The History of Electrical Resonance

By JULIAN BLANCHARD

OUR earliest knowledge of electricity was of the static kind; later came the voltaic cell and the direct current. But not until the discovery of alternating or oscillating currents of electricity could the phenomenon of electrical resonance make its appearance. Today, as we turn the dials of our radio receivers and "tune in" on the station we want it is recognized how widespread its application has become. Nevertheless, it seems that few have given thought to how this important principle came to light and how and when it got into common use.

THE OSCILLATORY NATURE OF THE LEYDEN JAR DISCHARGE

The Leyden jar, discovered in 1746, was for many years one of the most important instruments in the meager equipment of electrical experimenters. When the jar was charged by an electrical machine and the discharging knobs brought close enough together a spark would jump between them. The savants of those days reasoned that this doubly coated jar was a storer of electricity, a condenser; that before the spark passed there was an accumulation of positive charge on one coating and of negative on the other; and when the spark passed these charges neutralized each other and the jar was discharged. But they did not know or suspect that this discharge was oscillatory, that first one side and then the other became positively charged, until the motion gradually came to rest.

The view that such was the case seems first to have been put forward in 1826 by Felix Savary, in France. It had been observed by him, and very likely by others as well, that a steel needle magnetized by the discharge of a Leyden jar did not in all circumstances have the same polarity. In the following words he suggested the idea that the results were due to the oscillatory discharge of the jar:

"An electric discharge is a phenomenon of movement. Is this movement a continuous translation of matter in a determined direction? Then the opposite polarity of magnetism observed at different distances from a straight conductor, or in a helix with gradually increasing discharges, would be due entirely to the mutual reactions of the magnetic particles in the steel needles. The manner in which the action of a wire changes with its length appears to me to exclude this supposition.

"Is the electric movement during the discharge, on the other hand, a series of oscillations transmitted from the wire to the surrounding medium and soon attenuated by resistances which increase rapidly with the absolute velocity of the moving particles?

"All the phenomena lead to this hypothesis which makes not only the intensity but the polarity of the magnetism depend on the laws in accordance with which the small movements die out in the wire, in the surrounding medium, and in the substance which receives and conserves the magnetism."[1]

Some fifteen years later Joseph Henry in America was experimenting with the Leyden jar and studying the currents induced in adjoining conductors by the discharge through another conductor. To determine the direction of the induced current he observed the polarity of a small steel needle magnetized by the current. In describing his experiments at a session of the American Philosophical Society he made reference to the work of Savary and stated that he had undertaken to repeat this investigator's experiments before attempting any new advances. He observed the same effect, the occasional reversal of the polarity of the needle after a discharge, and arrived at the same explanation:

"This anomaly which has remained so long unexplained, and which at first sight appears at variance with all our theoretical ideas of the connection of electricity and magnetism, was after considerable study satisfactorily referred by the author to an action of the discharge of the Leyden jar which had never before been recognized. The discharge, whatever may be its nature, is not correctly represented (employing for simplicity the theory of Franklin) by the single transfer of an imponderable fluid from one side of the jar to the other; the phenomena require us to admit *the existence of a principal discharge in one direction, and then several reflex actions backward and forward, each more feeble than the preceding, until the equilibrium is obtained.* All the facts are shown to be in accordance with this hypothesis, and a ready explanation is afforded by it of a number of phenomena which are to be found in the older works on electricity, but which have until this time remained unexplained."[2]

The published account of Henry's observations is not precisely in his own words but apparently in those of the reporter or secretary of the Society before which he spoke. It would seem from the above quotation, if it correctly represented the author, that Henry had overlooked the conclusions drawn by Savary, for they appear to be the same as his own.

This was in 1842. At a meeting of the Physical Society of Berlin in 1847 Helmholtz read his celebrated paper "On the Conservation of Force" (*Über die Erhaltung der Kraft*). Among the many illustrations of the conservation of energy principle in various branches of physics he discussed the case of the Leyden jar discharge, and incidentally noted another bit of evidence in favor of its oscillatory nature, an experiment by Wollaston in electrolysis. Commenting on the energy relations found to hold in this case he said:

"It is easy to explain this law if we assume that the discharge of a battery is not a simple motion of the electricity in one direction, but a backward and forward motion between the coatings, in oscillations which become continually smaller until the entire *vis viva* is destroyed by the sum of the resistances. The notion that the current of discharge consists of alternately opposed currents is favored by the alternately opposed magnetic actions of the same; and secondly by the phenomena observed by Wollaston while attempting to decompose water by electric shocks, that both descriptions of gases are exhibited at both electrodes."[3]

It may be interesting to note in passing that this now famous memoir by Helmholtz on the conservation of energy was considered so advanced and speculative as to be refused publication in the leading German scientific journal of the time. In it there was set forth, with far more thoroughness and generality than had been done before (by Mayer and Joule, for instance), the theorem that in any closed system the sum total of the energy is constant; a principle that at once denies the possibility of perpetual motion. It was privately published in pamphlet form in 1847. Its author, later to be recognized as the greatest German physicist of the century, was then an obscure young army surgeon, just twenty-six years of age.

By this time, it can be assumed from the foregoing, it was generally accepted by the learned in electrical science that the spark of a Leyden jar discharge was an oscillatory motion of electricity. This conclusion was arrived at as a logical and reasonable deduction from the results of various experiments, although the mode of action was still obscure. It was time now for a more analytical examination of the subject, and this was soon to appear.

