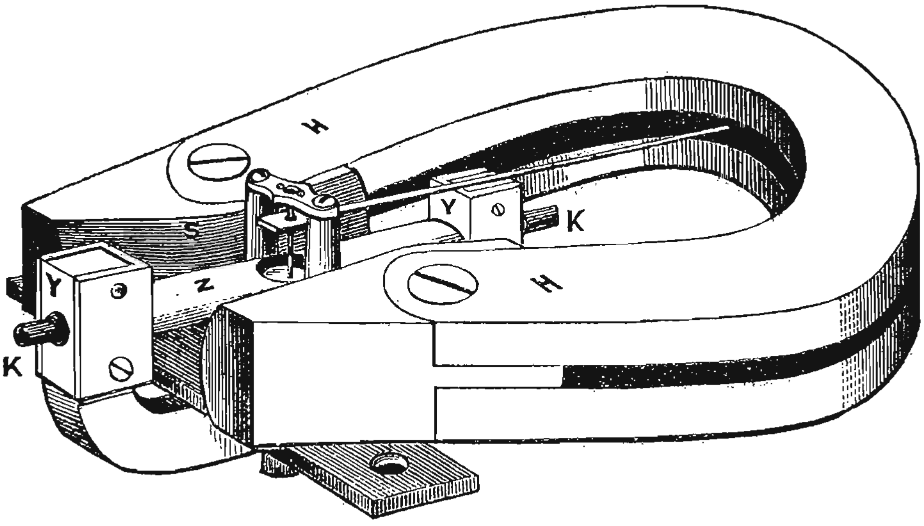


Fig 9e

because the coil's field is opposite here, augments its effect. This is the method used in the Siemens & Halske self-contained Wheatstone bridge shown in Fig. 3 where the second needle is also the pointer. Aluminium paddles inside the brass sectors above the pointer are attached to give air damping although this is quite inadequate.

The full astatic galvanometer utilises a second coil connected in series, but wound oppositely, which embraces the second needle (Fig. 4). In this galvanometer, by Nalder Bros & Co, London, bar magnets above and below can be rotated to control sensitivity, speed and zero position. The needles (Fig. 4d) each consist of four parallel pieces of magnetised watch hair spring.

Linesman's galvanometer

The other variant of the tangent galvanometer in widespread use over a long period was the linesman's galvo (Fig. 5). The earlier one is anonymous and has a full ±90° deflection whilst the WG Pye version of 1917 is restricted to ±70°. They have astatic movements with opposed central and front mounted needles, the latter acting as pointer. The controlling 'spring' is provided by gravity with the lower parts of the needles slightly heavier. The vertical coils of both instruments have bone former ends in the tradition of the philosophic instrument maker. The 'Q' (Quantity) terminals have a resistance of about 0.2Ω and are for current whilst the 'I' (Intensity) terminals are for voltage and are about 100Ω. Although relative comparisons can be made using tangents, the scale readings have no absolute reference.

Practical instruments

Most of the instruments so far discussed require levelling and separation from external magnetic effects, which in a power station may greatly exceed that of the earth's field. A practical instrument should, as far as possible, overcome these restrictions and should be robust. William Thomson (Lord Kelvin) devised many ingenious new instruments, although not always convenient in use. Ayrton, and his former students, Perry and Mather, also introduced many instruments which on the whole, were more practical. Other inventors of note include the Siemens brothers, the Varleys, Crompton, Evershed, Weston and many whose names attach to a specific instrument. Over the years most of these have been improved and many discontinued.

Electrodynamometers

The dynamometer principle harks back to Ampère who, a few weeks after Oested's observation in 1820, noticed that two parallel wires close to each other were attracted or repelled depending on whether the currents were passing in the same or opposite directions. Thus dynamometer instruments do not need magnetic material to operate.

Siemens dynamometer ammeter

The first direct-reading ammeter was introduced by Siemens & Halske in 1877 based on this *electrodynamic* principle (Fig. 6) although this principle had been used by Weber to make an absolute measurement of current in 1845 and refined versions for this purpose have continued up to recent times. The outer, moving, coil is set at right angles to the inner coil and is suspended by a torsion wire which provides the '*spring*' control. The electrical connections to it are made by mercury cups below ensuring good conduction with minimal friction.

The upper end of the torsion wire is attached to a rotating head with a pointer and scale. The moving coil has another pointer which should be at zero when the coils are at right angles with no current flowing.

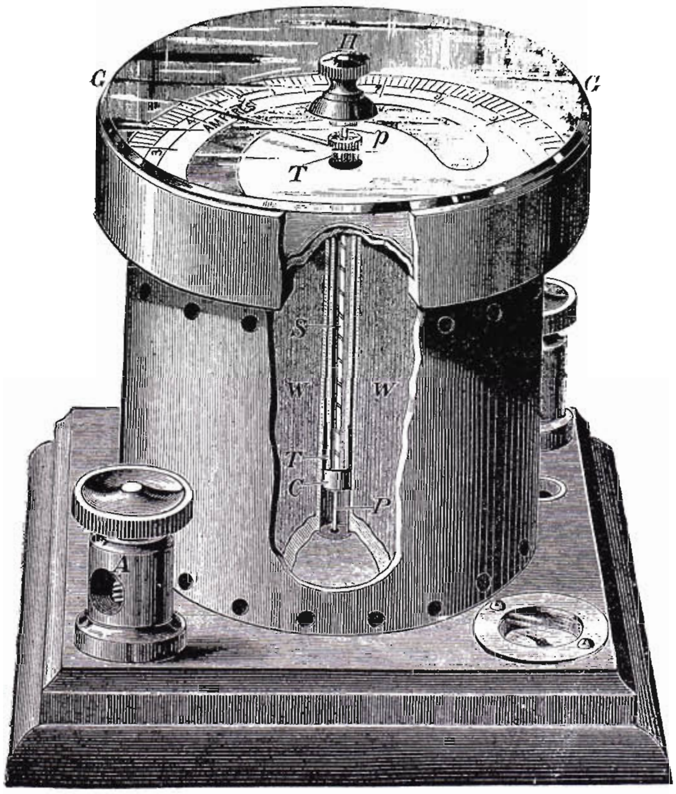


Fig 10a: Ayrton & Perry's Magnifying Spring Ammeter

Fig 10b

Current rotates this coil and pointer to a stop. The torsion head is then rotated to bring it back to the null position and the current read-off from the new position of the head.

