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Galileo Ferraris and the post-Maxwellian Electrical Engineering **

Abstract – This is a preliminary study of the process of transformation of the Maxwellian electromagnetism into an electrical technology and of Galileo Ferraris' contributions to this process. In the last quarter of the nineteenth century, a research on the post-Maxwellian electrical science flourished in the Western countries and it soon grew out into the new discipline of electrical engineering. To this special period of the Western scientific evolution, Heaviside and Helmholtz gave outstanding contributions. Because of the special historical situation and the special context of Maxwell's theory, its transformation into concepts and tools suitable for the new discipline was a hard and complex affair. One aspect of Maxwell's program, especially underlined by Heaviside, opened great possibilities to electrical technology and electrical engineering. When Maxwell's theory emigrated to Germany, Helmholtz and Kirchhoff tried to conceal its field characteristics with the German circuital theories. In the same period of time, Ferraris followed lectures in electrodynamics given by G. Codazza that included the theories of F.O. Mossotti, R. Kirchhoff and H. Helmholtz. On the whole, Helmholtz' theory was widely influential on the Continent. However, Ferraris's ways of looking to the electromagnetic phenomena presented an advanced standpoint with respect to post-Helmholtian trends. He adopted Maxwell's field theory standpoint supported by Heaviside and Poynting, and he considered the Poynting's vector as an energy-density flux directed towards the wire conductor.

INTRODUCTION

At the end of the nineteenth century, inventors and scientists in the European countries and in USA co-operated in the invention of new electrical apparatuses and in the construction of new theories, in a overall effort to put at disposal of the

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socially and industrially developing western countries the new form of energy, the electrical energy.

The transformation of concepts and practices from the existing electromagnetic theories to the new occurrences of the electrical technology required a research of great ingenuity and skill. Taking its inspiration from Maxwell's theory, especially from its reinterpretation on behalf of O. Heaviside and J.H. Poynting, this research represented the background for what was later labelled as electrical engineering, a new form of knowledge required to solve the problems posed by the production, transmission and transformation of the new form of energy.

Many European and American universities soon recognised the need for this type of knowledge and for the related professionals, and introduced appropriated courses in their curricula. The Milano Polytechnic was one of the first Western institutions to introduce in 1877 a semester course for the formation of electrical engineers, soon imitated in 1880 by the Regio Museo Industriale in Torino.[1]

To this special period of the Western scientific evolution, Galileo Ferraris (1847-1897) gave outstanding contributions. As recent researches[2] have evidenced, the most celebrated of his contributions to electrical engineering, his pioneering invention of the asynchronous motor, could have represent for itself an outstanding contribution to electrotechnics. But this invention acquires new overtones when considered in the frame of Ferrari's insights towards a general program for a social and industrial utilisation of the new form of energy. His studies on the "secondary generator" and on the advantages of the distribution of alternative versus continuous currents are part of this frame.[3]

Thus, it should be recognised that, because of his technical contributions, Ferraris was one of the outstanding pioneers of electrical technology. He also contributed to the construction of theories suitable for the needs of the future electrical engineering.[4] These theories were to be extracted from the great electromagnetic science of Kelvin, Helmholtz, Maxwell and Heaviside. Maxwell's Electromagnetic theory was surely the most extended and consistent piece of work from which the new electrical technology could have derived its concepts and tools. But,

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[1] Sigfrido Leschiutta, "Galileo Ferraris uomo e ricercatore", in Andrea Silvestri (edit.), *Il centenario AEI e Galileo Ferraris*, quot., pp. 57-77, on p. 66.

[2] R. Manigrasso, A.P. Morando, *La nascita dell'ingegneria elettrica*, Tecniche Nuove, Milano 1997, pp. 92, *passim*.

[3] G. Ferraris, "Ricerche teoriche e sperimentali sul generatore secondario Gaulard e Gibbs", in Andrea Silvestri (edit.), *Il centenario AEI e Galileo Ferraris*, quot., pp. 81-151. G. Ferraris, R. Arnò, "Un nuovo sistema di distribuzione elettrica dell'energia mediante correnti alternative", in *L'Elettricista*, I° Maggio 1896, Vol. III, pp. 315-29. Andrea Silvestri, Note allo stesso in: Andrea Silvestri (edit.), *Il centenario AEI e Galileo Ferraris*, quot., pp. 240-245.

