newsletter

OF THE JAMES CLERK MAXWELL FOUNDATION, EDINBURGH

Issue No.14 *Spring 2020*

ISSN 2058-7503 (Print)
ISSN 2058-7511 (Online)

Maxwell's contribution to standardising the unit of electrical resistance

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(Based, with permission of IEEE, on Grant P.M. and Thompson J.S., (2019), *'Standardization of the Ohm as a Unit of Electrical Resistance, 1861–1867', Proceedings of the IEEE*, Volume 107, Issue 11, pp. 2281–2289, DoI:10.1109/JPROC.2019.2945495)

Introduction

The first working electrical telegraphs were built in the 1830s. They were adopted for land-based communication prior to the laying of the first undersea telegraphic cable across the English Channel and then across the Atlantic Ocean.

However, a string of failures on long distance undersea cables led to the acceptance of a need to measure, accurately, the resistance of both the wire and its attendant insulation. Prior to 1860, there was no widely-accepted system of electrical units or standards.

Telegraphic Communication

The early work on telegraphs is due to Francisco Salvà Campillo in Barcelona and Pavel Shilling in St Petersburg. In 1833, Carl Fredrich Gauss and Wilhelm Weber, in Göttingen, are credited with the construction of one of the first *practical* electromagnetic telegraphs, which operated over 1km, taking signals between Gauss' Astronomical Observatory and Weber's laboratory. In 1837, William Cooke and Charles Wheatstone, in London, subsequently introduced the first *commercial* telegraph.

In 1841, with the opening of the Great Western Railway by Isambard Kingdom Brunel, there was a growing need for more effective methods for long distance communication.

Figure 1: *Siemens pointer electric telegraph, courtesy Museum at the Siemens Munich HQ*

In 1847, Werner Siemens developed his pointer telegraph (*Figure 1*). In 1848, he built the first long-distance telegraphic line from Berlin to Frankfurt, a distance of some 500 km.

These early electric telegraphic systems could be used with either overhead wire or cable transmission. They were often associated with railway communication and signalling.

In 1850, the 'Submarine Telegraph Company' in England, laid the first undersea telegraphic cable across the English Channel. It was comprised of simple copper wire insulated with gutta-percha (a type of rubber). This was unsuccessful as it lacked outer-armouring. The next year, a cable with an armoured outer-core was laid to give protection from damage by ships and anchors. By 1853, further cables linked Britain with Ireland, Belgium and the Netherlands.

A string of failures on the early cables led to more care being taken, in testing the quality of the conductor, in assessing the gutta-percha insulation and in improving techniques for the localisation of the (inevitable) faults in the installed cables.

The first attempt at laying a *transatlantic* telegraphic cable was made in 1857 but the cable broke precipitately. This inspired Maxwell, with his pawky sense of humour, to write a poem of which this is an extract:

The Song of the Atlantic Telegraph Company
No little signals are coming to me,
Something has surely gone wrong,
And it's broke, broke, broke,
What is the cause of it does not transpire,
But something has broken the telegraph wire,
With a stroke, stroke, stroke.

In 1858, the 'Atlantic Telegraph Company' finally succeeded in linking Ireland to Newfoundland by undersea cable without *'something breaking the telegraph wire'.*

On August 16, 1858, a congratulatory message from Queen Victoria was received by the President of the United States, James Buchanan. The Queen's ninety-eight word message took sixteen hours to transmit! The President replied and this first official telegraphic exchange over the newly laid transatlantic cable ignited a great celebration in New York. Regrettably the cable was only operational for just one month.

In the 1850s and early 1860s, telegraphic coded messages were limited to only two or three words per minute. On shorter route submarine cables, much higher rates of some twenty words per minute were typically achieved by the early 1870s.