As the current flows through both coils, the effects *multiply* and it is a *square-law* device, agnostic to the polarity, and thus suitable for both AC & DC. The scale therefore follows a square-root law which can be calculated to give accurate subdivision with 'open' readings at higher values. The overall sensitivity is set by the length and stiffness of the torsion wire. Although this was a widely used instrument it stretches the concept of direct-reading and was not ideal for use in the field.

Kelvin current balance

Another early *electrodynamic* instrument was William Thomson's current balance of 1887 (Fig. 7). Although this was produced commercially it was more practicable in the lab for calibrating other instruments. The magnetic forces between two moving coils, at the ends of a balance beam, and fixed coils above and below them are balanced by a weight moved along the calibrated beam. The moving coils are energised in the same sense (e.g. both N poles upwards) so that the effects of the earth's field are cancelled, whilst the four static coils are wired to give an upward force at one end and downward at the other. Several different models were produced for measurements from 10mA to 2,500A AC or DC.

Moving iron meters

Moving iron meters operate in a variety of ways, the simplest relying on a single piece of iron being pulled into a solenoid. By placing two or more pieces in close proximity within the solenoid the forces between them become lateral, across the axis of the solenoid. All pieces are magnetised in the same direction so, when placed in parallel, like poles are adjacent and repel. When placed end to end, opposite poles adjoin and they attract. For both types, both pieces of iron become magnetised in proportion to the current flowing so the effects multiply making them square-law devices equally suitable for AC or DC.

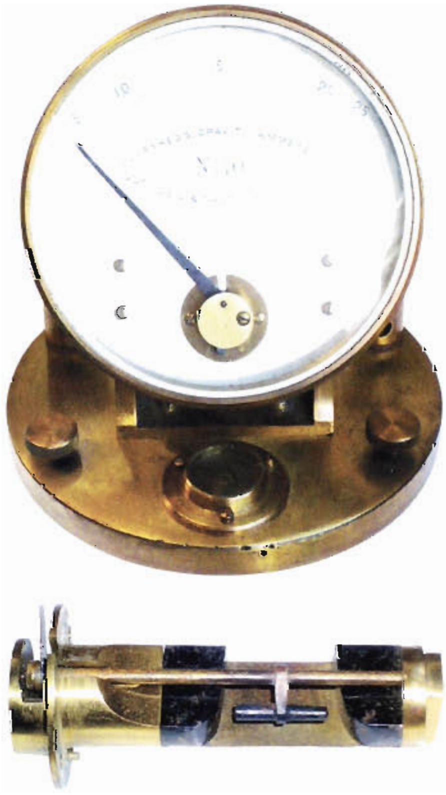


Fig 11a and b: Evershed's Gravity Ammeter (attraction)

Unfortunately the situation is more complex as the degree of magnetisation depends on the B-H curve (Fig. 8) in which the magnetisation B increases as the magnetic field H is increased but reaches a *saturation* point. When reduced back to zero, *permanent* magnetisation remains, which only returns to zero for a negative field. By continuing the process to negative saturation then returning to positive saturation a complete B-H curve is plotted. The slope of the curve represents the *permeability.* These curves exhibit non-linearity, saturation and *hysteresis* (magnetic backlash), which depend on the constitution and heat treatment of the magnetic material, and influence in turn how closely the AC and DC responses correspond. Nevertheless use of suitable materials and design within these restrictions has resulted in a very useful class of instrument.

Ayrton & Perry's first am-meter

(Bench use, 8.3cm scale linearly marked in degrees, 45-0-45, Paterson & Cooper, London No.263).

Ayrton & Perry described the concept of 'direct-reading' in 1881 illustrating it with a meter in which the scale readings were directly proportional to the current in Webers (Fig. 9a). This derives from the Deprez 'fishbone' galvanometer of 1880. Although the needle is soft iron it becomes magnetised by the strong permanent magnet and is thus more akin to a *tangent* galvanometer in which the earth's field is swamped by the much stronger field of the magnet. They claimed that linearity resulted from the special shape and proportions of their needle and pole pieces (Fig. 9b).

The deflecting coil was wound with

Fig 12a: Ediswan Gravity Ammeter (repulsion)

Fig 12b

Fig 12c

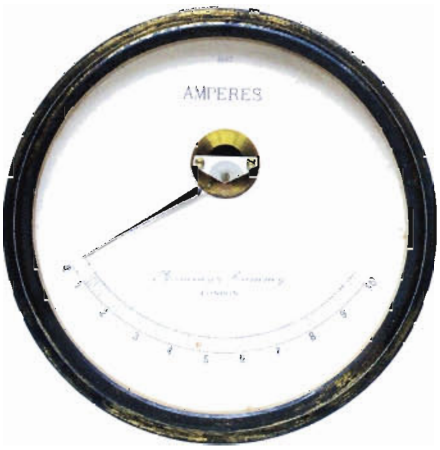


Fig 13a: Rumney & Rumney Ammeter (repulsion)

Fig 13b

ten-strand insulated wire (Fig. 9c) which could be connected in series or parallel by a commutator (Fig. 9d). This gives two ranges with sensitivities differing by a factor of ten, whose initial purpose was to allow calibration at a lower current than it was designed to measure. To do this a standard 1Ω resistance was incorporated and from the readings with and without this, and the known battery voltage, it was possible to calculate the sensitivity constant in Webers per degree.

