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From Volta’s Pile to Ferraris’ Motor: A History of Instruments and Theories

Abstract[3]

The theory of Volta’s pile was initially included into Electrolysis and Chemistry. Only after Oersted’s discovery of the magnetic effect of electric currents, Ampére constructed a dynamical theory of their interactions. In the middle of nineteenth century, Faraday’s electromagnetic induction represented one of the main effects at the basis of Maxwell’s field theory, and, at the same time, the fundamental process for industrial production of electric power.

The transmission at distance of this power became feasible only through Galileo Ferraris’ invention of the asyncronous motor and his Maxwellian theory of the transformer.

The history of Electricicty is thus considered an emblematic example of a chain of tight connection between theories and instrumental operations, and Volta’s pile stands as the most important among the initial rings of this chain.

1. Introduction

Volta’s discovery of a continuous source of electrical power represented the beginning of a process which, at the end of the Nineteenth Century, led to the social and industrial exploitation of electrical energy. At the middle of century, Faraday’s 1931 discovery of a mechanical production of electrical power and the inventions of new theories and of new technical innovations were fundamental aspects of this process.

Following the examples of Heaviside, Hertz, Lodge, et alii, electricians would never have denied the merits of Maxwell’s theoretical approach; as mathematical physicists, they were so familiar with it that their only need was to re-read it, in order to adapt its theoretical content to the requirements of their projects, which increased day after day.

The electricians of this period were no longer scientists-inventors but mathematical physicists who became engineers while working with technical aspects of electro-magnetism, Their main task was that of defining the role played by the Maxwellian paradigm as compared with the recent developments of their knowledge. From this explanation of method, essential to the birth of modern electro-technology, emerged in a definitive manner the post-Maxwellian character typical of present day electrical engineering.

This trend, which continued in the spirit of modern electrical engineering, was fully summarised in the post-Maxwellian evolution of the mutual inductor theories, from Maxwell to G. Ferraris and from these to C.P. Steinmetz up to H.F. Weber.

2. Theoretical and Experimental Interbreeding in the Construction of Electrodynamics nd Electromagnetism

The role plaid by new apparatuses and instruments in the theoretical construction of electrodynamics is illustrated by Volta's pile and by its implicitly historical conceptual function of bridging the gap between electrostatics and the electromagnetic effect of the electric current. The effect was firstly qualitatively detected by Örsted in his 1820 experiment, but only A.M. Ampère, through his celebrated electric balances was able to determine a quantitative law for the mechanical force excerpted by two currents (as a function of their direction and intensity). Through his theorem of equivalence, he reduced magnetism to currents, eliminating even the name magnetism from the title of his book on "Electrodynamique". Ampère' differential galvanometer, a direct output of his balances, allowed to fix the zero of the scale and the addition of the quantity: "intensity of current". One finds no better illustration for the Helmholtian assertion[1] that in physics instrumentation lays the foundations for the metrics of the theories to be tested.

It was Wilhelm Weber's merit to continue bridging the gap between electrostatic and electrodynamics by determining[2] the conversion coefficient between the static and the dynamical measure of the electric current, thus establishing the metrics of a synthetic theory encompassing in a unique law both electric and magnetic effects. Again, this unification was reached through the usage of newly invented instruments, such as the ballistic galvanometer and the electrodynamometer.

Passing from the metrical to the metrological level, it is noteworthy that Gauss and Weber founded the Metrology of the Absolute Systems of electric and magnetic units. Electrodynamics thus received a complete (for that time) mathematical vest and it was remarkable that, due to the above systematic arrangements of units, electric laws could be written in the form of algebraical equations, including physically significant proportionality constants. From this algebraization of physics laws issued one important feature of modern physics, i.e., the theoretical predictability of the value of physical quantities. The other feature was no less than the introduction of a second universal constant C. Added to the Newtonian gravitational constant, it conferred a remarkable conceptual role to the Weberian technical approach to electrical metrology.