In 1853 the British physicist Sir William Thomson, afterwards Lord Kelvin, published a paper with the title "On Transient Electric Currents,"[4] which, like that of Helmholtz, became in time a classic. In this paper the generalized problem of the discharge of a condenser through a conductor was treated mathematically. In addition to resistance and capacity he recognized the effect of inductance (called by him the "electrodynamic capacity") upon the discharge, and established an equation expressing the fact that the energy of the charged condenser at any instant during discharge is partly being dissipated as heat and partly conserved as current energy in the circuit; his equation being, in present day terminology,

$$-\frac{d}{dt}\left(\frac{1}{2}\frac{q^2}{C}\right) = \frac{d}{dt}\left(\frac{1}{2}Li^2\right) + Ri^2,$$

or

$$L\frac{d^2q}{dt^2} + R\frac{dq}{dt} + \frac{q}{C} = 0,$$

an equation that is easily solved. He analyzed the various solutions, which depend upon the relative values of the constants, or their ratios, and showed that under certain conditions the discharge is unidirectional and under others it is oscillatory, but damped. This beautiful bit of mathematical analysis, exact and thorough as it was, and clarifying the entire phenomenon, passed almost unnoticed at the time; but it came into its own with the arrival of wireless telegraphy.

There followed a few years later a direct experimental verification of the theory of the oscillatory nature of the Leyden jar discharge. In 1858 Feddersen[5] examined the spark by means of a revolving mirror, and extended his researches during the following year by the use of photography. There was thus obtained visual evidence of the reversal of direction of the discharge, and it was even possible to determine the frequency; photographs of these oscillatory sparks were sent to Thomson, who had suggested in his paper this very possibility of proof. Other experimenters followed with variations of this method of investigation, and in 1890 Boys[6] improved upon it by photographing the spark by means of a series of rapidly revolving lenses. Shortly before this a very important discovery had been made in connection with the spark discharge, Hertz's discovery of electric waves, and as a consequence more physicists were turning to a study of its characteristics, chiefly with the aid of photography.

The Effect of Capacity in an Alternating Current Circuit

It will be noted that the foregoing account is concerned with the very rapid, and transient, motion of electricity in open circuits. While knowledge of this sort of electric current was being advanced, Faraday's (and Henry's) discoveries in electromagnetic induction had made possible the invention of the dynamo and the production of a sustained alternating current—ordinarily of much slower motion. This generator, at first in the form of the feeble magneto, was for a long time not much more than a toy, and experience continued to be limited largely to the direct "galvanic" current. When eventually alternating currents began to be employed to an appreciable extent, in experiment and in industry, there were some new phenomena encountered, and those less theoretically grounded were slow to realize the peculiar effect of a condenser in the circuit, although the choking effect of an inductance alone was easily apparent.

The name of the great genius Maxwell now comes into our history. As we have seen, Lord Kelvin was the first to give a mathematical treatment of the oscillations of a Leyden jar discharge. So Clerk Maxwell was the first to publish an analysis of the effect of capacity in a circuit containing inductance and resistance and an impressed alternating electromotive force, and to show the conditions for resonance. The way in which he came to solve this problem makes an interesting story, and it was told in a characteristically interesting manner by the late Professor Pupin in the course of a discussion at a meeting of the A.I.E.E. Some preliminaries to this story may first be related.

For long the Ruhmkorff induction coil and the magneto-electric machine had been familiar objects in physical laboratories. In 1866 there appeared a description of Henry Wilde's striking experiments in which he virtually reinvented and introduced the separately excited dynamo, passing the small (commutated) current from a magneto-electric generator through the field magnet windings of another machine, from the armature of which a very much larger current was obtained. Sir William Grove, reading of these experiments, had the idea that a magneto might also be used advantageously to operate a Ruhmkorff coil with an alternating current. Induction coils had always been excited by means of a battery with a self-acting circuit breaker to interrupt the primary current, and in order to prevent sparking at the contacts and to stop the current more abruptly a condenser was connected across the contact terminals. Grove screwed up and kept closed the contact breaker, thus short-circuiting the condenser, and applied an ordinary medical magneto-electric machine to the primary terminals of his induction coil. To his surprise he found that he could get no secondary discharge at all; but by holding open the contact breaker, and so putting the condenser permanently in series with the primary coil and the armature of the magneto-electric machine, he obtained sparks nearly a third of an inch in length between the ends of the secondary. He saw that the effect was dependent upon the presence of the condenser in the circuit; "But why there should be no effect, or an appreciable one, when the primary circuit is completed, the current being alternated by the rotation of the coils of the magneto-electric machine, I cannot satisfactorily explain," he said.[7]

And now Professor Pupin's story:

". . . Maxwell, I think, was the first to show the effect of introducing a condenser into an alternating current circuit, and it is very interesting to observe this circumstance. Maxwell was spending an evening with Sir William Grove who was then engaged in experiments on vacuum tube discharges. He used an induction coil for this purpose, and found that if he put a condenser in parallel [it was in series, rather] with the primary circuit of his induction coil he could get very much larger sparks, which meant, of course, that he got a very much larger current through his primary coil, an alternating current generator being used to feed the primary. He could not see why. Maxwell, at that time, was a young man. That was about 1865, if I do not err. [It was 1868.] Grove knew that Maxwell was a splendid mathematician, and that he also had mastered the science of electricity as very few men had, especially the theoretical part of it, and so he thought he would ask this young man how it was possible to obtain such powerful currents in the primary circuit by adding a condenser. Maxwell, who had not had very much experience in experimental electricity at that time, was at a loss. But he spent that night in working over his problem, and the next morning he wrote a letter to Sir William Grove explaining the whole theory of the condenser in multiple [series] connection with a coil. It is wonderful what a genius can do in one night! He pointed out the exact relations between the condenser, the self-induction and the frequency which would give the largest current, and he was the first to do this, so far as I know . . ."[8]

Maxwell's letter, which began with the sentence, "Since our conversation yesterday on your experiment on magneto-electric induction, I have considered it mathematically, and now send you the result," was dated March 27, 1868; it was sent by Grove to the Philosophical Magazine, where it was published in May. Preliminary to the mathematical treatment Maxwell gave in this letter an unusually clear exposition of the analogy existing between certain electrical and mechanical effects, and from the standpoint of pedagogy as well as physics it will be interesting to see the language he used. He expressed himself thus:

"The machine produces in the primary wire an alternating electromotive force, which we may compare to a mechanical force alternately pushing and pulling at a body.

