Electroscopic and Electrodynamic Actions of Free Electricity in Closed Circuits

Wilhelm Weber

Editor's Note: An English translation of Wilhelm Weber's posthumous paper "Elektroskopische und elektrodynamische Wirkungen der freien Elektricität geschlossener Ketten".[1]

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[1] [Web94].

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Chapter 1

Editor's Introduction

A. K. T. Assis[2]

Wilhelm Weber (1804-1891) discussed in Sections 28 to 36 of his second major Memoir of 1852 on *Electrodynamic Measurements*[3] two situations in which a current can flow along a resistive conductor.

The first situation appears in Figure 1.1.

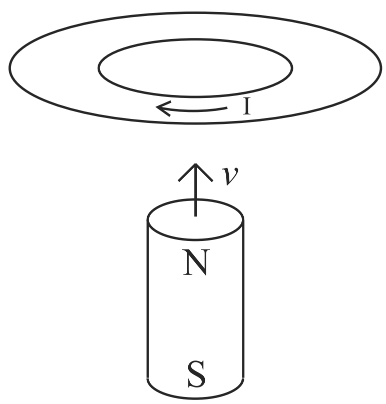

Figure 1.1: A magnet moving with velocity v along the axis of a resistive ring, perpendicular to its plane, and inducing an azimuthal current I.

Consider a cylindrical magnet NS which is orthogonal to the plane of a circular homogeneous copper ring whose cross-section is the same everywhere. When the magnet moves with velocity v along the axis of the ring, it exerts the same electromotive force on all elements of the ring as a result of that motion. Since all elements of the ring are also endowed with the same resistance, an equal electric current will be generated simultaneously in all of the elements of the ring by that motion, flowing along its azimuthal direction. The value of the current may depend on the distance between the magnet and the ring. But it will have the same value along the azimuthal direction, that is, it will not depend on the azimuthal angle

[2]Homepage: `www.ifi.unicamp.br/~assis`

[3][Web52] with English translation in [Web21]. These Sections have been discussed in detail in Appendix A of the book *The Electric Force of a Current: Weber and the Surface Charges of Resistive Conductors Carrying Steady Currents*. It is available in English, [AH07], Portuguese, [AH09], and German, [AH13]. See also [Ass21a].

θ along the ring. From this it will follow that a greater or smaller accumulation of positive or negative electricity, varying along the azimuthal angle θ, cannot arise at any location on the ring. We will then have the case here of a current in a closed circuit without variation of free electricity along the azimuthal direction in the circuit.

The second situation appears in Figure 1.2.

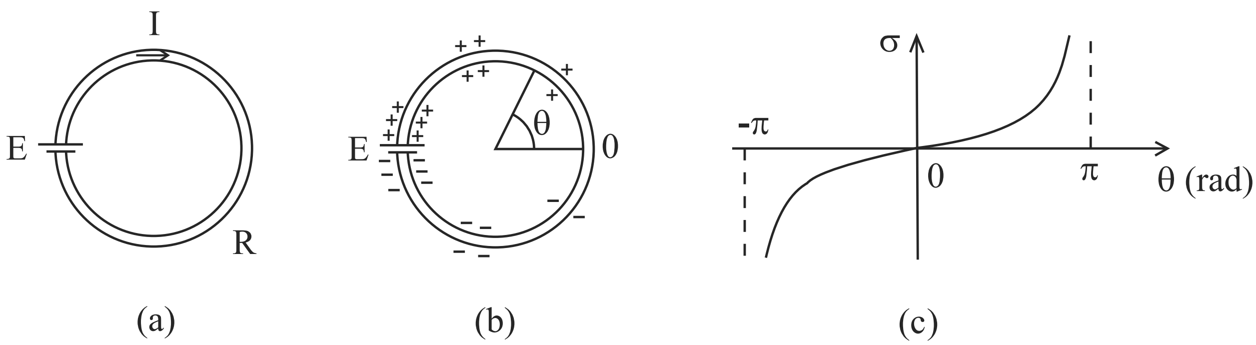

Figure 1.2: (a) Resistive ring connected to a battery and carrying a steady current I. (b) Charges distributed along the surface of the ring. (c) Surface charge density σ as a function of the azimuthal angle θ.