One technically interesting part of Maxwell's 1868 Memoir[3] dealt with a

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[1] VON HELMHOLTZ (1977), pp 73-103.

[2] WEBER (1893), 25-211. WEBER and KOHLRAUSCH (1856), pp. 597-608.

[3] MAXWELL (1868), pp. 643-58.

description of his experiment to measure the conversion coefficient between static and dynamical effects of an electric charge. His strenuous efforts were directed at proving that this conversion coefficient really measured a propagation velocity of electromagnetic waves and of light, not, as Weber had claimed, a velocity of motion of electrical particles. He inserted Weber's constant in a completely modified theoretical context supported by his new approach to physical equations as bearers of "dimensions".

The history of the development of absolute systems of units and of their dimensions can be considered as original illustrations of the remarkable influence on cognition exerted by the metrological innovations, which are often considered as merely technical procedures.

A second remarkable result of Maxwell's that fired Galileo Ferraris' imagination is illustrated in the ensuing pages.

Needless to say, Maxwell's introduction of differential equations as a representation of the locality of the electromagnetic field was a great innovation in the electromagnetic theory which had to wait for Hertz's experiments in order to receive a complete empirical support.

From the viewpoint of instrumentation, Heinrich Hertz introduced new instruments as detectors and metrical devices for the radiation field which replaced the former electromechanical instruments whose rise-time was too large for detecting the radiation effects. In the experiment[4] performed in 1888, he used his "Kreiss" detector for measuring the radiation wavelength in a stationary wave system in air.

By the usage of electromagnetic oscillators as detectors of the radiation field, Hertz opened the way to a new category of instruments (the modern electromagnetic radiators and detectors of signals). The former electromechanical devices (essentially: electrometers and galvanometers and/or their combinations) were improved and specialised as meters, necessary for the measurements of electric power in its industrial applications.

3. The Maxwellian Treatise: A Paper Theory for Electrical Engineers

Concerning electrical technologies, the Nineteenth Century opened up with the discoveries of Volta and ended triumphantly with the polyphase-technology experiments at Laufen-Frankfurt that were forerunners to the establishment of modern electrical engineering.

Around the middle of the century, electricians were animated by expectations prompted by the designs of the first large plants and tended to ignore the technical aspects implicitly contained in the highly motivated theories of Maxwell's Treatise.

More interested in the apparent evidence of the electromagnetic phenomena, and totally unfamiliar with mathematical physics, they did not trust anything that could not

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[4] HERTZ (1888), p. 610; in HERTZ, *Electric Waves*, Dover Pbl. Undated, pp. 124-36.

immediately be observed, being unable to appreciate the applications hidden in the Maxwellian legacy. To such an extent that the Treatise, paradigmatic of all electrical engineering, was for several years assimilated to a simple paper theory, incapable of providing a tangible and immediate answer to the urgency of their queries.

Thus, it came about that the transformer, whose expected industrial development was depending on the technical feasibility of alternating current, made its first appearance fifty years after Faraday's law. Initially, its operation was rightly found not to be particularly simple, and , though justified by magneto electric induction, its operating principle, considered to be openly in contrast with the energy conservation principle, was actually rejected.

Things went even worse in the following years because technicians, and, among them, in 1887, the very same J. Hopkinson, actually missed the energy balance of the transformer because they calculated the average power as a semi-product of the maximum voltage and current values by incorrectly assimilating the sinusoidal to the stationary regimes. The resulting efficiency was such as to devoid of any technical feasibility the transformation process. In their initial attempts, being entirely unfamiliar with Maxwell's laws on magnetic circuits, electricians even failed to adopt the expediency of winding the solenoids around closed magnetic circuits. In order to avoid losses due to eddy currents in the ferromagnetic nucleus, some technicians summarily proposed in 1884 to replace ferromagnetic with wooden nuclei. Technicians did not avail themselves of the already existing theory and did not rigorously formalise the general principles which govern magneto electric equipment. By proceeding by trial and error, they were running the risk of being unable to reconcile Faraday's law with energy conservation. Due to the sparse results achieved by practitioners, around the last quarter of the century, electricians soon realised that it was necessary to undertake an in-depth review of their methodology in order to face the expanding technical applications.