By 1882 the unit of current became the *Ampere* instead of *Weber* and Ayrton & Perry had coined the names *ammeter* and *voltmeter* and had recognised the utility of the lower range for measuring lamp currents. They also introduced voltmeters and single range instruments of various sensitivities working on the same principle and others using spring control.

By 1884 they had devised a magnetic return path (Fig. 9e, Y-Y) to increase sensitivity and soft-iron cores (K-K) to allow adjustment to true direct reading. They claimed these cores also fully linearised the scale which was now inscribed in *amps* or *volts*. This would allow manufacturers to print scales and avoid individual calibration, a hope that was not fully realised for another 60 years.

Thus their 'Am-meter' made by Paterson & Cooper (Fig. 9c&d) must date from 1881-2. The strong field, acting as a stiff controlling spring, together with the use of a small needle and very light aluminium pointer (not a common metal in those days) results in a high resonance frequency of 11Hz or period of <0.1s. This speed was wasted because inherent damping is low and the pointer vibrates for about 4s. The instrument comes with a magnetic keeper which, contrary to a moving coil meter, increases sensitivity and reduces speed when in place. Even with its silver commutator contacts the resistance is variable at less than 0.1Ω in parallel and 0.4Ω in series giving voltage drop and power values of about 1.8V and 8W at fsd (full scale deflection).

Initially the instrument over-read by 27% up to half scale, implying a loss of magnetism. After remagnetising it now reads +1% up to half scale and -8% at fsd. Although this does not quite match Ayrton & Perry's claim it is two to three times better than the theoretical tangent relationship.

Ayrton & Perry's Magnifying Spring ammeter

(Bench use, 20cm 270° horizontal mirror-backed circular linear scale 15-75A, The Acme Electric Works, Ferdinand St, London No.S190).

This was patented in 1883 and operates on the *simple attracted iron* principle but in which the motion is greatly magnified by the unwinding of a helical spring (Fig. 10). A thin soft iron tube is suspended by an internal flat helical spring from a zeroing knob at the centre of the dial

Fig 14a: NCS Gravity Ammeter (repulsion)

Fig 14b

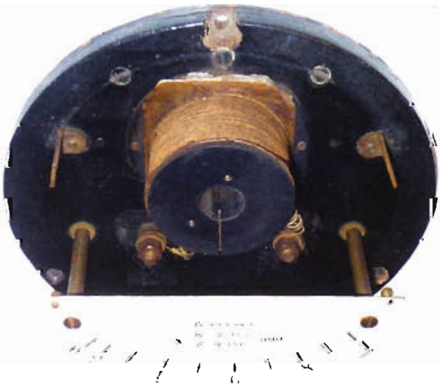


Fig 14c

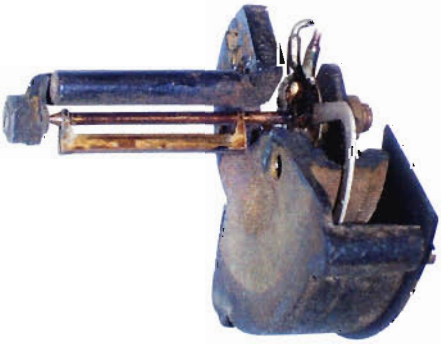


Fig 15: NCS Spring-controlled ammeter (repulsion)

Fig 15b

glass. The upper end of the tube carries a thin aluminium pointer which approaches the scale imperceptibly as it rotates. The lower end of the tube is supported by a pin sliding and rotating inside a bearing.

The attractive force is produced by a vertical solenoid of heavy gauge copper which pulls the tube downwards towards its centre. As the helical spring is stretched it unwinds, rotating the tube together with the pointer. The direction of the current is indicated by a small compass inscribed BLUE INWARDS WHEN A POSITIVE.

The instrument under-reads (-5.5±1.5% on DC and -30% on AC). Although the scale is individually marked, it appears to have been linearly interpolated between the calibrated positions at the extremes. The movement is underdamped with a period of 0.3s. The coil has a resistance of 5mΩ giving a maximum voltage drop of 0.37V and consumption of 28W at fsd.

Evershed's gravity ammeter

(Bench use, 9cm angled non-linear scale 0-25A Goolden & Trotter, Westminster No.10).

This probably dates between 1886 when Evershed joined the company and 1888 when it changed to WT Goolden & Co. In this design (Fig. 11) three pieces of soft iron (painted black) are situated inside a solenoid where they are each magnetised in the same direction by the current. Thus it is a *compound attraction* instrument as the forces are between the iron pieces where unlike poles adjoin. The two outer ones are fixed and shaped so that as the moving element is pulled backwards, the force tends to increase as the gaps decrease but to decrease as they come more in to line. This results in an open scale between 10 and 20A. The pointer and attracted rod are off balance so that *gravity* provides the restoring force and brings the pointer to zero when the instrument is level. Unusually for a gravity controlled movement it is tilted back at 30° for ease of reading as a bench instrument - a consideration almost unique among instruments I have come across. It is provided with levelling feet and a spirit level.

Fig 16: Current Transformers (a) Smith Hobson Ltd.

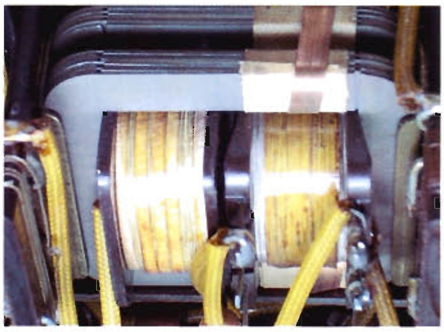


Fig 16b: AVO-7

On DC its accuracy is +1±3% partly owing to hysteresis (the present reading depending on previous readings) whilst on AC it is -2±1%. The response is underdamped with a period of 0.3s. It has a resistance of 68mΩ giving 1.7V and 42W at fsd.

Ediswan gravity ammeter

(Vertical bench use, 10cm non-linear scale 0-20A, Ediswan).