Figure 2: *William Thomson, Lord Kelvin, by kind permission of the Master and Fellows of Peterhouse, University of Cambridge.*

Attempts in 1865 and 1866 used a more advanced cable design and produced the first *successful* transatlantic cable. William Thomson (*Figure 2*) – later Lord Kelvin – sailed on the cable-laying expeditions of 1857, 1858, 1865 and 1866 resulting in an operational cable. The principals of the project were knighted by Queen Victoria in November 1866 in recognition of this significant technological advance.

In these long-distance undersea cables only a very small current reached the receiver, which was often operated using a galvanometer.

To further exploit his inventions, Thomson entered into a partnership with Cromwell Varley, the chief engineer of the 'Electric and International Telegraph Company'. Varley was a member of the 1859 Joint Committee between the 'Board of Trade' and the 'Atlantic Telegraph Company' which advised the Government on cable projects and investigated cable failures.

The other partner was Maxwell's former Edinburgh Academical schoolfriend, Fleeming Jenkin (*Figure 3*), a distinguished engineer who had been responsible, in 1855, for fitting out the 'Elba' cable-laying ship at Greenock.

Varley was an astute businessman and the partnership that he had formed with Thomson and Jenkin (who, by this time, held between them more than 35 international patents) used their respective telegraphic inventions and yielded significant personal profits.

Figure 3: *Fleeming Jenkin, courtesy University of Edinburgh.*

Fleeming Jenkin was, for several years, the engineer in charge of international cable laying operations.

By the late 1860s, telegraphic cables comprised (a) one across the Atlantic (b) several across the English channel and Irish sea and (c) others spanning the Mediterranean ocean.

These installations grew rapidly to satisfy the requirement for efficient rapid long distance communication. In 1866, Jenkin delivered the public 'Cantor Lecture' on 'Submarine Telegraphy' to the Royal Society of Arts. The map (*Figure 4*) shows the subsequent state of the international cable deployments connecting Great Britain with its colonies in India, the Far East, Australia and New Zealand.

In 1868, Fleeming Jenkin was appointed as the first Regius Professor of Engineering at the University of Edinburgh. Clerk Maxwell, FRS, FRSE published his two volume *'Treatise on Electricity and Magnetism'* in 1873 and Fleeming Jenkin, FRS, FRSE published his, more introductory, *'Electricity and Magnetism'* in 1876.

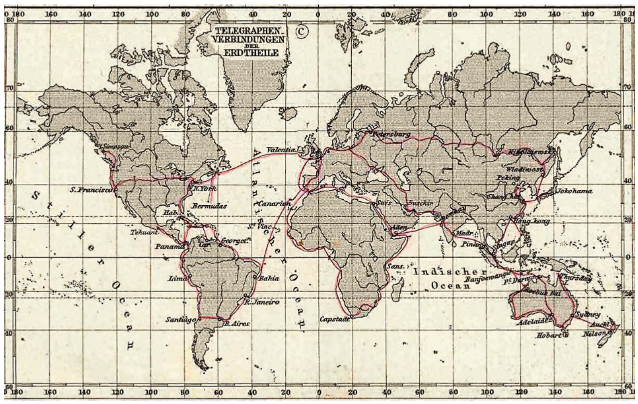

Figure 4: *This German map of 1891 shows the extent of global telegraphic cables, after Wikipedia.*

Cable Constraints

Telegraphers and other early users of electricity needed a practical unit of measurement for resistance. Resistance was often expressed as a multiple of the resistance of a standard length of telegraph wire and units were not readily interchangeable. Electrical units were not coherent with the units of mass, length, and time. The rapid rise of intercontinental telegraphy and electrotechnology created a demand for a coherent and agreed international system of units for electrical quantities.

Retardation (distortion)

In the 1850s, Faraday and Thomson had shown that the capacitance of the cable caused 'retardation' (later called 'distortion') of the transmitted pulses. Thomson then established the theory of such signal transmission, demonstrating that 'retardation' depended on the product of the total resistance and total capacitance of the cable, with the total retardation increasing as the square of the cable length.

This contributed to a desire to know the precise resistance of a conductor to ensure adequate quality control during manufacture.