The foundation of a new electrical engineering needed a beneficial osmosis with an electro-magnetic science which was already broadly consolidated, capable therefore of clearly specifying methods and objectives for the applications. This innovation appeared increasingly more difficult to postpone due to major costs of design for more powerful electrical machines and for more extended nets of electric current.

4. From the Mathematical Physicist to the Scientist-Inventor: Ferraris' Contributions

A theory on the mutual inductor, the basis of every scientific study of the transformer, had been fully formulated and published by Maxwell twenty years earlier, in his 1864 essay "A Dynamical Theory of the Electromagnetic Field".

It was Galileo Ferraris' merit to have revived the theory of the Maxwellian mutual inductor model and to have applied it to the transformer case, thus presenting the first scientific theory of the transformer. I was also his merit the mathematical deduction of the active power formula: $VI\cos\varphi$. Thanks to this relationship the transformer efficiency was finally found to have such a value as to justify its utilisation in a technical context. In this sense, Ferraris must be considered as the first and most important scientist responsible for the initial success of the whole context of the alternating current technique. His subsequent invention of the asynchronous machine, which at his time responded to the needs of the industrial growth, must also be included in this context, because he viewed this invention as a realisation of a desired objective, the insertion of the spontaneous torque alternating current motor as a downstream of a transformer.

His combination of a transformer with an asynchronous machine, specifically finalised for a well defined energetic strategy, also represents the typical of a mathematical physicist of a Maxwellian mould. In fact, as already remarked, his theory of the transformer originated from his conscious recourse to the mutual inductor theory included in Maxwell's Dynamical Theory. Moreover, as for the case of the asynchronous machine, Ferraris relied on the concept that the magnetic contribution of the Maxwellian displacement current to the production of a rotating wave, could be replaced in a slowly variable regime by the contributions of time-dephased currents circulating in space-dephased windings. The theorem that bears Ferraris' name affirms that, under the above conditions, a radial magnetic field of constant amplitude, rotating at such a speed as to travel a double polar pitch during the period required by the currents to describe a cycle, is generated in the magnetic gap.

From a conceptual viewpoint, Ferraris transferred the range of validity of Fresnel's laws from the optical frequencies to the electric current low frequency domain. In this sense, Ferraris' results can be considered one of the first confirmations of the Maxwellian unification between electromagnetism and optics.

5. Conclusions

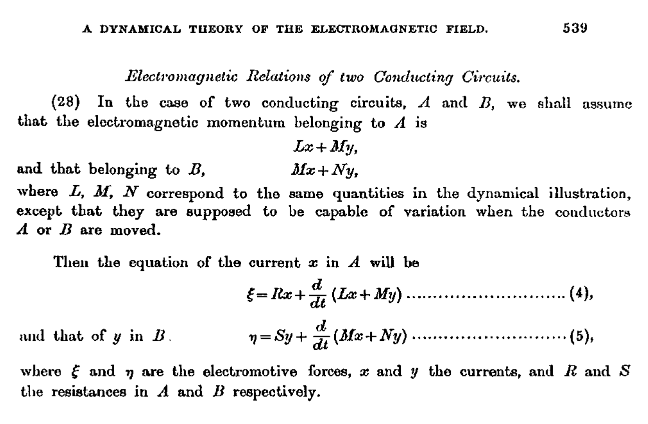
In conclusion, it can be affirmed that Ferraris' theory of the transformer represented the first approach of a scientific nature along the route of the future achievements in the transformer's theory. However, this theory was restricted in his approach by the very Ferraris' mentioned adhesion to Maxwell's in his Dynamical Theory.