This meter (Fig. 12), which appears to date from about 1890-1900, works on the *repulsion* principle. The moving part consists of iron laminations (black) carried on a brass arbor with steel pivots in jewelled bearings and solid aluminium pointer. This is repulsed by a parallel bundle of iron wires packed inside the brass tube behind. The solenoid consists of about ten turns of 4.5mm diameter stranded copper wire. The instrument under-reads (on DC -10% at 4A and -3±2% between 7 & 20A and on AC -20% at 4A and -5±3% between 7 & 20A). It has an underdamped period of 0.4s, and a resistance of 36mΩ giving 0.74V and 14W at fsd.

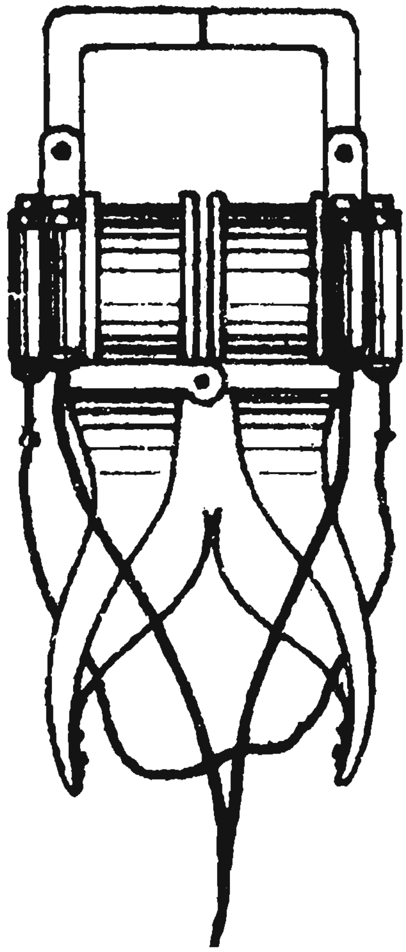


Fig 16c: clamp type

Rumney & Rumney amperes

(Wall mounting 14cm near-linear scale 0-10A, No.3665)

Like the previous meter this works on the *repulsion* principle but with *spring* control (Fig. 13). The fixed iron rod is soldered to the outside of the brass tube (Fig. 13b left side). This repulses a parallel rod causing the pointer to rotate, both rods extending the length of the solenoid of about 30 turns of 14SWG wire. As in most meters of this kind, the arbor is displaced from the axis of the solenoid to allow the necessary movement and scale law. On DC it under-reads slightly, -2±2%, but clearly is not intended for AC use at -11±2%. It has a period of 0.75s but with no damping takes about 30s to settle. Solenoid resistance is 12mΩ giving a voltage drop of 0.12V and power of 1.2W at fsd.

NCS gravity ammeter

(Wall mounting, 10cm non-linear scale 0-1A, indicated for 100~, R = 2.35Ω, Z = 4.15Ω, No.183943).

Like the previous meters it works on the *repulsion* principle but with gravity control. It uses solid iron parts and incorporates air damping by an aluminium piston moving within an annular dashpot, but is slightly underdamped (Fig. 14). Although indicated for 100Hz it over-reads only

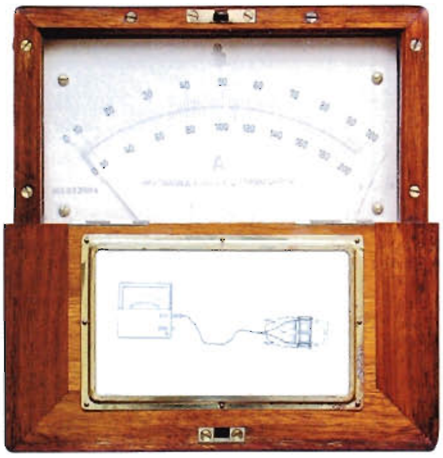


Fig 17a: Hartmann & Braun ammeter (repulsion)

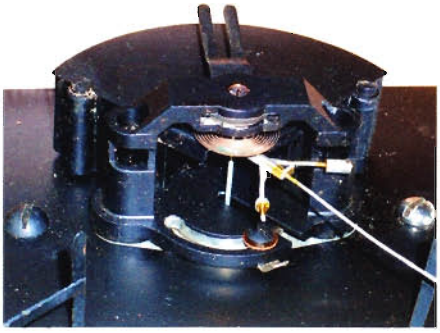


Fig 17b

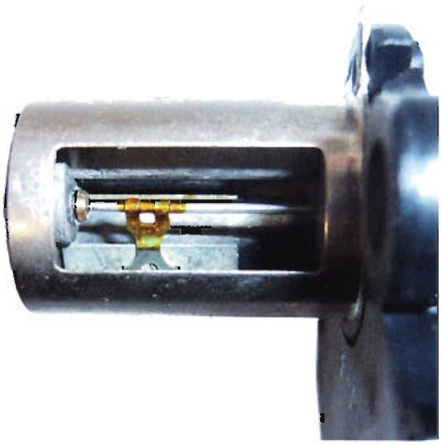


Fig 17c

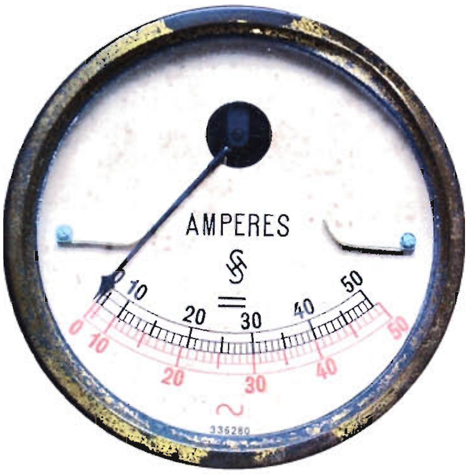


Fig 18a: Siemens & Haiske ammeter (simple attraction)