We have a battery of negligible internal resistance and generating a constant voltage or electromotive force E between its terminals. The ring has a total resistance R and a small opening at a certain point. When the two terminals of the battery are connected to the two extremities of the opening of the ring, there will be a distribution of charges along the surface of the ring. Soon there will be a steady state configuration in which a constant current I flows everywhere along the azimuthal θ direction of the ring. This current will satisfy Ohm's law $E = RI$.[4] In this steady state situation, the surface charge density σ (amount of charge per unit area) along the surface of the ring will be constant in time, but its magnitude will vary along the azimuthal direction θ. It will be zero in the opposite side of the battery, that is, at $\theta = 0$ in Figure 1.2. The amount of positive charges will increase towards the positive terminal of the battery and the amount of negative charges will increase towards the negative terminal of the battery, as indicated in Figure 1.2 (b) and (c).

In this second major Memoir on *Electrodynamic Measurements* published in 1852 Weber performed pioneering calculations of the distribution of the surface charge density σ for different resistive circuits carrying constant currents. In particular, he considered a straight cylindrical wire and a resistive ring. He calculated how σ varied along the length of the cylindrical wire. He also calculated how σ varied along the azimuthal direction of the ring.

The present paper was published posthumously in 1894 in Volume 4 of Weber's Collected Works.[5] Its goal was to obtain an equation describing the total amount of positive and negative charges distributed along a closed conductor of total resistance R carrying a steady current I when connected at a point by a battery generating a voltage or electromotive force E between its terminals. In particular, Weber considered the situation in which the current had a numerical value $= 1$ in a certain system of units. In this case, from Ohm's law $E = RI$, the electromotive force E and the resistance R had equal numerical values in

[4]Georg Simon Ohm (1789-1854). Ohm's law is from 1826: [Ohm26a], [Ohm26c], [Ohm26d], [Ohm26b] and [Ohm27] with French translation in [Ohm60] and English translation in [Ohm66].

[5][Web94].

the same system of units. This system of units might be, for instance, the absolute system of units created by Carl Friedrich Gauss (1777-1855) and W. Weber.[6]

We can illustrate Weber's goal with Figure 1.2, although in this posthumous paper he didn't consider specifically a conducting ring. If Weber were considering this ring in this posthumous paper, he would be interested in the total amount of positive charge distributed between $\theta = 0$ and $\theta = \pi$, together with the total amount of negative charge distributed between $\theta = 0$ and $\theta = -\pi$, as shown in Figure 1.2 (b) and (c).

After this introduction, we present the English translation of Weber's paper. The words between square brackets, [ ], were introduced by myself or by the translator in order to clarify the meaning of some sentences.

[6] [Ass21b].

Chapter 2

Electroscopic and Electrodynamic Actions of Free Electricity in Closed Circuits

Wilhelm Weber[7,8,9]

Approximate calculation of the amount of electricity, which needs to be distributed over a closed circuit, if an electromotive force, equal to the resistance of the circuit, is acting on one position of the circuit, such that the intensity of the current is $= 1$ *everywhere in the circuit.*

In a closed circuit, a steady current without charge can only persist, if the electromotive forces of all circuit elements are proportional to the resistance of the elements.[10] If this proportionality is not maintained, the intensity of the current differs in different elements [of the circuit], and, as a consequence of this inhomogeneity, in some parts of the circuit (where the intensity of the current decreases) positive electricity, and in other parts (where the intensity of the current increases) negative electricity will be released, or the circuit will be charged. From this charging of the circuit, additional electromotive forces are formed, from which higher intensities of the current will be reduced, while lower [intensities of the current] will be enhanced. The remaining inhomogeneities produce additional charges and therefore additional electromotive forces, resulting in a compensation of the remaining inhomogeneities of the current intensity, and this [process] continues, until a particular amount of charge has been generated in the circuit, at which an equal amount of current intensity can persist in all elements [of the circuit].[11]

[7] [Web94].

[8] Translated by F. J. Linz, fjlinz@posteo.de, and edited by A. K. T. Assis, www.ifi.unicamp.br/~assis

[9] The Notes by F. J. Linz are represented by [Note by FJL:], while the Notes by A. K. T. Assis are represented by [Note by AKTA:].

[10] [Note by AKTA:] An example of this situation was discussed by Weber in 1852, as illustrated in Figure 1.1. In this case there is no variation of free charges distributed along the surface of the ring. That is, the amount of free charges does not depend on the azimuthal angle θ.