Electrical Resistance Standards

In the 1840s, resistance coils had been calibrated in feet of copper wire. They had been introduced for laboratory use by Charles Wheatstone, Hermann Jacobi and others.

In 1843, Wheatstone had proposed adopting a foot of coiled copper wire weighing 6.5 grams as a standard. In 1848, Jacobi had sent copies of a longer coil to various physicists. Neither of these wire coils were widely adopted.

Figure 5: *Siemens Mercury column resistance unit, after Wikipedia, https://en.wikipedia.org/wiki/Siemens_mercury_unit*

In 1860, Werner Siemens had published an alternative method based on a spiral or folded column of pure mercury, of one square millimetre cross section, one metre long and at zero degrees centigrade. His mercury-based unit, *Figure 5*, which, although not being coherent with standard units, at least had the advantage of being about 1/20th of the resistance of a mile of ordinary telegraph wire. It was a helpful step forward.

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In the 1850s and 1860s, Charles Bright and other engineers had suggested the adoption of these larger magnitude (wire based) units. This was more in keeping with the Siemens unit. Fleeming Jenkin later noted, *"…the first effect of the commercial use of resistance was to turn the 'feet' of the laboratory into 'miles' of telegraph wire…"*.

Bright's coils were indeed calibrated in equivalents of a mile of wire. The replication and refinement of such resistance coils was thus crucial to the spread of precision electrical measurement among both engineers and physicists.

The British Association

In 1861, the eminent cable engineers, Latimer Clark and Charles Bright, presented a paper at the British Association for the Advancement of Science (BAAS) suggesting that standards for electrical units be established. They suggested names for these units, such as 'Ohma', 'Farad', and 'Volt' derived from the eminent physicists, Georg Ohm, Michael Faraday and Alessandro Volta.

The BAAS responded by appointing, on William Thomson's suggestion, a British Association Committee on Electrical Standards. With Fleeming Jenkin appointed as secretary, this Committee was tasked to *"report upon and define Standards of Electrical Resistance"*. The Committee's objectives were to devise units that were of convenient size, coherent, stable, reproducible and part of a complete system for electrical measurements based on the French c.g.s. system.

By 1862, the Committee were seeking a set of *material* standards which would represent the units for everyday work and particularly those which would be suitable for use by telegraphy systems engineers.

This Committee initially included Thomson, Jenkin, Wheatstone and others. Later members, up to 1870, included Bright, Charles Hockin, Clark, James Joule, Maxwell, Carl Siemens (the younger brother of Werner Siemens), Balfour Stewart and Varley. The Committee thus comprised predominantly individuals whose scientific achievements had been recognised by the award of Fellowships of the Royal Society or the Royal Society of Edinburgh.

In 1863 **[1]**, Maxwell and Jenkin recognised the preference for a coherent system of electrical units based on the fundamental international standards adopted for the centimetre, gram and second and not dependent on the 'whims' of *"…this or that regulator or man of science"*.

The committee thus created the *'BA unit of resistance',* an absolute unit based on the c.g.s. system.

However, on working out the size of the absolute e.m.u./c.g.s. unit of resistance they again found it to be far too small for the needs of the telegraph engineers. Thus, they recommended a theoretical unit of resistance to be 10^9 times larger than the e.m.u./c.g.s. absolute unit of resistance. In one sense, the choice of 10^9 was somewhat arbitrary, except that it led to one mile of the usual size of telegraph wire having a resistance of ten Ohms (in today's notation).

Thus, the practical standard was designed to realise, as nearly as was possible, the theoretical standard of a velocity of 10^9 centimetres a second ('resistance' had the dimensional analysis of a velocity on the e.m.u./c.g.s. system).

The resulting BA unit of resistance, as adopted by the Committee, was also just a few percent larger than Siemens' mercury unit and so it was of a more convenient size for cable engineers. Their standard resistance coils consisted of loosely wound wire, mounted in annular copper cans, which were then filled with paraffin.