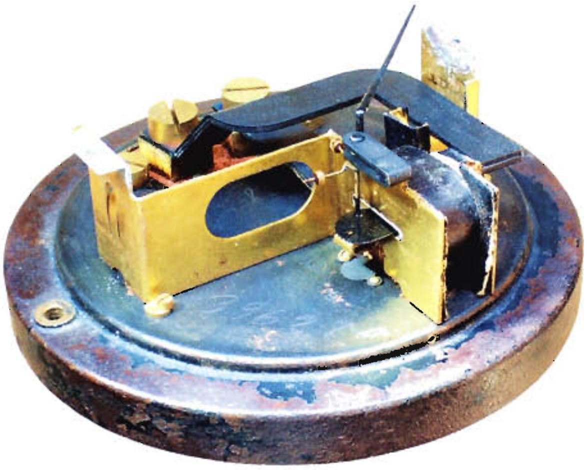


Fig 18b

slightly by +2±2% at 50Hz and +1±2% on DC with a resistance of 2.35Ω, voltage drop of 2.4V and power of 2.4W at fsd.

NCS spring-controlled ammeter

(Vertical bench use, non-linear scale for use with current transformer No.1077, 0-500A at 50~ using current transformer No. 1077, or 0-5A direct, No.131064).

This again works on the *repulsion* principle using bundles of iron wire with dashpot damping and balancing force provided by a hairspring with zero set lever in the base (Fig. 15). It over-reads by +3±1% on both AC and DC with direct connection. The response period is 1s under-damped, and resistance 60mΩ, giving 0.3V and 1.5W at fsd. Presumably with its lower serial number it is slightly earlier than the previous instrument. With no information on NCS I would guess at 1900 to 1920.

Current transformers

For high current and multiple ranges on an AC ammeter it is necessary to employ a current transformer. This is because the solenoid of a moving iron instrument has an impedance containing a significant inductive component which it would be necessary to match pro-rata in each shunt. Matters are worse for moving coil meters, where rectifiers are used to measure AC, as the series resistance is highly dependent upon the current.

The current transformer 'kills two birds with one stone'. It not only circumvents the above problems but reduces the fsd voltage drop in proportion to the current range. We are familiar with the impedance converting properties between an output valve and a low impedance loudspeaker, $\mathbf{Z_{in} / Z_{out} = n^2}$, where **n** is the turns ratio. The voltage is reduced by a factor **n** whilst the current is increased by the same factor n. In an ideal transformer with infinite self inductance and zero leakage inductance its impedance would be zero with its secondary short-circuited, and infinity with its secondary open-circuited. Ideally no power is dissipated in the transformer, and that consumed by the meter remains the same on all ranges.

In fact, as seen in the first Ayrton & Perry Ammeter above and the Weston Ampèremeter below it is possible to provide multiple ranges by using multifilar windings. It is not, however, possible simply to use separate windings as in a transformer because, with an 'open' magnetic circuit, and in the words of *Animal Farm*, 'some turns are more equal than others'. At the other extreme in the case of Sullivan's Inductive Voltage Divider (BVWS Bulletin **35** (4) p.28), by using multifilar windings and efficient toroidal cores, ratios could be specified to 2 parts in 10^8.

Fig.16 illustrates three types: (a) is a four range example by Smith Hobson Ltd (No. 67846) for use with a 5A 50~ AC meter and should work satisfactorily with the NCS meter above. This then gives ranges of 10, 20 or 50A via the terminals or, by passing the current conductor through the hole in the centre, 500A. Presumably, the transformer core encircling the hole will be standard transformer alloy either as a stack of flat stampings with holes in the centre or as a long rolled-up strip, the copper turns being wound round this as a toroidal transformer. The large size is needed to achieve a high inductance with few turns and it is rated at 7.5VA.

Fig. 16(b) illustrates an instrument transformer from an AVO 7 multimeter giving current ranges of 0.01, 0.1, 1.0 and 10A. In this case the high inductance is obtained by using a high permeability core material such as mu-metal. This also allows it to be used over a large range of frequencies, in this case 15Hz to 15kHz.

Fig. 16(c) illustrates the clamp type transformer in which the core is in two halves held together by a spring which can be opened by the handles to clamp it round a live conductor without disturbing the circuit. The meter can be attached by leads as here (for the following instrument) or it can be an integral item.

Hartmann & Braun

(Vertical or horizontal bench use 14cm scale separately calibrated 0-100A, 0-200A, 50Hz Hartmann & Braun A-G, Frankfurt a/M No.1072004)

This meter (Fig. 17) is again a *repulsion* type with dashpot damping for use with a current clamp transformer. In this case the two ranges are obtained using different sets of terminals. As its transformer is missing it is not possible to test it meaningfully. It is spring controlled and dashpot damped. One of the rectangular repulsion plates is attached radially to the rotating arbor whilst the

Fig 19a: Weston Ampéremeter (repulsion)