[4] Because of the recognition of the high level of his contribution to science he was elected to the membership of various Academies. He was also a member of our "Accademia delle Scienze, detta dei Quaranta".

because of the special historical situation and the special context into which Maxwell's theory was embedded, its transformation into concepts and tools suitable for the new discipline was a hard and complex affair.

These difficulties were of a double order: some were related to the specific origins of Maxwell's theory, *i.e.*, to its feature of a transition theory from a mechanistic conception to a field conception of nature. This aspect of his research represented his epoch-making contribution to the development of modern physics. However, due to this special situation, Maxwell was induced to deepen the philosophical sides of his theory, placing it on a conceptual level which was not the most favourable for the needs of an electrical technology. The other difficulty concerned the so-called pure field aspect of the Maxwellian electromagnetism and his related rejection of the convective conception of currents.[5] In Chapter Two of the first book of his *A Treatise on Electricity and Magnetism*, Maxwell dealt with many problems related to the distribution of current in nets, a topic of great concern for the transmission of electric power, but his interests were primarily directed to problems related with electrolysis, resistance measurements, conduction in surfaces and solids, conduction in dielectries, ete. Although his Treatise represented an inexhaustible source for specific problems, the emerging electrical technology had to look elsewhere to find theoretical solutions to the difficulties implied in the production of electric power, its distant transmission and its extended net-distribution.[6]

MAXWELL'S PROGRAM: PROGRESSIVE AND REGRESSIVE SHIFTS IN THE TRANSITION FROM A MECHANISTIC TO A FIELD CONCEPTION OF NATURE

In his 1864 "A Dynamical Theory of the Electromagnetic Field",[7] Maxwell achieved an important advance towards the transition to a non-mechanical theory of electromagnetism. He presented a new method for proving the electromagnetic induction law which reversed the mechanical type approach to prove the law, the approach formerly adopted by Thomson and Helmholtz. In fact, Thomson and Helmholtz had started from the law of the mechanical force between currents in order to derive the law of electromagnetic induction. Maxwell avoided this approach and contrasted it with his own, which consisted in reversing the process, i.e., starting from the electromagnetic induction and deriving from it the mechanical forces. The induction law between two circuits was considered the fundamental law from which the mechanical action was to be derived:

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[5] Jed Z. Buchwald, *From Maxwell to Microphysics*, The University of Chicago Press, 1985.

[6] R. Manigrasso, A.P. Morando, *La nascita dell'ingegneria elettrica*, quot.

[7] Maxwell, "A Dynamical Theory of the Electromagnetic Field", in Maxwell, *Scientific Papers*, 2 Vols., Dover Repr. New York 1965, Vol. 1, pp. 526-597. Italian transl.: J.C. Maxwell, "Una teoria dinamica del campo Elettromagnetico" (a cura di S.D.) Ed. Teknos, Roma 1996.

> The phenomenon of the induction of currents has been deduced from their mechanical action by Helmholtz and Thomson. I have followed the reverse order, and deduced the mechanical action from the law of induction. I have then described experimental methods of determining the quantities L, M, N on which these phenomena depend.[8]

Let us consider induction as presented in Maxwell's 1864 Memoir. In the introductory part of this essay, after stating the similarity between the optical and the electromagnetic ether, he added:

> … each part of the field is in connection with both currents, and the two currents are put in connection with each other in virtue of their connection with the magnetization of the field. The first result of this connection which I propose to examine is the induction of one current by another, and by the motion of the conductor in the field.

In a few words, due to Maxwell's ideas of an ethereal connecting mechanism and to the priority assigned to it in the computation of currents interactions, his calculation of the induction coefficient of a coil was strictly related to his field conception: he derived from it a number of important consequences in the computation of the self-induction of a current loop and in the interaction between two closed loops.

In his 1873 *A Treatise on Electricity and Magnetism*, Maxwell abandoned the mechano-elastic analogies, shifting to a more extended usage of Lagrange's equations and to metrological arguments[9] in order to write his field equations. This was another decisive step in the direction of freeing his theory from its early connections with elastic ether and with mechanicism.

Maxwell was also a member of a Committee appointed by the British Association on Standards of Electrical Resistance and, in this position, he was concerned with technical problems in the limited areas of the determination of absolute units for electric and magnetic quantities and of the calculations of capacitances and inductances. Due to this circumstance, electrical technology is indebted to Maxwell's 1863 Memoir[10] because these calculations were of fundamental importance for the then developing electrical technology.

