The electrical connection

François Piquemal tells the story of the ampere, which bridges mechanical and electromagnetic units.

In everyday electrical life, watt and volt probably mean more than ampere: when replacing a lamp, you need the right wattage, when changing a battery, voltage is what you check. A quick explanation of the 'amp' is that a current of 1 A generates a power of 1 W in a conducting element to which a voltage of 1 V is applied.

This definition is equivalent to the one approved during the first International Exposition of Electricity held in Paris in 1881: the ampere is the current produced by one volt in one ohm. The name ampere — after André-Marie Ampère, the founder of electrodynamics (pictured) — was chosen to avoid confusion: at the time, a unit named weber (after Wilhelm Weber) quantifying electrical current was in use in both the United Kingdom and Germany, but differing by a factor of ten!

Formulating electromagnetic measurements in terms of mechanical quantities (length, mass and time) was pioneered by Carl Friedrich Gauss, who in 1832 expressed his result for the intensity of the Earth's magnetic force using the millimetre, the milligram and the second² — the starting point for the centimetre–gram–second (CGS) system, later replaced by the metre–kilogram–second (MKS) system.

By the early twentieth century, the need had arisen to express the electrical units in terms of physical standards, and a new system of international units for practical use was introduced. The international ampere was defined as the current that deposits a silver mass of 0.001118 grams per second (ref. 3) on the cathode of a silver nitrate electrolyser. It was envisaged that such standards would travel between countries and be compared to each other. For the international ohm, this was a delicate affair: the standard was based on a column of mercury (with a cross section of 1 mm² and a length of 106.3 cm) — unimaginable today given the international regulations concerning mercury's toxicity!

In reality, international standards remained at home and metrological institutes used secondary, transportable standards.

Dissatisfaction about expressing electrical quantities in a limited 3D system of (mechanical) units soon became a critical issue. In 1901, Giovanni Giorgi had demonstrated the possibility of designing one coherent 4D system by linking the MKS units with the practical electrical system via a single base electrical unit from which all others could be derived. After some debates, the ampere was preferred to the ohm as the connecting unit, leading to the well-known MKSA system adopted from 1948 and superseded by the *Système International d'Unités* (SI) in 1960. The definition of the ampere as the unit of electric current was then given its present

form⁴: “that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per metre of length.”

Because of the low achievable accuracy (parts in 10^6 at best) when implementing such a thought experiment, realizations of the ampere are derived in practice from the ohm and the volt or, for currents less than 100 pA, from the farad, the volt and the second.

The discovery of two condensed-matter quantum phenomena, the Josephson effect in 1962 and the quantum Hall effect in 1980, marked the beginning of a new era in metrology. These effects enable accurate measurements of the Josephson constant, $K_J = 2e/h$, and the von Klitzing constant, $R_K = h/e^2$, and hence determinations of the elementary charge, e , and the Planck constant, h . Highly reproducible present-day quantum standards for the volt and the ohm are based on these phenomena — and play a

crucial role in the planned redefinition of the ampere (and the kilogram)^{5,6}.

History seems to repeat itself. Like the past schism between the practical international electrical units and the CGS system, the conventional (quantum-standard) ohm and volt — in use since 1990 and based on defined values of K_J and R_K (ref. 5) — are not embedded in the SI.

Fortunately, progress in metrology is being made, and a revision of the SI, solving this and other issues, is planned for 2018 (ref. 6). In the new SI, the ampere will be defined as the electric current corresponding to the flow of $1/(1.602176xyz \times 10^{-19})$ elementary charges per second, with the elementary charge fixed at $1.602176xyz \times 10^{-19}$ C. The three last significant digits, xyz , are not settled yet.

The new definition of the ampere is ‘future-proof’ as it does not imply a way for realizing the ampere — unlike the 1948 definition. A straightforward way is via quantum realizations of the volt and the ohm. A still very challenging method is based on the very definition of current itself: measuring the quantized flow of charges in a certain time interval in a nanodevice in a controlled way. Interestingly, the first method relies on collective phenomena accounted for by the wave nature of electrons, whereas the other approach involves a device based on the electron's corpuscular nature! □

FRANÇOIS PIQUEMAL is at the Fundamental Electrical Metrology Department, Laboratoire National de Métrologie et d'Essais, 29 avenue Roger Hennequin, 78197 Trappes CEDEX, France. e-mail: francois.piquemal@lne.fr

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