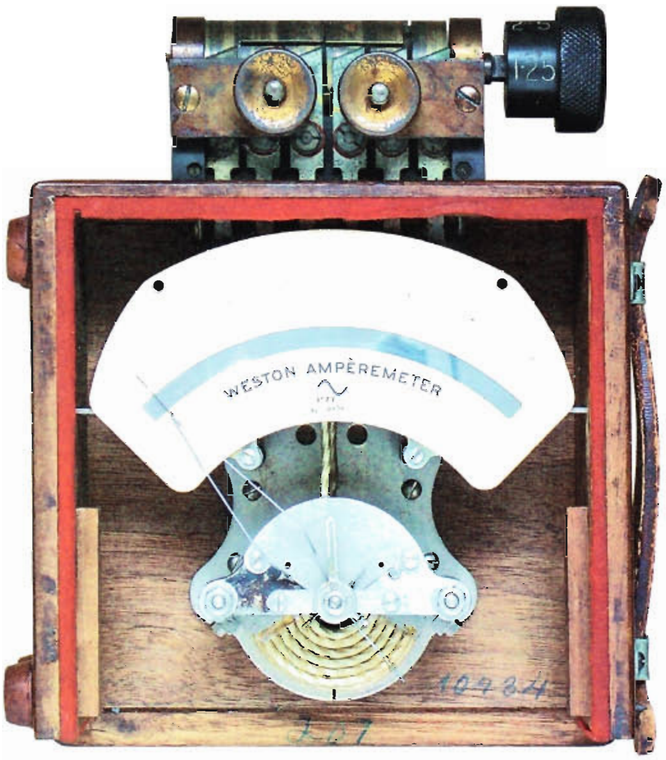


Fig 19b

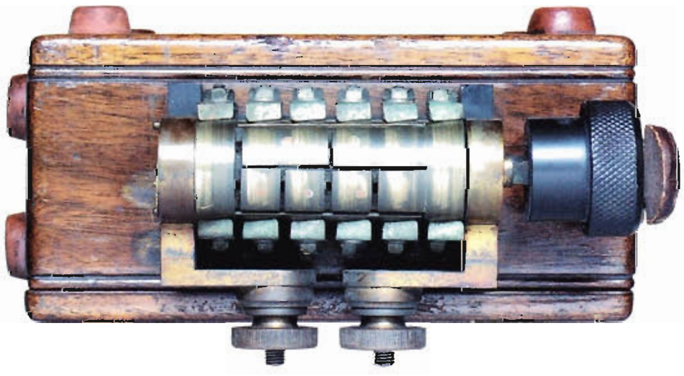


Fig 19c

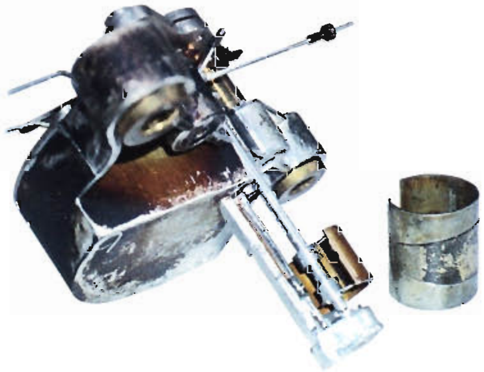


Fig 19d

other (seen edge-on in Fig. 17c) is attached radially inside a plated brass canister which can be rotated (after loosening a screw in an annular slot seen in Fig. 17b) to adjust sensitivity. Period 2s, near critical damping.

Siemens & Halske
(Wall mounting, 8cm scale separately calibrated 0-50A black DC and red AC, SH No.33680)

This is a *gravity* controlled *simple attraction* type with a shaped vane pulled into a narrow slot in a solenoid of four turns of triple thickness copper strip (Fig. 18). The shaping of the vane results in an almost linear scale between 10 and 50A. The period is about 0.6s with no damping provided. It has a resistance of 0.5mΩ, and voltage drop of 25mV and fsd power of 1.25W.

Weston Ampéremeter
(Horizontal bench use, 13cm scale nonlinear 0 - 100, ranges 1.25, 2.5 & 5A. Weston Electrical Instrument Co, Newark, NJ, USA. Model 155, No.10434)

This is a three-range *repulsion* spring-controlled ammeter based on a number of Weston patents from 1888 to 1901 with cylindrical elements centred on the axis of the solenoid (Fig. 19). The moving half-cylindrical shell (Fig. 19d) rotates towards the camera from the tip end of the encircling tongue-shaped ferrous piece set into a brass cylindrical shell fixed to the aluminium support. Magnetisation occurs along the axis so that, say, N poles are towards the pointer. It is spring-controlled and dash-pot damped and indicated for AC.

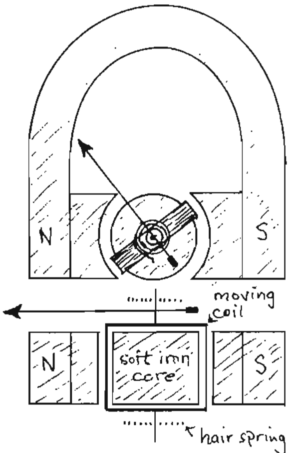
The solenoid is wound with four-strand insulated wire which can be interconnected by the commutator switch in series (1.25A), series-parallel (2.5A) or fully parallel (5A). It over-reads by +2+1% on AC and DC. Period 1s critically damped by dashpot; resistance 0.8, 0.3 & 0.1Ω respectively; 0.5-1V & 1.25W at fsd.

Moving coil ammeters
A *moving coil* meter works on the same principle as a *moving magnet* instrument but with fixed and moving parts interchanged. The new geometry, however, results in a much greater efficiency as revealed by the power at fsd.

A rectangular coil is situated in an annular gap between a central soft iron cylinder and the shaped pole pieces of a permanent magnet (Fig. 20a). This very small gap in the magnetic circuit gives a very high flux density. The coil is mounted between jewelled bearings with hair springs to lead the current in and out and to provide the restoring force. Because the field in the annular gap is uniform and the spring torque is proportional to the deflection, the scale is linear, but limited to DC unless a rectifier is added.

Although the form of instrument with which we are familiar derives from a design patented by Edward Weston in 1888, its origins are much earlier. In 1856 CF Varley patented a very similar design, in 1867 Thomson patented his siphon recorder, part of which is a moving coil galvanometer. Its form as a galvanometer is due to d'Arsonval and Deprez in 1881-4 with improvements by Ayrton and others. The Weston meter was slow to be adopted because of expense, but ultimately became supreme. In 1903 Robert Paul introduced the *Unipivot* version which reduced friction.

For an ammeter it is desirable to fill the available coil space with few turns of thick wire to produce a low *voltage drop* at fsd whilst for a voltmeter the highest number of the thinnest wire turns should be used for a *low current* at fsd. For a given amount of copper the power at fsd should be the same.