In the 1864 Third Report, the resistance unit was referred to as *'BA unit'* or *'Ohmad',* with Jenkin requesting that the practical construction of this resistance standard be deposited in a 'public institution' in London (this matched how the 'standard yard' had been dealt with).

After many painstaking measurements by Jenkin, Maxwell, Stewart and others, the Committee finally issued its official resistance standard via the 1865 Committee Reports.

The BA Committee had decided to adopt *"one particular standard, constructed of very permanent materials and laid up in a 'national repository"*.

The actual instrument, designed by Thomson, to define the *'BA unit of resistance'* (shown alongside Maxwell in *Figure 7*) employed a magnet suspended within a spinning coil of standard wire. Jenkin rotated the coil and Maxwell took the measurements. Spinning the current carrying pair of coils in the Earth's north-south magnetic field produced an induced east-west magnetic field and caused the magnet to be deflected from its normal magnetic north-south orientation. The current in the spinning coils was inversely proportional to the coil resistance and so the angle of deflection of the compass needle lead to the experimental verification of the coil resistance. These measurements were made at King's College in London when Maxwell was a professor there from 1860–65.

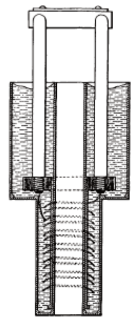

Figure 6: *The 'BA Standard Resistor', first published by Cambridge University Press. The materials are metal, ebonite, paraffin and the wire (visible as dotted line) is bent back on itself.*

By 1865, (*Figure 6*), the BA Committee had ten standard resistors with several copies of these standards.

The portrait in *Figure 7*, painted in 1929 by R. H. Campbell, was based on a photograph of Maxwell that was in the possession of the eminent electrical engineer, Sir Ambrose Fleming who had attended the Cavendish Laboratory when Maxwell was Cavendish Professor. The painting was commissioned by Eric Atkinson (being a member of the Institution of Electrical Engineers) and he donated it to the IEE in 1929.

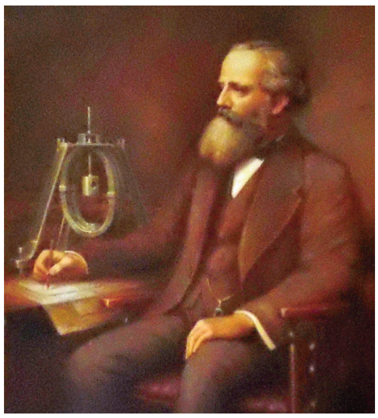

Figure 7: *Maxwell with the apparatus to measure the ohmic coil resistance, courtesy Institution of Engineering and Technology archives.*

Today, this painting resides in the archives of the Institution of Engineering and Technology, London. A copy, donated by Prof. David Ritchie of the Maxwell Foundation, is on display at the Royal Society of Edinburgh.

The revolving-coil apparatus shown in the Maxwell portrait was designed by Lord Kelvin and was the one used in 1863 to first determine the value of the Ohm.

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Seventeen such standard resistances were donated to the 'Directors of Public Telegraphs' in nine continental states as well as India, Australia and with a further sixteen copies being sold. In a brief note, Jenkin intimated that copies of the standard resistance coils were now available, and that *"...a unit resistor and box will be sent on receipt of the remittance of two pounds and ten shillings".* Michael Faraday purchased the first of these early copy standards.

The Reports of the BAAS Committee, published along with those of Wheatstone and the Siemens brothers, culminated, in 1867, with William Preece proposing the adoption of the symbol, Ω, because of the similar sound between the words 'ohm' and 'omega'.

Later, in 1872, the Committee recommended a change from the name *'BA unit of resistance'* to the *'Ohm',* naming it after the German physicist and mathematician, Georg Simon Ohm, in recognition of his discovery of the direct proportionality between the potential difference (or voltage) across a conductor and the resultant electric current.