It is worth remarking that Maxwell was innovative not only in the technical aspects of his field theory of electricity and magnetism, but also in his conception of a physical theory. His analogical view of theory completely changed the former conception of theory and, together with it, the theory's ontological status, as Ludwig Boltzmann very aptly remarked.[11] From the methodological standpoint, his

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[8] Maxwell, "A Dynamical Theory …", quot., p. 533.

[9] S. D'Agostino, "Absolute Systems of Units and Dymensions of physical Quantities", *Physis*, Vol. XXXIII (1996), Nuova Serie, fasc. 1-3, pp. 5-51.

[10] "Report of the Committee appointed by the British Association on Standards of Electrical Resistence", *The Report of the British Association for the Advancement of Science*, 1st series, 32, 1863, 111-176.

[11] L. Boltzmann, *Theoretical Physics and Philosophical Problems*, Dordrecht-Boston, 1974,

conception of physical research represented a counter-trend to the methods of mathematical physics — mainly to the French methods — and an initial foundation for the methods of theoretical physics. Infact, in his views on the role of mathematics in physics, he warned against the danger that analytical subtleties might draw aside the mind from the subject and that mere symbols do not readily adapt themselves to the phenomena to be explained.[12]

Not that he discourages the usage of mathematics, but he extolled new relation between mathematics and physical concepts, a relation which he named embodied mathematics.[13] In fact, he thought that in physical analogies mathematics was presented to the mind in an embodied form and that, as such, these analogies were sources of "physical conceptions". One of the most fecund analogies was William Thomson's parallelism between heat propagation and electrostatics, which suggested to him a field theory of the latter. Another was Maxwell's analogy between an elastic fluid in vortex motion and the electromagnetic field in a vacuum, whereby hydrodynamic equations furnished a model for Maxwell's celebrated equations.

In the years of his scientific maturity, Maxwell clearly formulated his preferred method, "the dynamical explanation of phenomena". In his paper "On the Dynamical Evidence of the Molecular Constitution of Bodies" (circa 1874) he thus introduced this method:

> … when a physical phenomenon can be completely described as a change in the configuration and motion of a material system, *the dynamical explanation* of that phenomenon is said to be complete. We cannot conceive any further explanation to be either necessary, desirable, or possible, for as soon as we know what is meant by the words configuration, motion, mass, and force, we see that the ideas which they represent are so elementary that they cannot be explained by means of anything else [Italics mine].[14]

He tells us that he applied his dynamical explanations in his "endeavours to bring electrical phenomena within the province of dynamics". He found that Lagrange's equations represented the most suitable mathematical formalism for his dynamical ideas.[15]

Using Lakatos' historiography,[16] Maxwell's dynamical reasoning can be considered the progressive aspect of Maxwell's program. The other side of Maxwell's programme, to which scientists like Kelvin and Larmor gave their support, was the

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an almost integral Engl. Transl of L. Boltzmann, Populaere Schriften (Leiptsig 1905; Vieweg 1979). S. D'Agostino, "Boltzmann and Hertz on the Bild-conception of Physical Theory", *History of Science*, xxviii (1990) 380-98.

[12] J.C. Maxwell, "On Faraday's Lines ot Force", *The scientific papers*, quot., pp. 155-56.

[13] *Ibid*., p. 87.

[14] Maxwell, "On the Dynamical Evidence of the molecular Constitution of Bodies", in Maxwell, *Scientific Papers*, 2 Vols., Dover Repr. New York 1965, Vol. 2. pp. 418-438, p. 418.

[15] Maxwell, "A Dynamical Theory …", quot., p. 537.

[16] Imre Lakatos, "Criticism and the Methodology of Scientific Research Programmes", in *Proceedings of the Aristoteliena Society*, 69 (1968).

search for detailed ethereal “mechanical” models. He was also leaving to future research the working out of a detailed mechanism of the ethereal rotations.[17] In Lakatos terminology, this aspect represented the regressive side of Maxwell’s electromagnetic program.