[11] [Note by AKTA:] An example of this situation appears in Figure 1.2 in which a battery is connected at a point of a closed resistive ring. For a steady current to exist in this configuration, it is necessary a

This charge of the circuit is of great importance for the theory of the current formation, but has been of little importance in application so far, because it [the charge of the circuit] always adjusted itself instantly, and their peculiar actions, independent on the current [of the circuit], are so small, that the most accurate means of observation can only hardly detect them. These hardly observable actions of the charges of a closed circuit are called electroscopic actions, and to their exploration, only few and imperfect experiments have been performed so far.

These electroscopic actions recently gained greater practical meaning, e.g. in Rühmkorff's *machines*,[12] for which the requirements to the insulation of the wire winding, to avoid sparks arcing over, depends on this charge [which causes the electroscopic actions], as the striking distance of the sparks from one end of the induced wire[13] to the other [end of the wire], furthermore in *electrical telegraphy*, for which the speed of signaling depends significantly on the speed of current formation. However, this current formation is strongly delayed if the charging of the circuit required for a steady current is to be formed, for example, under the influence of a capacitor, as it is the case in submarine telegraphs, where the encircling metal tube together with the surrounding water of an isolated wire, forms such a capacitor.

To avoid this delay of the charge and hence the accompanying delay of the signals, it will be inevitable, to lead the current back, instead through the earth or sea, through a second conducting wire which is embedded in the same cable isolated from the first [conducting wire]. The opposite charges of equal configuration,[14] which thereupon must be preserved by these two wires in each position during formation of the current, compensate each other in their action on the encircling metal tube, the most perfect [compensation], if the distance of the two wires to each other is very small compared to their distance to the metal tube. The metal tube will thereupon not take any appreciable charges and consequently will not exert any noticeable reaction on the formation of the charge in the enclosed wires. — Thus, at the same time, the induction of currents in the circuit by variations of the terrestrial magnetism will be avoided.

Thereby, the study of electroscopic actions of a closed circuit and of the laws of the charge [distribution], which they [the electroscopic actions] are depending on, gained practical interest. For this purpose, the experiments will no longer be sufficient upon which the investigation was limited so far, namely, to use these charges of a closed circuit to charge fine capacitors and sensitive electroscopes, from which the name of the *electroscopic actions* of the circuit originates.

Very important to these investigations are the specifications, which will be obtained by the help of submarine telegraphs even over the duration of the formation of steady currents; yet it is easy to check, that even the most accurate observations of such telegraphs will not give an accurate determination of this duration of the formation [of steady currents], because of the manifold other influences which are involved, on which the time between signaling and

distribution of free charges along the surface of the ring. The surface density of charges is constant in time for a constant current, but its magnitude varies along the length of the ring. That is, the surface charge density σ varies along the azimuthal angle θ, as shown in Figure 1.2 (b) and (c).

[12] [Note by FJL and AKTA:] In the original text: "Rhumkorff'sche Maschinen". Rühmkorff's machines or induction coils were named after Heinrich Daniel Rühmkorff (1803-1877), a German instrument maker, [Nor96].

[13] [Note by FJL:] In the original text: "induzierter Draht", so the wire in which the induced current flows.

[14] [Note by FJL:] In the original text: "entgegengesetzt gleichen Ladungen", meaning that in the two wires, the charges have the same magnitudes, but opposite signs, such that their actions cancel.

signal observation also depends. In addition, the most influential conditions[15] during current formation in such telegraphs are invariable and therefore provide only incomplete data from which no laws can be established, if the same [laws] have not yet been discovered in a different way.

A different approach is featured by the electrical oscillations, when steady currents are formed in a closed circuit, but only of short duration and with changing direction. Thereby, those electrical charges [mentioned above] are also generated, but alternately quite different charges. The transition from one charge to another, or the formation of a different [charge] distribution, is associated to a movement distinct from the equal amount of current in the whole circuit, which [movement] differs in the individual parts of the circuit.

It is clear from this, that in all parts of the circuit the same synchronous oscillation can, strictly speaking, not occur alone, if the excitation is originating from one position of the circuit, but it [the synchronous oscillation] is necessarily connected to another oscillation, which [the second one] can be considered approximately synchronous, but very inhomogeneous in different parts of the circuit. This latter oscillation results directly, following Ampère's laws,[16] in *electrodynamical forces*, which modify the observed deflection of the dynamometer; furthermore from the laws of electrostatics and induction result additional electromotive forces, which modify the intensity of the current and hence directly act on the dynamometer and need to be observed and studied by accurate observations of the dynamometer.