The fact that electric current was proportional to the potential difference was first discovered by Henry Cavendish in 1781 but he failed to publicise these discoveries. Hence, this did not become known until Georg Ohm published his pamphlet in 1827. The majority of Henry Cavendish's electrical experiments remained unknown until they were collected and published, in 1879, by Maxwell, who had established and directed the Cavendish Laboratory in Cambridge since its establishment in the early 1870s.

UK standard resistance coils were located in the Kew observatory, the Cavendish Laboratory and other places before their eventual transfer, in 1955, to the London Science Museum. Today the Science Museum holds the set of nine original standard resistance coils, representing the *'BA unit of resistance',* as constructed in 1865 for the British Association Committee on Electrical Standards.

Recognising these early developments

An IEEE historical bronze 'milestone plaque' on *'The Standardisation of the Ohm as the Unit of Electrical Resistance 1861–1867'* (*Figure 8*), was installed in 2019, in the Hunterian Museum in Glasgow, alongside the permanent exhibition of Lord Kelvin's scientific apparatus. A duplicate plaque is installed in the home of the Foundation.

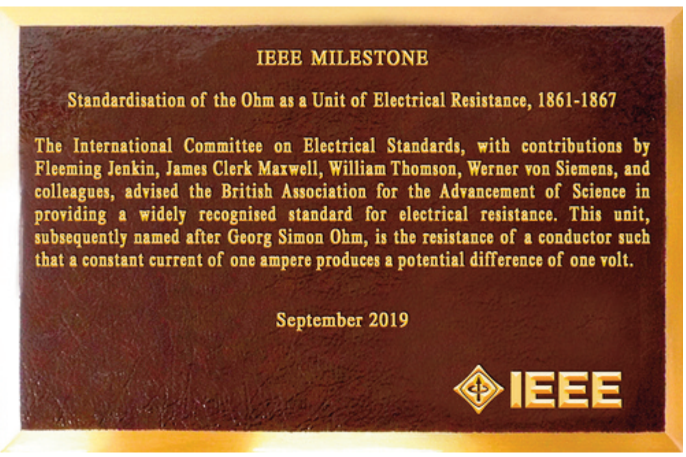

Figure 8: *IEEE Historical plaque as installed in the Hunterian Museum, University of Glasgow.*

Subsequent developments

These early resistance coils created by Thomson, Maxwell, Jenkin and others are accurate to within 1.3% of the Ohmic value used today.

In documents printed before World War II, the unit symbol often consisted of the raised lowercase omega (ω), such that 56 Ω was written as 56^{ω}.

In the electronics industry, it is common to use the character, *R*, instead of the Ω symbol, thus, a 10 Ω resistor may be represented as 10R as recommended by the British standard no. 1852. In many instances where the value has a decimal place, e.g. 5.6 Ω, this is listed as 5R6 to avoid adding the decimal point.

In 1948, the Ohm was redefined in absolute terms using the International System (SI) of units.

By 1956, a cable (called TAT1) stretched 2,240 miles from Oban in Scotland to Clarenville in Canada. It allowed for thirty-six simultaneous transatlantic telephone conversations which typically cost three pounds (sterling) per minute! TAT1 was retired in 1978.

Maxwell advocated that future resistance standards should be, if possible, based on Nature's constants (e.g. speed of light) as opposed to man-made constants (e.g. centimetres). Today, the definition of the Ohm is based on the quantum 'Hall Effect' for which Klaus von Klitzing received the Nobel prize in 1985. The advantage of this definition is that it does not require a physical resistor to represent it but, instead, following Maxwell's view in **[2]**, the resistance standard is now based on a reliable and reproducible property of Nature which can be measured anywhere.

Today, we use fibre-optic cables which offer an enormous capacity to convey data by cable.

The transmission of Electromagnetic waves

In 1865, Maxwell developed the theory for electromagnetism and, in 1888, Heinrich Hertz demonstrated the generation of electromagnetic waves. In due course, Marconi's wireless telegraphic operations were developed and cable operations were merged into wireless communications within the company "Cable and Wireless".

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