"The resistance of the primary wire we may compare to the effect of a viscous fluid in which the body is made to move backwards and forwards.

"The electromagnetic coil, on account of its self-induction, resists the starting and stopping of the current, just as the mass of a large boat resists the efforts of a man trying to move it backwards and forwards.

"The condenser resists the accumulation of electricity on its surface, just as a railway buffer resists the motion of a carriage towards a fixed obstacle."[9]

Using such concepts as these he gave a simple and lucid explanation of the problem without resort to mathematics; and then in a postscript, or appendix, he gave the mathematical theory of the experiment, employing a schematic diagram of the apparatus. Using different, but equivalent, symbols, he derived and solved the now familiar expression for the current i in such a circuit,

$$E \sin \omega t = L \frac{di}{dt} + Ri + \frac{1}{C} \int i dt$$

This is recognizable as similar to that set up by Lord Kelvin for the discharge of a condenser $\left(E \text{ being zero in that case, and } i \text{ being equal to } \frac{dq}{dt} \right)$. The solution of this equation is

$$i = \frac{E}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C} \right)^2}},$$

from which Maxwell pointed out that the current would be a maximum when $\omega L = \frac{1}{\omega C}$ (ω being proportional to the frequency and L and C being the inductance and capacity, all in their proper units). Effecting this condition would of course be a case of "electrical resonance", brought about by electrical "tuning", though Maxwell himself did not specifically make use of these terms.

It is apparent, therefore, that all the knowledge necessary for the realization of electrical tuning was available in 1868 when this little communication of Maxwell's was published. Yet it was some years before electrical resonance was encountered to any extent in practice, or any practical use deliberately made of it. It was something known about by advanced physicists, perhaps, but outside the ken of most of those experimenting with electricity at that period; it must be remembered that there was no profession of electrical engineering as early as this. Not until 1884 do we find any other published discussion of the effect of a condenser in an alternating current circuit. This was in a technical paper by John Hopkinson, Cambridge trained physicist and later to become one of the foremost electrical engineers of his day. The paper had to do with alternating current theory and the operation of alternating current machines, and in it occurs the following:

> "Some time ago Dr. Muirhead told me that the effect of an alternating-current machine could be increased by connecting it to a condenser. This is not difficult to explain: it is a case of resonance analogous to those which are so familiar in the theory of sound and in many other branches of physics.
>
> "Take the simplest case, though some others are as easy to treat. Imagine an alternating-current machine with its terminals connected to a condenser; it is required to find the amplitude of oscillation of potential between the two sides of the condenser. . ."[10]

By setting up an equation similar to that used by Maxwell the required expression was found; and by assuming certain reasonable values of the frequency, resistance, inductance and capacity, he calculated that the amplitude of the potential difference across the condenser might be many times the voltage of the generator. It is apparent from the language he used that he had a perfectly clear understanding of electrical resonance.

The First Electrical Resonance Curve

Following Maxwell, there was another brilliant young physicist destined to become famous who showed a thorough acquaintance with electrical resonance and who made good use of it in his celebrated researches. This was Heinrich Hertz, in Germany, who applied it in the detection of electric waves produced by a spark discharge, the oscillatory nature of which had already been well investigated, as we have seen. The simple device he used for exploring the field in the vicinity of the discharge was a rectangle or circle of wire containing a minute spark gap, the loop being of such dimensions as to be in resonance with his high frequency oscillator. It was by this careful exploration that Hertz demonstrated, for the first time, the existence of electromagnetic waves in space. In the first of his series of papers describing these experiments, "On Very Rapid Electric Oscillations," published in 1887, he devotes one section to a discussion of "Resonance Phenomena." An extract from this will show how he was thinking:

"But it seemed to me that the existence of such oscillations might be proved by showing, if possible, symphonic relations between the mutually reacting circuits. According to the principle of resonance, a regularly alternating current must (other things being similar) act with much stronger inductive effect upon a circuit having the same period of oscillation than upon one of only slightly different period. If, therefore, we allow two circuits, which may be assumed to have approximately the same period of vibration, to react on one another, and if we vary continuously the capacity or coefficient of self-induction of one of them, the resonance should show that for certain values of these quantities the induction is perceptibly stronger than for neighbouring values on either side."[11]

A series of experiments along these lines demonstrated the effect conclusively. In the secondary circuit the length of spark that could be obtained across the adjustable gap increased to a maximum when the two circuits were in tune. The first electrical resonance curve ever published is given in the above mentioned paper,[12] a relation between the length of wire in the detecting loop and the greatest length of spark obtainable for each length of wire, all other conditions remaining unchanged. The curve shows the familiar sharp peak at the point of resonance. In all his succeeding researches on electric waves Hertz used this simple tuned circuit as a detector. It was the forerunner of the resonance type of wave-meter to be used later in the yet unborn art of radio.

Among the prominent British physicists Oliver Lodge at this time was also experimenting with electrical resonance and writing and lecturing about it. He had from the first taken a keen interest in the work of Hertz and in fact came close to anticipating Hertz in the discovery of electric waves through his notable work on lightning conductors. In a brief article published in 1890 he described a method, which he had used a year before in a lecture, of displaying the spark producing power of electric radiation by tuning the circuit of one Leyden jar to that of another containing a spark gap and excited in the usual way.[13] When the secondary circuit was in resonance with the first its Leyden jar would "overflow." But Lodge objected to the use of the term "resonance" and preferred the term "syntony"; "the name 'resonance' is too suggestive of some acoustic reverberation phenomenon to be very expressive," he maintained.[14] Although he and some of the other English writers continued to say "syntony" and "syntonic", this terminology did not permanently stick.