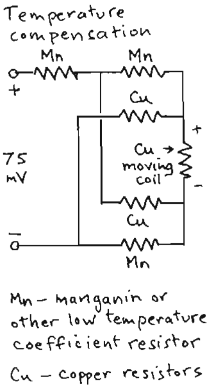


Fig 20a: Elliott Moving Coil Ammeter (Weston)

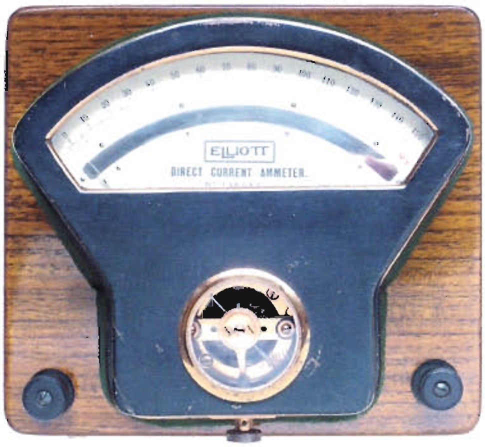


Fig 20b

Fig 20c

Elliott Direct Current Ammeter
(Bench use, 13cm linear scale marked 0-150, 75mV for use with external shunts 3, 15, 150, 750, 1500A (missing). Elliott Portable Standard Ammeter No.130932, certified 0.5% accurate 9.Nov.1921).

Elliott Bros were agents for The Weston Electrical Instrument Co, who manufactured this spring-controlled *moving coil* instrument (with Weston serial number prefixed by '1'). An interesting inclusion is a temperature compensation network using, presumably, copper and manganin resistors (Fig. 20, inside magnet). For current measurements with a shunt, a constant *voltage* sensitivity is required. The copper cross-coupling resistors reduce the sensitivity by a factor of about five, but less at higher temperatures, counteracting the reduction of reading due the increase in coil resistance. The resulting temperature coefficient was measured at 0.3%/10°C compared with 3.9%/10°C uncorrected.

As found the sensitivity was too high (69.8mV instead of 75mV fsd) but could be adjusted by sliding the copper plated magnetic shunt further across the magnet (Fig. 20c). Period 1s critically damped, impedance 1.6Ω, 44mA and 3.5mW at fsd with network (17.6mA, 13.4mV & 0.24mW direct).

DC Shunts
As indicated above, the range of an ammeter can be extended by the use of shunts. A low resistance is used to short-circuit the movement taking say 99% of the current and allowing 1% through the meter giving, in this example, a range multiplication of 100. This does, however, introduce certain problems. The most obvious perhaps is that switch contact resistance variability may not be negligible compared to the shunt. This can be avoided by using the principle of *4-terminal* connection, separate connections for the current and to the meter, although in a multirange instrument with a common terminal, it can be achieved with three switch contacts.

An alternative first described by Ayrton for use with galvanometers and adopted in the AVO, is the universal shunt. In this, the shunts are connected in series, with the meter movement permanently connected to the two ends, the neutral terminal to the high current end, and the live terminal to one of the junctions via a selector switch. Thus the shunt becomes the sum of the resistors to that point whilst the shunted resistance is the sum of the remainder plus movement resistance. Each shunt has to be able to carry the current up to that point. One disadvantage of using a universal shunt is that more voltage than necessary is dropped across the instrument.

Unfortunately the best practicable conductor, copper, increases in resistance by 3.93% for a 10°C temperature rise. Thus if the shunt resistance remains constant, the readings will be about 4% high at 10°C and 4% low at 30°C ambient temperatures. The answer might appear to be to make the shunt out of copper but with its high conductivity this would physically be very large. Furthermore, the greater problem is that considerable power will be dissipated in the shunt which will rise well above ambient temperature. Thus for the higher currents, which also require special terminals and switch contacts, it is normal to use external shunts made from a suitable alloy.

The earliest resistance materials were alloys of expensive metals such as platinum, iridium and silver or the much cheaper *German silver* (55-60% copper, 20-25% nickel, 20% zinc). Their temperature dependence was still rather large, although less than for copper. This led Edward Weston to develop *constantan* (60% copper, 40% nickel; *eureka* is similar 57% copper 43% nickel) which although excellent, suffered from high thermoelectric contact potentials. So in 1892 Weston went on to develop *manganin* (84% copper, 12% manganese, 4% nickel) which has a temperature coefficient of about 0.02%/10°C (20ppm/°C) and remained the standard resistance material for a century.

Everett Edgcumbe sub-standard ammeter
(Horizontal bench use 14cm scale marked 0-15 & 0-150A, ranges and shunts 1.5, 3.0, 7.5, 15, 30, 60, 300 & 450A all at 0.2V, calibration certificate 19.3.54. No.522352)

This is another high quality *moving coil*

Fig 21a: Sub-Standard Ammeter (Everett Edgcumbe)