The progressive side of Maxwell’s program liberated enormous scientific potentiality: Maxwell’s equations, in their symmetric form due to Hertz and Heaviside, remained the fundamental equations of classical electromagnetism. Between 1900 and 1905, other less known developments of his theory of dimensional analysis were given by Lord Rayleigh, who applied with success dimensional analysis to problems of mechanics, heat transfer, optics and electromagnetism.[18] Another potentiality of Maxwell’s progressive program was developed by Heaviside and the electrical engineers in the last decades of the century.[19]

Heaviside’s reinterpretation of Maxwell’s mechanicism

Oliver Heaviside was one of those post-Maxwellians[20] who grasped and developed the progressive side of Maxwell’s innovations. Writing in 1893, twenty years after the Maxwellian Treatise, he presented the following comment:

> The old objection that a mechanical theory of light was surely to be preferred to an abstract electromagnetic theory was very misleading. *The electromagnetic theory* [i.e., Maxwell’s theory] *is mechanical, without, however, a precise specification of the mechanism. An elastic solid theory is merely a special mechanical theory*. It cannot satisfy the electromagnetic requirements, but this failure, though immensely important in itself, is not the point here. Even if it did satisfy them, it would probably be less true than the electromagnetic theory; which, being abstract, does not assert so much. There may be many “mechanical” solutions of an abstract theory. Elastic solid theories are a great deal too precise in saying what light consists of, and mechanical speculations in general should be received with much caution, and regarded rather as illustrations or analogies than expressions of facts. We do not know enough yet about the ether for dogmatising (My underlying. Parentheses [] added).[21]

In his considerations Heaviside distinguished between a “mechanical theory of light” and a “precise specification of the mechanism”. The electromagnetic theory of light was for him “a mechanical theory”, even though it did not deal with “a pre-

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[17] J.C. Maxwell, *A Treatise on Electricity and Magnetism*, 1954 Dover reprint of the Third 1891 Edition, 2 Vols. Vol 2. p. 470.

[18] L. Rayleigh, *The principle of Similitude*, Nature, n° 2368, XCV, 1915, pp. 66-68. In 1914, E. Buckingham generalised Maxwell’s theorems of products with fixed dimensions in a theory of physically similar systems, the so-called “Π theorem”, through which dimensional analysis became a useful tool in the theory of physical similitude and of physical models.

[19] R. Manigrasso, A.P. Morando, *La nascita dell’ingegneria elettrica*, quot.

[20] Jed Z. Buchwald, “Oliver Heaviside, Maxwell’s Apostle and Maxwellian Apostate”, *Centaurus* 1985; vol. 28: pp. 288-330.

[21] Oliver Heaviside, *Electromagnetic Theory*, 3 volumes. I (1893), II (1899), III (1912), Dover publications, N.Y., 1950. Vol. I, on p. 83. Original Edition, pp. 326-327.

cise specification of the mechanism", *i.e.* a detailed description of the composition and movement of ether. The attempt at such a description was proper of the elastic theories of ether, which he considered "mechanical speculations" because, as he remarks, they were based on hypothetical assumptions, *i.e.* assumptions regarding properties of density and elasticity of ether and their modifications necessary to explain refraction.

Heavide continued:

> … On the other hand, the electromagnetic theory says that light consists of electromagnetic vibrations in the aether. This, too, is a hypothesis. But the auxiliary part, that refraction is caused by change of permittivity from one medium to another, is not a hypothesis, but a fact. Moreover, the theory works. Similarly, double refraction in elastic solid theories of light is explained by eolotropy as regards elasticity, or by something similar relating to the density. This is also hypothetical, and not without its troubles. But, on the other hand, Maxwell declared that double refraction occurs because the double refracting medium is electrically eolotropic. Now this is a fact too, and the theory is a clear one.[22]

The essence of Heaviside's position was that changes in permittivity and electrical eolotropy can be *independently* observed, (i.e. they can be observed through electrical experiments that do not imply elasto-optical concepts or theories), but that properties like density and elasticity of ether cannot be *independently* observed. The changes above concern factual properties or facts, while density and elasticity of ether remain hypothetical assumptions.[23]

According to Heaviside, scientific explanations should be limited to making evident the connection between observable properties, without any concern with the problem of explaining why the connection exists. It is the "relational" aspect of the connection which is relevant for science. This is a special conception of the scientific explanation and it offers new criteria for scientific research. Notice that this conception, the relational theory of optical and electrical properties, was first achieved by Maxwell's 1873 solution to the problem of the relationship between Weber's ratio and the velocity of light.[24]

In my opinion it was this side of Maxwell's program, especially underlined by Heaviside, which contributed to the development of electrical technology and electrical engineering.

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[22] *Ibid.*, p. 83.

[23] The same considerations can be addressed to Maxwell's theory on the velocity of light as a conversion factor between units. At bottom, Maxwell's metrological approach explained phenomena by connecting electrical properties with the optical properties, both independently observable, both "factual" in character (S. D'Agostino, "Absolute Systems of Units and Dymensions of physical Quantities …", quot.). Quite differently, when established through the mechano-elastic properties of bodies, this connection is too stringent because we do not have any independent observations of mechanical properties of ether ("… elastic solid theories are a great deal too precise in saying what light consists of …").