During the next decade, as electrical engineering developed somewhat, especially in alternating currents, we find more attention being paid to this subject, both by physicists and engineers. Among those interesting them-

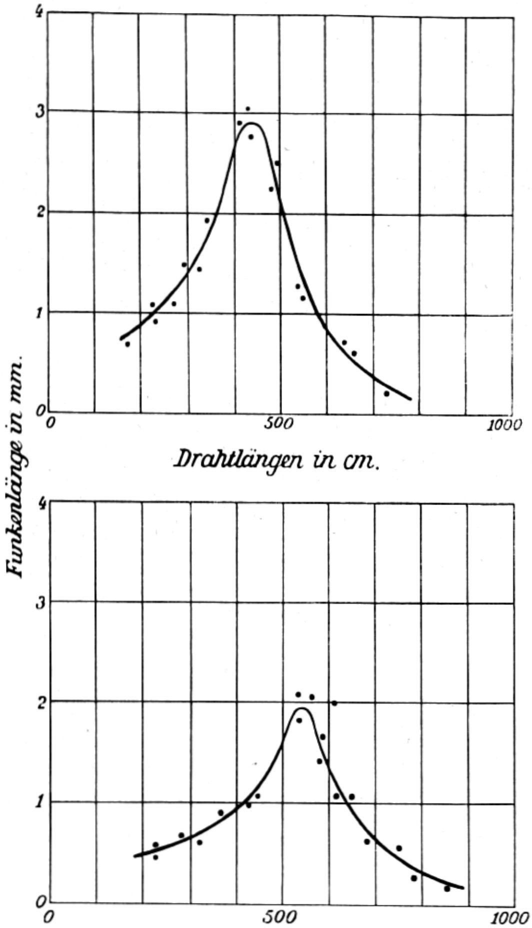

Fig. 1—The first electrical resonance curves published, by Hertz, 1887; showing the greatest length of spark obtainable in his detecting loop for various lengths of wire in the loop.

selves in the matter may be mentioned such men as T. H. Blakesley, Gisbert Kapp, J. A. Fleming, R. T. Glazebrook, James Swinburne, Maurice Hutin and Maurice Leblanc, Frederick Bedell and A. C. Crehore, Nikola Tesla, M. I. Pupin, and John Stone Stone; some of these being concerned with high frequencies, some with low. As indicating the general state of knowledge at this time concerning alternating current theory, a statement in a textbook by Blakesley, with preface dated May, 1889, is illuminating. This author says:

"It is often taken for granted that the simple form of Ohm's Law, total E.M.F. ÷ total resistance = total current, is true for alternating currents. That is to say, the E.M.F. employed in the formula is taken to be the sum of the impressed E.M.F.'s alone. That there are causes which modify the value of the current as deduced from this simple equation, such as mutual or self-induction, or the action of condensers, is often acknowledged in textbooks, and the values and laws of variation of the current are correctly stated for certain cases of instantaneous contact and breaking of circuit. But the effect of an alternating E.M.F. upon a circuit affected by self-induction, mutual induction, and condensing action, has not been, so far as I know, put into a tangible working form."[15]

Somewhat similar observations were expressed by Kapp in an article in the *Electrician* a year or so later. Referring to the paper by Hopkinson mentioned above, he commented as follows:

". . . he showed that with a certain capacity, periodic time, self-induction and resistance in circuit, the potential difference between the plates of the condenser may be 80 times the E.M.F. of the alternator. Startling as such a result must naturally appear, it failed at the time to attract much attention from practical engineers who, no doubt, preoccupied with the problems relating to continuous-current work, were content to let such an intricate and apparently abstruse problem lie at rest until such time as its consideration should be forced upon them. This time has now come, and what in 1884 was merely an interesting laboratory experiment, having no further application than perhaps the breaking down of a condenser, is at present an interesting practical problem, which the electrical engineer has to face. Phenomena arising from the effects of capacity in alternate-current circuits are forcing those who have to do with such circuits to give attention to the problems connected with the phenomena."[16]

This quotation gives a fair picture of the situation with respect to electrical engineering around 1890. Familiarity with capacity and resonant effects, it appears, was beginning to grow with the enlargement of professional experience.

Resonance in Electric Communication

While resonance, or an approximation thereto, is occasionally encountered in ordinary power engineering and electric lighting, here it is generally a case of something to be avoided, evidence of something gone wrong. An unintentional resonant condition in a power circuit could result in considerable damage due to excessive current flow. In electric communication, on the other hand, where frequencies are higher, and where *frequency* itself is one of the fundamental elements, and currents comparatively small, resonance is of prime importance and may be of great practical value.

As we consider the use of resonance in electric communication there may occur to some readers a recollection of a very early system of multiplex signaling known as the "harmonic telegraph", representing the attempts of Elisha Gray, Alexander Graham Bell, E. Mercadier and others to transmit simultaneously a number of telegraph messages over the same line; experiments which, in the case of Bell, led to the invention of the telephone. These various schemes, however, were all based on the principle of mechanical resonance; electromagnetically driven tuned reeds at the receiving end were set to vibrating by signaling currents generated by corresponding reeds at the transmitting end. The principle of electrical resonance was not involved in such methods.

