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Measuring Electrical Current: The Roads Not Taken

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Recently I wrote about the standard Weston meter movement\textsuperscript{1,2} that is at the heart of all modern analogue current measurements. Now I will discuss other techniques used to measure electric current that, despite being based on valid physical principles, are largely lost in technological history.

The coulometer

The first commercial electrical power distribution system was set up in 1882 by Thomas Edison's Edison Electric Illuminating Company on Pearl Street in Lower Manhattan. This was a direct current system, with dynamos powered by steam engines. The distribution system was based on the model provided by the illuminating gas systems in common use, with large mains close to the source and smaller pipes branching off. Large copper conductors led from the power station, and the distribution wires became smaller as they branched out to the individual users.

In the rush to get the system up and running, Edison and his staff did not have time to design individual power meters for each user. Instead, they used the somewhat awkward coulometer system shown in Fig. 1.\textsuperscript{3} The key element is the zinc electroplating system, with electrodes of zinc suspended in a bath of zinc sulphate. At regular intervals the cathode was weighed to give the amount of zinc deposited on it. A straightforward calculation, based on the fact (well established by the 1880s) that 96,500 coulombs are needed to deposit one gram-atomic weight of zinc (65.4 g), gave the total charge delivered to the consumer. The energy consumption in watt seconds was obtained by multiplying this amount of charge by the voltage across the meter.

The instrument in Fig. 1 was used in a three-wire system, so there are two circuits, one on either side of the neutral wire. Only a fraction of the current passes through the electroplating bath, while the rest passes through the heavy German-silver shunts at the top of the instrument. This technique is the standard arrangement for ammeters today. There was an inevitable voltage drop in the direct current transmission lines, and the voltage had to be measured directly at the meter. At the power station another sort of current-measuring device was used, and this is discussed in the last section of this paper.

The tangent galvanometer

I have written previously about the tangent galvanometer\textsuperscript{4} and so will give only a short description of it. Just as in the case of the moving coil meter movement developed by D'Arsonval and refined by Weston, there is an interaction between a magnetic field and an electric current. In the case of the moving coil meter, the magnetic field is supplied by a relatively large, fixed permanent magnet, and the coil carrying the current under test pivots on jeweled bearings. In the tangent galvanometer, the fixed element is the coil, which is oriented in the magnetic north-south plane. The magnet is reduced to a light compass needle that pivots in the magnetic field of the coil. This arrangement can be small, with a coil only a few tens of centimeters in diameter, or it can be as large as the instrument in Fig. 2, built at Cornell University by William A. Anthony (1835-1908) in the mid-1880s and used to calibrate other ammeters. Its range was 0.1 A to 250 A, and it was housed in a wooden building with nonmagnetic fastenings. Recently I

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Fig. 1. Coulometer of the type used in early Edison direct current installations.\textsuperscript{3}

Fig. 2. Cornell galvanometer, from Scientific American, 9/19/1885.

Fig. 3. A coil from the great Cornell tangent galvanometer, held up by Vince Kotmel, who is well over 6 ft in height.
discovered the coils from this instrument, carefully preserved in the attic of Rockefeller Hall, the Cornell physics building (Fig. 3).

An interesting variant of the tangent galvanometer is the small meter I made for my children 35 years ago, based on a model demonstrated by an overseas participant in a PSSC summer workshop at Rutgers University in the summer of 1960 (Fig. 4). The coil is wound on a section of a round oatmeal box, and the bar magnet, taken from a magnetic clasp of an eyeglasses case, is suspended by a strand of thin nylon monofilament fishing line.

**The moving magnet meter movement**

In my scientific travels I have discovered a number of meter movements of the type shown in Figs. 5 and 6. Inside the coil carrying the current to be measured is a bar magnet, pivoted at the middle and with an indicating needle attached at this point. An example of the lecture-table galvanometer in Fig. 5 is still in use at Cornell University, except that the scale has been painted red and white to enable it to be seen more readily in the lecture hall. With no current passing through the coil, the magnet is horizontal; a current causes a torque that rotates the magnet. The counter-torque is provided by a nonmagnetic mass hanging below the bar magnet.

The instrument in Fig. 6 is usually called a Breguet galvanometer, after the French watch and instrument maker and scientific experimenter Louis Breguet (1804-1883). As an aside, he made the slotted wheel that Leon Foucault used to make his 1850 measurement of the speed of light. In this galvanometer, the coil is circular and horizontal, and the bar magnet is mounted on a flat copper ring pivoted horizontally within the coil. The ring serves to provide eddy current damping so that the needle comes to rest rapidly. If the deflection is small, instruments of this type are reasonably linear, as the sine of the angular displacement of the magnet is related to the current of the coil, and for small angles the sine may be approximated by the angle.

**Solenoid-type ammeters**

In the early days of the electrical power industry, every component had to be designed from scratch: generators, motors, light bulbs and their sockets, switches and voltmeters,
and ammeters. Patent infringement was common, with the systems being put in place first and the legal issues sorted out later. However, the Edison system did avoid infringing on Weston's patents for the moving coil movement by using the instrument in Fig. 7 in the power station.

The direct current to be measured passes through the curved solenoid, and the resulting magnetic field exerts a force on a curved, soft iron slug on the end of the semicircular segment of wire. The other end of the wire is attached to the pivoting needle mechanism. The iron in the slug is magnetized to saturation almost immediately, so that the magnetic force is related directly to the current through the solenoid. The restoring force on the slug is supplied by the gravitational force acting on it. This instrument was designed for power plant use and reads 172 amperes full-scale deflection. The solenoid coil is made from wire 1.0 cm in diameter to carry the heavy current without heating up appreciably. Note that this instrument does not use a shunt; all of the current passes through it. Calibrating it from first principles is clearly quite difficult, and external standards must be used. For example, a standard resistor is placed in series with the instrument, and the voltage drop across it is measured with a potentiometer to compute the current using Ohm’s law.

The patent was granted to Montgomery Waddell, of Ontario, Canada, who assigned it to himself and William S. Andrews. Andrews (1847-1929) built 30 generating stations for the Edison Company during his career as an electrical engineer. The design must have been satisfactory, for the instruments were used in power stations for many years.

Coda

None of these instruments can be considered to be failures. In the rapidly developing electrical technology of the 1880s, multiple methods of current measurements lay before the practical engineer, but once the final decision to use the moving coil meter was made, there was no turning back. But in teaching students about the physics of current measurements, it is possible to “take the road less travelled by.”

References
7. In the spring of my senior year at Amherst College, I went to hear a poetry reading by Robert Frost (1874-1963). One of the poems that he recited was “The Road Not Taken” from 1920. This, with its final line, “I took the one less traveled by, And that has made all the difference,” has been the inspiration for the title and last line of this article and, in a larger sense, for a career of studying early physics apparatus.

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