The element of a closed circuit, in which the electromotive force ω acts, is enclosed between the cross-sections aa and bb (Figure 1).

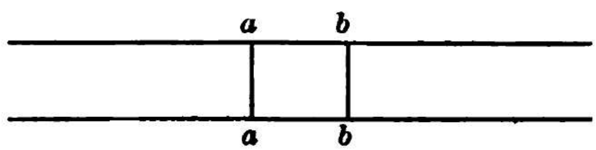

Fig. 1.

Suppose the electromotive force being spread in a way that it is increasing from both boundary surfaces towards the center, proportionally to the distance from the boundary surface. Suppose aa and bb are charged with positive electricity on both sides, such that the potential is constant within the (infinitely small) gap between both occupancies[17] of aa and bb. Let the average density of this charge be $= +e$. Since $[dV/dx]_{-\varepsilon} = 0$ between the two occupancies, beyond the occupancies we have

$$\left(\frac{dV}{dx}\right)_{+\varepsilon} - \left(\frac{dV}{dx}\right)_{-\varepsilon} = \left(\frac{dV}{dx}\right)_{+\varepsilon} = 4\pi e \ ,$$

if the repulsive forces are assumed to be positive.

One shall think of the charge directed towards bb being distributed uniformly until the center between aa and bb, and call the density of positive electricity uniformly distributed

[15][Note by FJL:] In the original text: "einflussreichsten Verhältnisse".

[16][Note by AKTA:] André-Marie Ampère (1775-1836). Ampère's masterpiece was published in 1826, [Amp26] and [Amp23]. There is a complete Portuguese translation of this work, [Cha09] and [AC11]. Partial English translations can be found at [Amp65] and [Amp69]. Complete and commented English translations can be found in [Amp12] and [AC15].

[17][Note by AKTA:] In German: *Belegungen*. This word can be translated as occupancies, allocations, assignments, surfaces, layers, coatings etc. There is one occupancy with a small gap around aa, and another occupancy with another small gap around bb.

in half the space of the element under consideration by k, and call the halfway distance bb from aa by α, then

$$k\alpha = e \ .$$

In this region of space then

$$\frac{d^2V}{dx^2} = 4\pi k \ ,$$

if $d^2V/dy^2 = d^2V/dz^2 = 0$ is assumed, and the repulsive forces are considered to be positive.

From this it follows that

$$\frac{dV}{dx} = 4\pi kx \ ,$$

if x is calculated from aa, where $dV/dx = 0$.[18] Consequently, the integral value of the electromotive force is[19]

$$\int_0^\alpha \frac{dV}{dx}dx = \int_0^\alpha 4\pi kxdx = 2\pi k\alpha^2 = 2\pi e\alpha \ ,$$

moreover suppose bb being charged with negative electricity on both sides, such that the potential is constant within the (infinitely small) gap between both occupancies [of negative electricity]. Let the average density of this configuration be $= -e$. As $(dV/dx)_{+\varepsilon} = 0$[20] (where $+e$ is located in the gap), it follows that

$$\left(\frac{dV}{dx}\right)_{-\varepsilon} - \left(\frac{dV}{dx}\right)_{+\varepsilon} = \left(\frac{dV}{dx}\right)_{-\varepsilon} = 4\pi e \ .$$

One shall think of the charge directed towards aa being distributed uniformly until the center between bb and aa, and call the density of negative electricity uniformly distributed in half the space of the element under consideration by $-k$, and call the halfway distance from aa to bb by α, then

$$k\alpha = e \ .$$

In this region of space then

$$\frac{d^2V}{dx^2} = -4\pi k \ ,$$

if $d^2V/dy^2 = d^2V/dz^2 = 0$ is assumed, and the repulsive forces are considered to be positive.

From this it follows that

$$\frac{dV}{dx} = 4\pi k(\alpha - x) \ ,$$

if x is calculated from the center, such that for $x = \alpha$, $dV/dx = 0$. Consequently, the integral value of the electromotive force is

[18] [Note by AKTA:] That is, $x = 0$ at aa. At this point $x = 0$ we have $dV/dx = 0$.