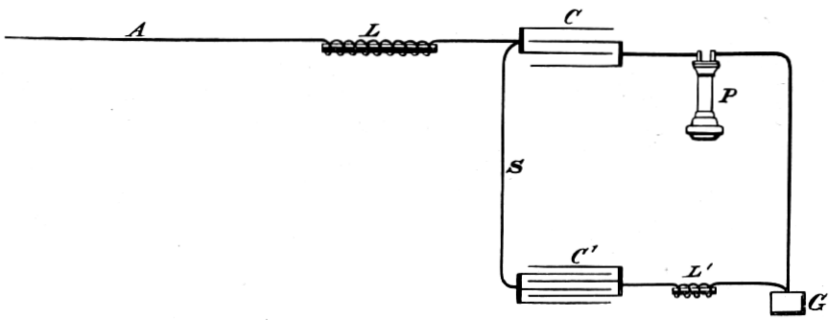

Fig. 2—Combination of series and shunt resonant elements to lessen interference of power source low frequencies with higher telephone frequencies; from U. S. patent of Stanley and Kelly, 1891.

Suggestions for the practical application of electrical resonance began to appear in the early 1890's. By this time, as our history shows, the phenomenon was generally understood by the technically trained and the well informed; it was one of the facts of science open to all. Henceforth, progress in the putting to use of it was largely in the hands of inventors and its history is to be found in the study of patents.

In telephony, one of the earliest proposals is illustrated by a United States patent issued to Stanley and Kelly in 1891,[17] showing methods for preventing interference with telephone currents by lower frequency currents induced in the line by power sources. One of the methods described was the insertion in series with the receiver of a capacity making a combination resonant to the mean speech frequency, supplemented by a shunt combination of capacity and inductance resonant to the interfering frequency. It need hardly be said that such an arrangement, favoring only a narrow band of the speech frequencies, would greatly promote distortion and would find little favor with telephone engineers.

Another application, for a different purpose, appeared in a French patent issued to Hutin and Leblanc during the same year.[18] These engineers were pioneers in the attempt at multiplex telephony by means of high-frequency carrier currents, a method now so greatly extended. In May, 1891, several months before their patent papers were filed, they had reviewed in a French journal the theory of resonance in an inductively coupled circuit in the course of a general article on alternating currents, and had briefly suggested therein its application to multiplex signaling.[19] The scheme disclosed in their patent comprised the transmission over the line of a number of super-audible frequencies, now called carrier currents, the modulation of each by a

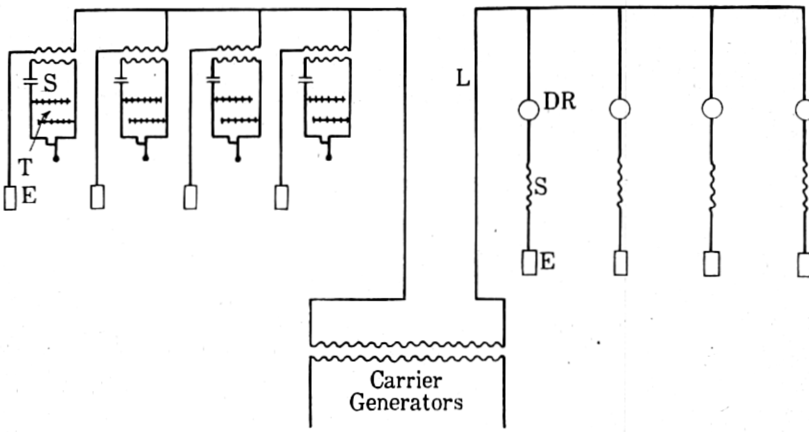

Fig. 3—Multiplex carrier telephone circuit of Hutin and Leblanc, as in their French patent of 1891. At each terminal are shown four branches, each of these branch circuits being tuned to one of the carrier frequencies.

separate telephone transmitter, and means for separating and detecting the individual messages. At both the transmitting and receiving ends, in their plan, there were branches from the connecting line, each of these branch circuits being tuned by means of a capacity which balanced the inductance in the circuit, so that each responded by resonance to its own carrier frequency to the exclusion of the others.* Here was a substitution of electrical resonance for the mechanical resonance of the older harmonic telegraph.

At about this same time Professor Pupin in his early research work at Columbia had developed a method of analyzing a complex current by picking out its components in an inductively coupled resonant circuit—a

* While their patent drawing fails to show tuning condensers in the receiving branches, without which the scheme would be inoperative, and the description on this point is vague, in the interference cases that later developed in the U. S. Patent Office (reference 24) it was claimed that this omission was an oversight. In a later French patent, No. 234,785, granted March 5, 1894, as in their U. S. patent, No. 838,545, this defect was corrected.

tool, or technique, that is now quite familiar in electrical laboratories. He made use of this in the study of the harmonics generated in a circuit by the magnetic reactions of an iron core upon the magnetizing current, an effect that had been observed and for the first time correctly explained by Rowland at Johns Hopkins, and a description of his method was published in 1893.[20] The following year, yielding to the suggestions of his scientific friends, according to the account he has written ("I often regretted it, because it involved me in a most expensive and otherwise annoying legal contest"[21]), he made application for a patent on "Multiple Telegraphy", applying this idea of selecting by resonance to the problem of separating the signals.[22] Very soon afterwards another inventor, John Stone Stone, appeared upon the scene with practically the same idea,[23] and interference cases thereupon resulted in the U. S. Patent Office and the courts involving these two and the French inventors Hutin and Leblanc, who had also filed in the United States.[24] Upon the claims of the contestants and the differences that characterized their schemes for multiplex signaling we need not dwell; suffice it to say that in the matter of priority Pupin was adjudged the winner.* It appears that this distinguished scientist was not unimpressed with what he considered the originality of his ideas about the practical use of resonance. In the inimitable story of his life, "From Immigrant to Inventor," he refers to this as "my invention of electrical tuning,"[25] and says again, "I called it electrical tuning, a term which has been generally adopted in wireless telegraphy."[25] In another place, and on another occasion, he said, "It was badly needed and I had it developed several years before Marconi had made his invention. . ."[26]

Before passing to other applications in the field of electric communication, chiefly in the radio art, it might be said that in these early proposals for multiplex operation the separation of the carrier frequencies could not be successfully achieved by so simple a means as an ordinary resonant circuit. For one thing, the distortion introduced would be prohibitive, unless the carrier channels were placed so far apart as to be uneconomic. It remained for the Campbell band filter, invented about twenty years later, to enable the frequencies to be squeezed close together and distortion and other difficulties to be overcome. Furthermore, the whole art had to wait for the invention of the vacuum tube as the perfect generator of the kind of currents required, as well as modulator, amplifier and demodulator of these currents.