[24] S. D'Agostino, "Absolute Systems of Units and Dymensions of physical Quantities …", quot., p. 37, *passim*.

German electrodynamics: another bridge between Maxwell's pure field theory and electrical engineering.

However, apart from the above outstanding contributions, extended theorisation of electric circuits were not at the focus of Maxwell's theory. The reasons are to be sought in the historical situation in which the theory had its origin. In fact, it grafted its conceptions of free propagation in ether onto Faraday's dielectric conceptions, which wavered between the different views of dielectric action as polarisation of space-filling matter and as independently existing lines of force.[25] Maxwell studied and rejected continental ideas of currents and charges but his own ideas concerning these quantities were anything but definitive and clearly expressed.[26] Maxwell's pure field theory was thus unlikely to contribute to the theory of conduction and propagation in wires.

When Maxwell's theory emigrated in Germany, it was Helmholtz who tried to conceal its field characteristics with the German theories. In 1870 Helmholtz began publishing a series of articles that presented a comprehensive study of the electrodynamics of his time. He approached the problem of action at a distance and contiguous action in an original way by combining Poisson's theory of dielectrics with Franz Neumann's potential theory to yield a Maxwell-type theory of propagation through a "medium".

Helmholtz' first article of the series, "On the Equations of Motion of Electricity for Conducting Bodies at Rest",[27] to which Hertz often referred in the course of his work, was a vast "tour d'horizon" of the competing theories of electrodynamics. It is significant that only sixteen out of the eighty-four pages of this large article were devoted to a theory of dielectric action; the remaining part was concerned with a form of potential theory and its consequences for induction and the motion of electricity in extended conductors.[28]

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[25] P.M. Heimann, "Maxwell and the Modes of Consistent Representation", *Archive for History of Exact Sciences*, 6 (1970), 171-213.

[26] Joan Bromberg, "Maxwell's Displacement Current and His Theory of Light", *ibid.*, 3 (1967), 218-234.

[27] Herman von Helmholtz, "Ueber die Theorie der Elektrodynamik. Erste Abhandlung. Uber die Bewegungsgleichungen der Elektricitat fur ruhende leitende Korper", *Borchardt's Journal fur die reine und angewandte Mathematik*, 72 (1870), 57-129; in *Wiss. Abhandl.*, 1, 545-628.

[28] Helmholtz started with an electrodynamic potential of two elements of circuits $d\boldsymbol{\sigma}_1$, $d\boldsymbol{\sigma}_2$ at a distance r from one another and carrying currents of intensity u_1, u_2. In modern vector notation, the potential is:

$$\frac{A}{2}\,\frac{u_1 u_2}{r}\left[(1+\mathrm{K})\; d\boldsymbol{\sigma}_1 \cdot d\boldsymbol{\sigma}_2 + (1-\mathrm{K})\,\frac{\mathbf{r}\cdot d\boldsymbol{\sigma}_1\;\mathbf{r}\cdot d\boldsymbol{\sigma}_2}{r^2}\right]$$

where A is Weber's ratio or conversion coefficient from electromagnetic to electrostatic units. The different values of h define the potential functions of Weber (K=-1), of Franz Neumann (K=1), and of Maxwell (K=0). When Helmholtz' potential is integrated around a closed circuit, any dependence on K is lost, so that only experiments with open circuits seemed suitable for discri-

In Helmholtz' treatment of theories of dielectric action, he regarded the polarisation of dielectrics in Poisson's sense as resulting not only from static forces but also from electromagnetic ones; *i.e.*, he recognised an additional polarisation produced by the time variation of an electric or magnetic field.

He interpreted Maxwell's displacement current in ether as a tentative extrapolation to ether of the dielectric polarizability of some material insulators. In his view, once the ether is considered magnetizable, the "moment is no longer far off when one can consider it also as a dielectric in Faraday's sense".[29]

Although Helmholtz presented a wave equation for the polarisation, his physical ideas were by no means identical with Maxwell's. Helmholtz was aware of the differences, pointing out that his and Maxwell's theories "are opposed to each other in a certain sense, since according to the theory of magnetic induction originating with Poisson, which can be carried through in a fully corresponding way for the theory of dielectric polarization of insulators, the action at a distance is diminished by the polarisation whereas according to Maxwell's theory the action at a distance is exactly replaced by the polarisation".[30]

Helmholtz' article of 1870, in which he placed the different electrodynamical theories of Weber, Franz Neumann and Maxwell on a basis that allowed for an experimental decision, was consistent with his general ideas on scientific inquiry. His concrete interpretation of Maxwell's displacement current as the dielectric polarisation of insulators was, perhaps, the best exemplification of this frame of mind.