This restriction was also typical of the scientists-inventors of the same period, because in acknowledging in the Maxwellian style the constant nature of the induction coefficient triplet $\{L_1,L_2,M\}$, they remained faithful to Maxwell's preliminary idea of an ideal magnetic nucleus.

As a mathematical physicist, Maxwell produced a theory of an ideal mutual inductor system rather than of a real transformer, and therefore he neglected crucial aspects regarding the operation of real electrical equipment, such as the dependence of the magnetic permeability of the ferromagnetic nucleus on the current circulating in the windings, as well as the simultaneous contribution of the leakage flux.

The post-Maxwellian transition from Ferraris to Steinmetz put initially to test a different reading of the ironless coils. Perhaps, precisely for this, C.P. Steinmetz, the first modern electrical engineer, was defined most fortunately by the Americans as a mathematical physicist who began to be an engineer. In fact, with him, mathematical physics became the essential heritage in the way of thinking about the electricity inherent to electro-technologies, thus happily linking the figures of Maxwell and Edison.

A heritage which would never cease to be fertile, as proved by the fact that 125 years after Maxwell's Treatise, modern mathematical laboratories re-read Maxwell equations using 3D calculating programmes, thus confirming their importance in modern engineering.



A DYNAMICAL THEORY OF THE ELECTROMAGNETIC FIELD. 539

Electromagnetic Relations of two Conducting Circuits.

(28) In the case of two conducting circuits, A and B, we shall assume that the electromagnetic momentum belonging to A is

$$Lx+My,$$

and that belonging to B, $\quad Mx+Ny,$

where L, M, N correspond to the same quantities in the dynamical illustration, except that they are supposed to be capable of variation when the conductors A or B are moved.

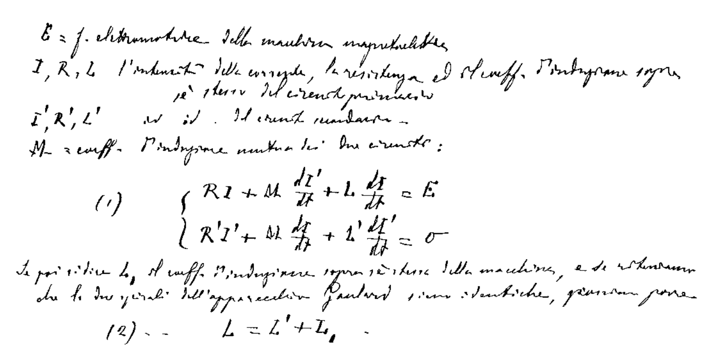
Then the equation of the current x in A will be

$$\xi = Rx + \frac{d}{dt}(Lx+My) \quad\text{..............................}\quad (4),$$

and that of y in B. $\quad \eta = Sy + \frac{d}{dt}(Mx+Ny) \quad\text{............................}\quad (5),$

where ξ and η are the electromotive forces, x and y the currents, and R and S the resistances in A and B respectively.

1864: mutual inductor equations in the Maxwellian Dynamical Theory



E = f. elettromotrice della macchina magnetoelettrica

I, R, L l'intensità della corrente, la resistenza ed il coeff. d'induzione sopra sè stesso del circuito primario

I', R', L' id id. del circuito secondario –

M = coeff. d'induzione mutua dei due circuiti:

$$(1) \quad \begin{cases} RI + M\dfrac{dI'}{dt} + L\dfrac{dI}{dt} = E \\ R'I' + M\dfrac{dI}{dt} + L'\dfrac{dI'}{dt} = 0 \end{cases}$$

Se poi si dice L_1 il coeff. d'induzione sopra sè stesso della macchina, e si ritiene che le due spirali dell'apparecchio Gaulard siano identiche, possiamo porre

$$(2) \ldots \quad L = L' + L_1 \ .$$

1884: notes by G. Ferraris in reference to the Gaulard-Gibbs transformer theory.

Figure1 Maxwellian deduction of the transformer theory by G. Ferraris.

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