Later developments in the intricate and complex technique of wire

* An examination of the report of the interference hearings (reference 24) shows that Pupin claimed to have conceived the idea of using electrical resonance in multiplex telegraphy in the summer of 1890, following a careful study he had made of the investigations of Hertz, and to have begun experimental work on it in October of that year, thus antedating Hutin and Leblanc. Upon the adjudication of this contest in favor of Pupin on the main issues, patents on some of their claims were also allowed Stone and the French inventors.

communication have brought forth more useful applications of the principle of electrical resonance than the examples cited above. But let us now turn to radio. Here the application of resonance is elemental and fundamental. But not so in the beginning, however. When Marconi brought his embryonic outfit to England in 1896 and demonstrated his best accomplishments over the next three or four years, the problem of selectivity was non-existent. Further, the type of detector then available, the Branly

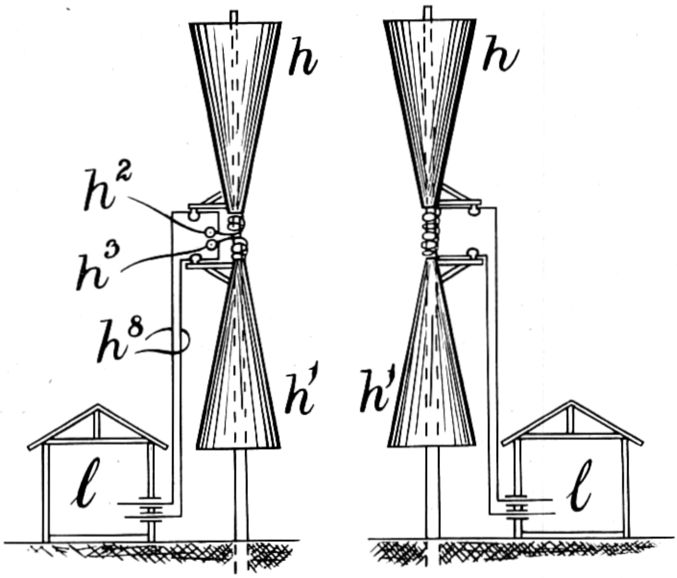

Fig. 4—First tuned radio transmitting and receiving antennas, as proposed in Lodge's British patent of 1897; tuning accomplished by inductance coils between the capacity areas *h* and *h'*.

metal filings coherer or modifications thereof, was responsive to electric waves varying considerably in frequency, so the need of tuning to obtain sensitivity was at first not actually imperative. This detector was connected directly in the untuned antenna circuit. Then the ambition to increase the distance of reception led to a search for greater sensitivity, and as a first step (1898) Marconi introduced into the receiving circuit his "jigger", or oscillation transformer.[27] The primary, of few turns, was in the antenna circuit; the tuned secondary, wound with an eye to the reduction of capacity, stepped up the voltage and applied it to the coherer. Here no adjustable tuning was provided, but instead there were different jiggers wound to suit the transmitted wave-lengths employed and thus secure the maximum effect.

It was foreseen in the early days of radio that if it were ever to become a commercial practicability it would be necessary to provide means for receiving one wave-length to the exclusion of others—to provide selectivity. Crookes in his prophetic Fortnightly Review article of 1892 had clearly envisaged this.[28] As a solution of this problem Lodge in 1897 applied for a British patent on "Improvements in Syntonized Telegraphy without Line Wires,"[29] the stated object of his invention being "to enable an operator by means of what is known as Hertzian wave telegraphy to transmit messages

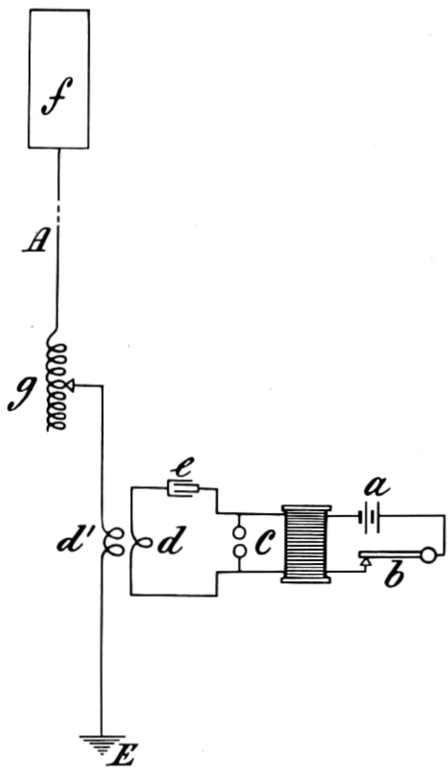

Fig. 5—The tuned inductively coupled two-circuit radio transmitter adopted by Marconi in 1900.

across space to any selected one or more of a number of different individuals in various localities each of whom is provided with a suitably arranged receiver." His radiator, modeled after Hertz, was a pair of "capacity areas", or triangular shaped metal plates (one of them preferably grounded), separated by a spark gap and having interposed an inductance coil of a few turns, for the purpose of tuning. This coil was not continuously adjustable but was to be replaced by others for changes of wave-length. The receiving station was provided with a similar arrangement except that in place of the spark gap there was connected a Branly type coherer as a wave detector.