Helmholtz was confident that the "conviction might gain ground that the only successful experimenter in physical science is the man who has a thorough theoretical knowledge", a combination that had been brilliantly demonstrated by Kirchhoff in the discovery of spectrum analysis. In Helmholtz' eyes, theoretical physics was also an empirical science and he struggled "to break down the barrier between experimental and theoretical physics".[31] His aversion towards a certain kind of abstractness stemmed, too, from his polemic against the late followers of German *Naturphilosophie*.

minating among the competing theories. Helmholtz extended his potential for linear currents at positions p and p′ to volume currents: the potential per unit volume of a current of density u at the position p and time t is:

$$-A^2\mathbf{U}\,(\mathbf{p},t)\cdot\mathbf{u}\,(\mathbf{p},t),$$

where

$$\mathbf{U}\,(\mathbf{p},t)=\int_{?}^{?}\left[\frac{1+K}{2}\,\frac{\mathbf{u}}{\mathrm{r}}+\frac{1-K}{2}\,\frac{\mathbf{r}}{\mathrm{r}^3}\,(\mathbf{r}\cdot\mathbf{u})\right]d\tau$$

and

$$\mathbf{r}=\mathbf{p}-\mathbf{p}'\ \cdot$$

[29] Helmholtz, 1, "Über die Theorie ..." (1870), cit. 556.

[30] Helmholtz, 1, 556-557.

[31] Leo Königsberger, *Hermann von Helmholtz*, Dover Publ. 1965, p. 266 *passim*.

Helmholtz' theory was widely influential on the Continent. Hertz took it as the starting point for his researches in 1887, as did H.A. Lorentz, who accepted action at a distance in the Helmholtian formulation as the basis for his investigation of Maxwell's electromagnetic theory of light. Henri Poincaré devoted many pages of his *Electricité et Optique*[32] of 1901 to an assessment of Helmholtz' theory and its relation to Maxwell's. Pierre Duhem, after a strong criticism of Maxwell's theory and of Boltzmann's formulation of it, recommended Helmholtz' theory as "a natural continuation of the theories of Poisson, Ampere, Weber, Neumann", establishing a "continuity of tradition, without missing any of the recent conquests of electrical science".[33]

Galileo Ferraris an Italian Maxwellian

In the last quarter of nineteenth century, the Italian research on the post-Maxwellian electrical science channelled into three distinct directions.

Mathematical physicists such as E. Beltrami and E. Padova, working in the Italian universities, devoted a relevant part of their researches to constructing mechanical models of an electromagnetic ether suitable for supporting the strain and stresses of Maxwell's theory.[34] They failed to reach this particular goal, but succeeded in pushing further mathematical analysis and tensorial theory.[35]

A second direction was represented by Italian physicists such as Pietro Blaserna and Antonio Garbasso, who improved their postgraduate formation under Helmholtz's guidance. Helmholtz papers are often quoted in their contributions.[36] They were inspired by the German interpretation of Maxwell's electromagnetism, especially by the Helmholtzian Elektrodynamik. Hertz's theory and his great experiments on the propagation of electromagnetic waves were sources for the experiments of Augusto Righi.[37]

As a third direction, another type of research in the electrical science, flourished in Italy and in some European countries in the last quarter of the century, i.e. electrical engineering. G. Ferraris was a pioneer in the new discipline.[38] He fol-

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[32] Henri Poincaré, *Electricité et Optique* (Paris 1901). See especially chapter 5.

[33] Pierre Duhem, *Les Théories electriques de J.C. Maxwell* (Paris 1902), p. 225.

[34] E. Beltrami, "Sull'interpretazione meccanica delle formole di Maxwell", 1886, in: *Opere IV*, 190-223. E. Padova, "La teoria di Maxwell negli spazi curvi", *Atti della R. Accademia Nazionale dei Lincei*, (4) 5, 875-880.

[35] Rossana Tazzioli, "Ether and Theory of Elasticity in Beltrami's Work", *Archive for History of Exact Science*, vol. 46, N. 1, 1993, pp. 1-37.