[19] [Note by FJL:] In the original text, there is an equal sign in between, $\int_0^\alpha \frac{dV}{dx} = dx = ...$, which has been removed.

[20] [Note by FJL:] In the original text, two different brackets are used here: $[dV/dx)_{+\varepsilon} = 0$.

$$\int_0^\alpha \frac{dV}{dx}dx = \int_0^\alpha 4\pi k(\alpha - x)dx = 2\pi k\alpha^2 = 2\pi e\alpha \ .$$

From this results the electromotive force for the whole element under consideration

$$= 4\pi e\alpha \ .$$

One shall set this electromotive force oppositely equal to the given [electromotive force] $(-E)$, hence

$$4\pi e\alpha = E \ .$$

Then, instead of the outer occupancy of aa, the surface of the wire is now covered [with electricity] from aa to the point which bisects the entire length of the wire, and denote this half length by L. The thickness ε of this coating grows from the midpoint to aa from 0 to $[8\alpha/\pi r]\cdot e$[21,22] proportionally with the length of the wire from the midpoint to the point under consideration, then, if the wire is very long compared to its thickness, the electromotive force $\left(-\frac{1}{2}E\right)$ will act in a distributed manner over the length of the wire L, and its distribution can be considered to be approximately uniform.

It follows thereupon that the charge of the length of the wire L, which causes this uniform distribution of the half given electromotive force $\left(-\frac{1}{2}E\right)$, if r is the radius of the wire,

$$= \int_0^L 2\pi r\varepsilon dx \ ,$$

wherein

$$\varepsilon = \frac{8\alpha e}{r\pi L}\cdot x \ ,$$

thus

$$= \int_0^L \frac{2\pi re}{L}\cdot\frac{8\alpha}{r\pi}xdx = \pi r\frac{8\alpha}{r\pi}eL = \frac{2LE}{\pi} \ .$$

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[21][Note by WW:] According to Clausius (Poggendorff, Annalen 1852, Vol. 86, p. 203), for a capacitor, with radius a [of the plates] and distance c between the plates, the charge of one plate can be expressed by

$$M = -\frac{a^2}{4c}\cdot F\left[1 + \frac{c}{a\pi}\left(\lg\frac{17.68a}{c} + 2\right)\right] \ .$$

The charge of the second plate by

$$N = \frac{a^2}{4c}\cdot F\left[1 + \frac{c}{a\pi}\left(\lg\frac{17.68a}{c} - 2\right)\right] \ .$$

If one adds to the bound electricity N so much free electricity N', such that $N + N' = -M$, then $N'/(N+N')$ gives the free electricity in parts of the total charge a. Yet it is

$$\frac{N'}{N+N'} = \frac{4c}{a\pi\left[1 + \frac{c}{a\pi}\left(\lg\frac{17.68a}{c} + 2\right)\right]} \ ,$$

or in case of very small c/a, $N'/(N+N') = 4c/a\pi$. If one substitutes in our case 2α for c and r for a, then $N'/(N+N') = 8\alpha/r\pi$ is the fraction of the free electricity of the total charge. If the density e corresponds to the total charge, then the density $[8\alpha/r\pi]\cdot e$ corresponds to the free charge.

[22][Note by AKTA:] [Cla52].

The same amount of negative electricity is found distributed on the other half of the wire. Thus, if we denote the whole length of the wire to be $l = 2L$, then

$$\pm\frac{lE}{\pi}$$

is the amount of positive or negative electricity distributed in the closed circuit; consequently, if

$$E = w \ ,$$

where w is the resistance of the circuit, then

$$\pm\frac{lw}{\pi}$$

is that amount of positive or negative electricity which must be distributed in a closed circuit, in which the current = 1 flows, when the current is generated from one point of the circuit.[23]

[23][Note by AKTA:] Weber is here writing Ohm's law as $E = wi$, where E is the electromotive force acting at one point of the circuit. The circuit has a total resistance w. This electromotive force produces a constant current i along the circuit. If $i = 1$ in a certain system of units, then $E = w$ in this system of units. The total amount of positive electricity distributed in half of the circuit will be given by $lE/\pi = lw/\pi$, while the total amount of negative electricity distributed in the other half of the circuit will be given by $-lE/\pi = -lw/\pi$, where l is the total length of the circuit under consideration.

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