While the particular forms of apparatus shown were never adopted in practice, nevertheless Lodge's tuning patent was upheld as valid in a legal contest for priority later on (1911) and it was purchased by the Marconi

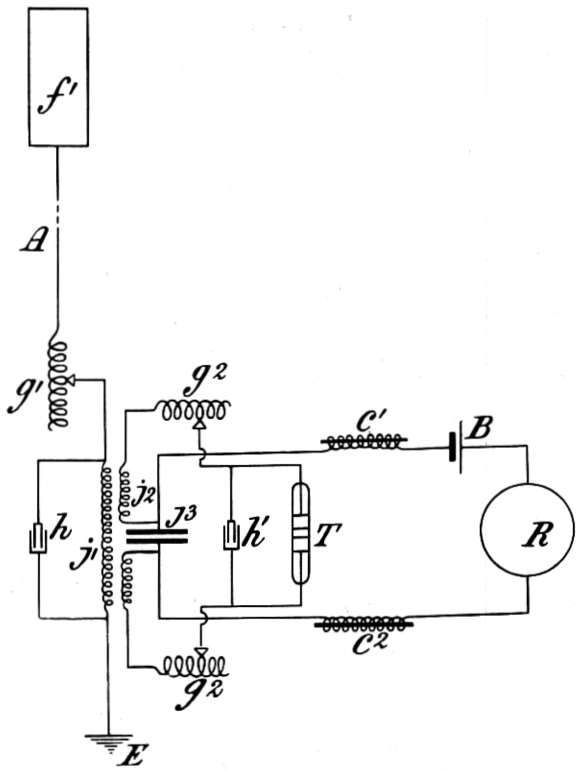

Fig. 6—Marconi's tuned radio receiving antenna and circuit of 1900.

Company as a result of the litigation.[30] Lodge, in his autobiography "Past Years", speaking with the usual modesty of the inventor rather than the scientist that he was, says, "Real selective tuning became possible through my patent of 1897. . . "[31]

In Marconi's first patent on wireless telegraphy, applied for in 1896 (British patent No. 12,039, the very first patent in radio), there was no reference whatever to the matter of tuning. But his well-famed patent No. 7777 of 1900[32] was primarily concerned with this object and went much ahead of his jigger ideas of 1898. Here there were four tuned circuits. At the sending station the spark gap circuit was inductively coupled to the transmitting aerial (an improvement credited to Ferdinand Braun of Germany), and by means of a variable condenser in the former and a variable inductance in the latter these two circuits could be tuned and brought into resonance with each other. This accomplished the production of a much more persistent train of oscillations in the aerial and a more efficient radiation of energy. At the receiving end the aerial was tuned to the incoming waves by means of a variable inductance, and the inductively coupled detector circuit was in turn tuned to resonance, likewise by means of a variable inductance. It was partly through such steps in the realization of greater sensitivity as well as selectivity that Marconi eventually succeeded with transoceanic telegraphy.*

In this patent the inventor gave the specifications for nine different *tunes*, as he called the different frequencies intended for different stations, or for different distances; that is to say, the details of design of the aerials, transformers, inductances and capacities of the transmitting and receiving circuits for each tune. Thus interference between one station and another might be avoided by using different frequencies. It may be observed here, however, that the matter of selectivity was not so easy at that time when the rather broad-spectrum spark transmitter was the only kind available. Very sharp tuning had to wait upon the advent of continuous waves, supplied first by the Poulsen arc or the high-frequency alternator and then by the vacuum tube. But many other improvements, and new wonders besides, were waiting on the vacuum tube.

It hardly seems necessary to pursue our subject further than this point, considering how it so quickly thereafter became a commonplace item in our electrical storehouse. Our interest was chiefly in how it got started. We have seen how it had its roots in certain experiments with the Leyden jar; how the results of experiments were clarified by mathematical analysis and a correct theory formulated; and then, as the need and opportunity arose, how the principle was applied and made use of by inventive minds: the wilderness first entered, then surveyed, and at last inhabited. So it is, we find, with most new ideas in the scientific world.

References

1. Felix Savary, "Memoire sur l'Aimantation" ("Memoir on Magnetization"), *Annales de Chimie et de Physique*, vol. 34, pp. 5–57, 1827. (Read before the Academy of Sciences, Paris, July 31, 1826.)

* Tesla's brilliant experiments with resonance and high-frequency currents during this period and his knowledge and handling of tuned coupled circuits should be noted here. Although his work for a time was concerned largely with the conversion of ordinary power source currents into currents of very high frequency and voltage (his "Tesla coil" of 1891 is still well known) for a proposed system of electric lighting by vacuum tube discharges, much of it was applicable to wireless telegraphy. Particularly, his synchronous discharger with adjustable electrodes and provision for tuning the low-frequency circuit to resonance, patented in 1896, could very readily have been incorporated into a wireless transmitter.