[36] A. Garbasso, "La teoria di Maxwell dell'elettricità e della luce", *Rivista di matematica* (Estratto) 1863, p. 1.

[37] G. Giuliani, *Il Nuovo Cimento, Novant'anni di fisica in Italia 1855-1944*, Percorsi della Fisica, La Goliardica Pavese, 1996.

[38] Extended news on Ferraris' life and scientific career are in: S. D'Agostino, A. Rossi (edits), *Galileo Ferraris e il suo tempo*; a volume dedicated to G. Ferraris and the rise of electrical engineering in Italy. *Physis*, Vol. XXXV (1998), Nuova Serie, Fasc. 2.

lowed lectures in electrodynamics given by G. Codazza that included the theories of F.O. Mossotti, R. Kirchhoff and H. Helmholtz.[39] His 1872 doctoral research expanded Kirchhoff' 1857 contributions.[40]

Helmholtz's mixed approach between the original Maxwellian programme and the continental Electrodynamics influenced the majority of Italian physicists. However, it can be stated that, at difference with this majority,[41] in his maturity Ferraris privileged an approach to electromagnetism more keen to Maxwell's, and to the post-Maxwellians' Heaviside and Poynting. In fact, Maxwell's theory was the preferred reference in Ferraris' last lectures on Electromagnetism.[42] In these lectures, Maxwell's equations were introduced dynamically, as a consequence of Faraday's and Ampere's law, when the latter was completed with the displacement current term.

On the whole, Ferraris's ways of looking to the electromagnetic phenomena presented and advanced standpoint with respect to post-Helmholtian trends.[43] Ferraris adopted[44] the local-theory standpoint supported by Heaviside and Poynting, and he considered the Poynting's vector as an energy-density flux directed towards the wire conductor also in the stationary case.[45] In his "Lezioni di Elettrotecnica", he affirmed that "Poynting started from Maxwell's equations in order to prove how the electromagnetic energy is propagated", and that, "following Maxwell's full confirmation through Hertz's experiments, Poynting's deductions have acquired an enormous relief".[46] In the same passage, he referred to Poynting's 1884 paper.[47]

In order to have a more detailed understanding of the relationship between Maxwell's electromagnetic theory and Ferrari's achievements in the electrical technology, let us examine Maxwell's celebrated equations of the two coupled circuits, which were taken by Ferraris as the basic assumptions for his "secondary generator", i.e., the transformer.[48]

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[39] R. Manigrasso, A.P. Morando, *La nascita dell'ingegneria elettrica*, quot., p. 93. Sigfrido Leschiutta, "Galileo Ferraris uomo e ricercatore", in Andrea Silvestri (edit.), *Il centenario AEI e Galileo Ferraris*, Ass. Elettrotecnica Italiana, 1997, p. 66.

[40] R. Kirchhoff, "Über die Bewegung der Elektricitätet in Leitern", *Ann. der Physik*, CII (1857) 529-44. Cfr. also: M. Guidone, "Galileo Ferraris e i fondamenti scientifici dell'elettrotecnica" in *Physis*, Vol. XXV (1998), cit. pp. 273-290.

[41] As it is the case with Garbasso's 1863 paper.

[42] Ferraris, *Lezioni di elettrotecnica dettate nel Regio Museo Industriale di Torino*, Torino Fossati 1889; Torino Stern, 1921.

[43] See Ferraris' criticism to the current's simple idrodynamic model, in his *Lezioni di elettrotecnica*, quot. Ferraris, *Opere*, 3 Vols. Milano Hoepli, 1900, vol. 2, p. 462.

[44] Ferraris, *Opere*, quot., vol. 2, p. 467.

[45] G. Ferraris, "Sulla trasmissione elettrica dell'energia", 1894, estratto del rendiconto della Regia Accademia dei Lincei. Ferraris, *Opere*, quot., vol. 2, p. 463.

[46] G. Ferraris, *Lezioni di elettrotecnica*, quot., p. 389.

[47] J.H. Poynting, "On the Transfer of Energy in the Electromagnetic Field", *Phil. Trans. of the Royal Soc.*, 175 (1884), pp. 343-361.

[48] A. Morando, Note a G. Ferraris, "Ricerche teoriche e sperimentali sul generatore secondario di Gaulard c Gibbs", in Andrea Silvestri (edit.), *Il centenario AEI e Galileo Ferraris*, quot., p. 225.