Fig 21b

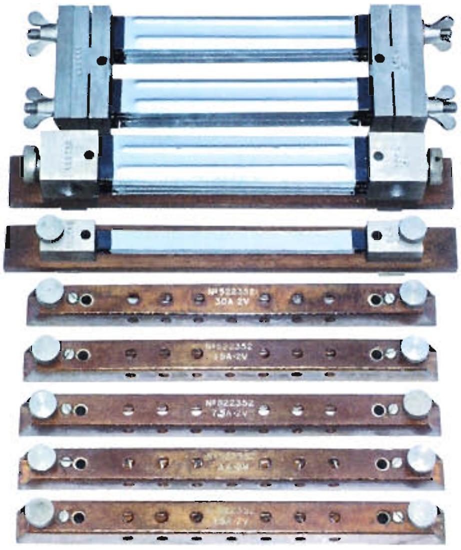


Fig 21c

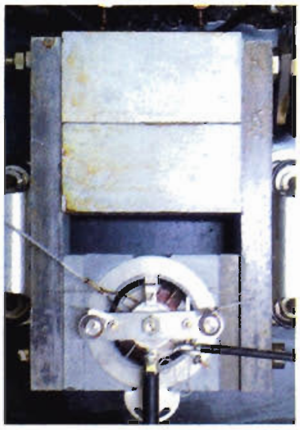
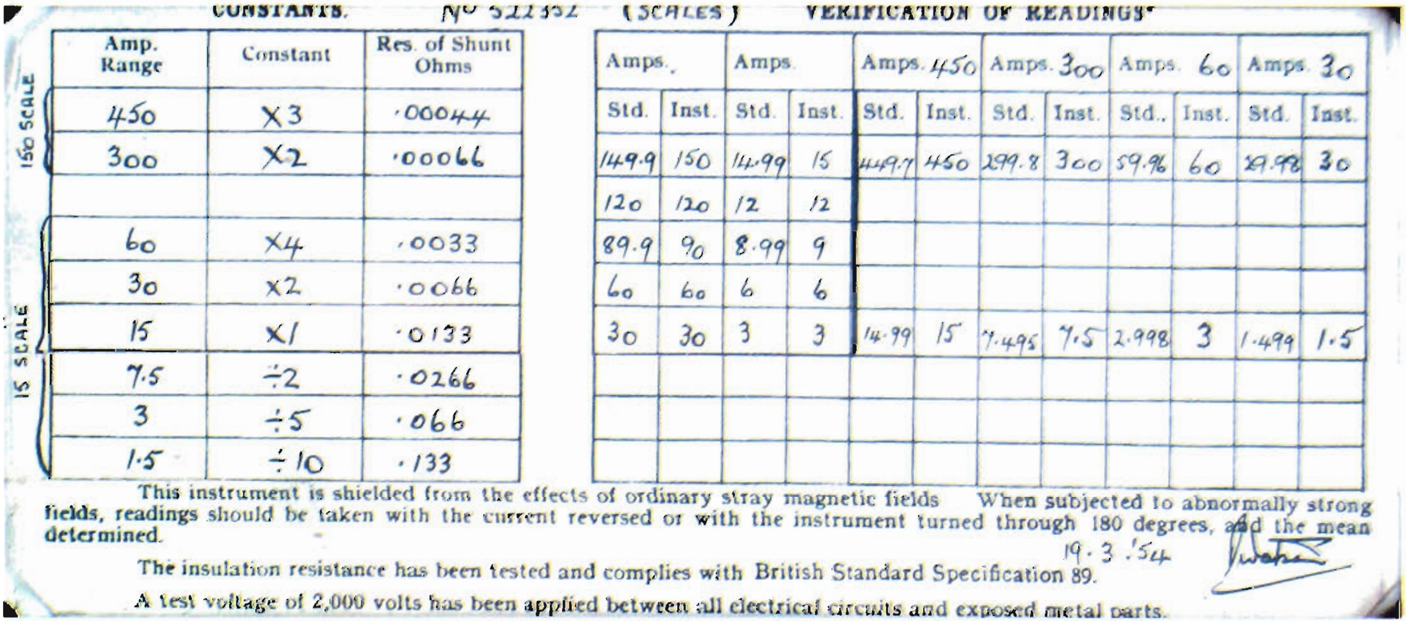


Fig 21d

instrument graded as Sub-Standard (the grades below being Precision and Industrial, the AVO normally being Industrial grade). It is supplied with eight four-terminal shunts (Fig. 21) which appear not to be manganin. The current terminals, which differ according to current range, are integral with solid blocks of brass, whilst the voltage leads to the meter are via plugs inserted in holes in these blocks.

The certificate on the base (Fig. 21e) shows on the left of the right-hand grid, the current flowing when the instrument indicates 30, 60, 90, 120 & 150 (3, 6, 9, 12 & 15) showing its linearity, whilst the right hand columns show the actual currents at fsd with each shunt. These indicate that the meter over-read by 1 part in 1500 (0.07%). A recent check indicates that it now under-reads by about 0.2%. Surprisingly the influence of temperature is not specified. Tests indicate that the 1.5A shunt has a coefficient of about +0.12%/10°C and the meter (~10Ω movement plus 40Ω series resistor which may have a slight negative coefficient) about +0.57%/10°C giving a net ambient dependence of 0.45%/10°C (i.e. under-reads with temperature rise and is inferior to the Elliott/Weston above). The meter movement takes about 4mA, consuming 0.16mW at fsd. With its shunts, however, it ranges from 0.3W at 1.5A to 90W at 450A fsd.

Whilst it would be logical to discuss milli-ammeters and micro-ammeters here, these will be included later when describing instruments more suitable for the radio and electronics field. Any corrections or further information on dating would be most welcome.



CONSTANTS. Nº 522352 (SCALES) VERIFICATION OF READINGS.

150 SCALE

15 SCALE

Amp. Range	Constant	Res. of Shunt Ohms
450	X3	·00044
300	X2	·00066
60	X4	·0033
30	X2	·0066
15	X1	·0133
7.5	÷2	·0266
3	÷5	·066
1.5	÷10	·133

Amps.		Amps.		Amps. 450		Amps. 300		Amps. 60		Amps. 30	
Std.	Inst.	Std.	Inst.	Std.	Inst.	Std.	Inst.	Std.	Inst.	Std.	Inst.
149.9	150	14.99	15	449.7	450	299.8	300	59.96	60	29.98	30
120	120	12	12								
89.9	90	8.99	9								
60	60	6	6								
30	30	3	3	14.99	15	7.495	7.5	2.998	3	1.499	1.5

This instrument is shielded from the effects of ordinary stray magnetic fields When subjected to abnormally strong fields, readings should be taken with the current reversed or with the instrument turned through 180 degrees, and the mean determined.

19.3.'54

The insulation resistance has been tested and complies with British Standard Specification 89.

A test voltage of 2,000 volts has been applied between all electrical circuits and exposed metal parts.

Fig 21e