2. Joseph Henry, "On Induction from Ordinary Electricity; and on the Oscillatory Discharge," *Proc. Am. Phil. Soc.*, vol. 2, pp. 193–196; June 17, 1842. "Scientific Writings of Joseph Henry," vol. 1, pp. 200–203, published by the Smithsonian Institution, Washington, D. C., 1886.
3. Hermann von Helmholtz, "Über die Erhaltung der Kraft," published in pamphlet form by G. Reimer, Berlin, 1847. Reprinted in volume 1 of "Wissenschaftlichen Abhandlungen von Hermann Helmholtz," by J. A. Barth, Leipzig, 1882. Reprinted in Ostwald's "Klassiker der exacten Wissenschaften," No. 1, by Wilhelm Engelmann, Leipzig, 1889. Translated into English by John Tyndall, in "Scientific Memoirs, Natural Philosophy," Article IV, pp. 114–162; edited by John Tyndall and William Francis, printed by Taylor and Francis, London, 1853.
4. William Thomson, "On Transient Electric Currents," *Phil. Mag.*, vol. 5, pp. 393–405; June, 1853. "Mathematical and Physical Papers," vol. 1, pp. 540–553.
5. W. Feddersen, "Beiträge zur Kenntniss des elektrischen Funkens," *Ann. der Phys.*, vol. 103, pp. 69–88, 1858; also vol. 108, pp. 497–501, 1859; vol. 112, pp. 452–459, 1861; vol. 113, pp. 437–467, 1861; vol. 115, pp. 336–343, 1862; vol. 116, pp. 132–170, 1862.
6. C. V. Boys, "Notes on Photographs of Rapidly Moving Objects and on the Oscillating Electric Spark," *Proc. Roy. Soc. Lond.*, vol. 11, pp. 1–15; Nov., 1890.
7. W. R. Grove, "An Experiment in Magneto-Electric Induction," *Phil. Mag.*, vol. 35, pp. 184–185; March, 1868.
8. M. I. Pupin, *Trans. A.I.E.E.*, vol. 10, p. 223, 1893. (Discussion.)
9. James Clerk Maxwell, "On Mr. Grove's 'Experiment in Magneto-Electric Induction'. In a Letter to W. R. Grove, F.R.S.," *Phil. Mag.*, vol. 35, pp. 360–363; May, 1868. "Scientific Papers," vol. 2, pp. 121–124.
10. John Hopkinson, "On the Theory of Alternating Currents, Particularly in Reference to Two Alternate-Current Machines Connected to the Same Circuit," *Jour. Soc. Tel. Engrs.*, vol. 13, pp. 496–515; Nov. 13, 1884.
11. Heinrich Hertz, "Electric Waves," p. 42. Translated by D. E. Jones. The Macmillan Company, London and New York, 1893 and 1900.
12. Reference 11, page 43.
13. Oliver Lodge, "Easy Lecture Experiment in Electric Resonance," *Nature*, p. 368, Feb. 20, 1890.
14. Oliver Lodge, "Modern Views of Electricity," p. 339, 2nd ed., 1892.
15. T. H. Blakesley, "Papers on Alternating Currents of Electricity, for the Use of Students and Engineers," p. 1, 3rd ed., 1891. Whittaker & Co., London.
16. Gisbert Kapp, "Capacity and Self-Induction in Alternate Current Working. I.," *The Electrician*, vol. 26, pp. 197–199; Dec. 19, 1890.
17. William Stanley, Jr., and John F. Kelly, "Means for Preventing the Interference with Speech on Telephone Circuits by Induced or Other Currents"; *U. S. Patent* No. 464,529, filed May 22, 1891, issued Dec. 8, 1891.
18. Maurice Hutin and Maurice Leblanc, *French Patent* No. 215,901, dated Sept. 3, 1891, delivered Dec. 15, 1891. See also *U. S. Patent* No. 838,545, filed May 9, 1894, issued Dec. 18, 1906.
19. Maurice Hutin and Maurice Leblanc, "Étude sur les Courants Alternatifs et Leur Application au Transport de la Force," *La Lumière Électrique*, vol. 40, p. 259; May 9, 1891.
20. M. I. Pupin, "On Electrical Oscillations of Low Frequency and Their Resonance," *Am. Jour. of Sci.*, vol. 44, pp. 325–334, April; pp. 420–429, May; pp. 503–520, June, 1893. "Practical Aspects of Low-Frequency Electrical Resonance," *Trans. A.I.E.E.*, vol. 10, pp. 370–394; May, 1893.
21. M. I. Pupin, "From Immigrant to Inventor," p. 300. Charles Scribner's Sons, New York, London, 1923.
22. M. I. Pupin, "Multiple Telegraphy," *U. S. Patent* No. 707,007; orig. filed Feb. 23, 1894, issued Aug. 12, 1902.
23. John Stone Stone, "Method of Electrical Distribution and Selective Distribution," *U. S. Patent* No. 726,368; orig. filed Apr. 4, 1894, issued Apr. 28, 1903; also 726,476, 1903; 729,103, 1903; 729,104, 1903; 638,152, 1899.
24. Interference in the U. S. Patent Office No. 17196 and No. 17197.
25. Reference 21, p. 19. See also pp. 294–302.
26. M. I. Pupin, "Fifty Years' Progress in Electrical Communications," *Jour. A.I.E.E.*, vol. 46, pp. 59–61, Jan.; pp. 171–174, Feb., 1927. (Presidential Address, Dec. 27, 1926.)

27. G. Marconi, "Improvements in Apparatus Employed in Wireless Telegraphy," *British Patent* No. 12,326; filed June 1, 1898, accepted July 1, 1899.
28. William Crookes, "Some Possibilities of Electricity," *The Fortnightly Review*, London, pp. 173–181; Feb., 1892.
29. Oliver Lodge, "Improvements in Syntonized Telegraphy without Line Wires," *British Patent* No. 11,575; filed May 10, 1897, accepted Aug. 10, 1898.
30. Oliver Lodge, "Past Years, An Autobiography," p. 236. Charles Scribner's Sons, New York, 1932.
31. Reference 30, p. 233.
32. G. Marconi, "Improvements in Apparatus for Wireless Telegraphy," *British Patent* No. 7777; filed April 26, 1900, accepted April 13, 1901.