In Maxwell's notation R, S are resistances of the primary and secondary circuits A and B, respectively, L, M, N, inertia coefficients in Maxwell's mechanical interpretation of induction, x and y are intensity of currents, $Lx + My$, $Mx + Ny$, are electromagnetic momenta belonging to A and B, respectively. L, M, N are assumed constants since there is not motion in the conductors; ξ is an electromotrice force acting on A.

The equations of the coupled circuits are:[49]

$$\begin{aligned} Rx + L\frac{dx}{dt} + M\frac{dy}{dt} &= \xi \\ Sy + M\frac{dx}{dt} + N\frac{dy}{dt} &= 0 \end{aligned} \qquad (13^*)$$

If x_0, y_0 are the current strengths at time $t=0$ and x_1, y_1 at time t, and if X, Y are the quantities of electricity which cross the circuit at time t, Maxwell's solutions of these equations are:

$$\begin{aligned} X &= \frac{1}{R}\,\{\xi t + L(x_0\text{-}x_1) + M(y_0\text{-}y_1)\} \\ Y &= \frac{1}{S}\,\{M(x_0\text{-}x_1) + N(y_0\text{-}y_1)\} \end{aligned} \qquad (14^*)$$

We see that Maxwell's solutions are here limited to the case of fixed coils and to a finite variation of current in the primary. The cases of the moving suspended magnet of the Weber's dynamometer and of the moving suspended coil of Weber's electrometer are treated without integrating the equations, with a method which has by then become a standard.

It is evident that the real referent of Maxwell's method is the problem of the coils of a measuring apparatus which can dispense of the iron core and that Maxwell's treatment is appropriate to the phenomenon he had in view. It is then inaccurate to consider Maxwell's approach as reductive and imprecise with respect to the further development of the method as applied to the two coils and the iron nucleus of the electric transformer. One should rather admit that we owe to the Maxwellian theory the fundamentals of any future calculation of induction coefficients in such a basic object of the electrical technology as the transformer.[50]

Let us compare Maxwell's theory of induction coils with Ferraris' theory of Goulard and Gibbs "secondary generator", in which the celebrated factor < cos f >

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[49] Maxwell, "A Dynamical Theory ...", in Maxwell, *Scientific Papers*, 2 Vols., quot., Vol. 1, on p. 544. Italian transl., quoted p. 24.

[50] R. Manigrasso, A.P. Morando, *La nascita dell'ingegneria elettrica*, quot., p. 546.

appeared for the first time.[51] Ferraris begins to treat the special case of equal primary and secondary coils consisting of closely situated and mutually alternating spirals, equally positioned with respect to the iron nucleus. The secondary coil consists of circuits in series. Through these specification and assuming that the nucleus magnetisation is proportional to the intensity of the primary current, he writes the following system of equations:

$$ri + aM\,(di/dt + di'/dt) + b(di/dt + di'/dt) = e$$

$$r'i' + aM\,(di/dt + di'/dt) + b(di/dt + di'/dt) = 0$$

Where, a, is the induction coefficient of the iron nucleus on the primary and the secondary coil; b, the mutual induction coefficient between the two spirals and of each spiral on itself; r, r' are the spirals resistances; M, a coefficient depending on the shape and dimensions of the apparatus.

The difference between Maxwell's and Ferraris' approaches are to be attributed to different research contexts: Maxwell was interested in a coupling between neighbouring currents in air — *i.e.*, the case of Weber's electrodynamometer — while Ferraris had as a referent a real transformer where the nucleus has the indispensable function of concentrating the flux of the magnetic induction and thus increasing the yield.

Ferraris' contribution to the theory of the transformer, and especially his elaboration of the active power formula VI cos f (V, I, potential and current intensity respectively, f, the so-called phase factor) are well known. However, only recently historians have underlined a more comprehensive view of the relationship among the various components of his discoveries.[52]

It was precisely thanks to his theory that transformer efficiency was finally found to have a value to justify its utilisation in a technical context. G. Ferraris must also be considered as responsible for the initial success of alternating current. His invention of the asynchronous machine is to be seen in this context: the spontaneous torque alternating current motor, downstream of an alternating current transformer, become through him a reality.

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[51] G. Ferraris, "Ricerche teoriche e sperimentali sul generatore secondario Gaulard e Gibbs", in Andrea Silvestri (edit.), *Il centenario AEI e Galileo Ferraris*, quot., pp. 81-151.

[52] S. D'Agostino, A. Rossi (edits), *Galileo Ferraris e il suo tempo*, quot.