ELECTRICAL DISTURBANCES AND THE NATURE OF ELECTRICAL ENERGY*

By Charles P. Steinmetz

The distinction between electrical surges or waves of different formation are first outlined and the manner in which such surges may affect the electric circuit illustrated by analogies between the action of electrical waves and the action of waves of the ocean. Light, heat, Hertzian waves and the fields of alternating current systems are shown to be the same phenomenon, differing one from the other only in frequency of vibration. Speculation is made as to what the electric wave is, leading to the contradictory deductions that for certain reasons the luminiferous ether must be considered as a gas of infinitely low density, and for certain others as a solid. The ionic theory is next discussed. It is shown that attempts to prove the correctness of this theory lead to inconsistencies, and in certain cases to contradiction of some recognized law of nature. The address is concluded with the statement that the same thing is true of all theories, which does not mean that these theories are fundamentally wrong, but simply that our present formulations of them are far from final correctness and represent only crude conceptions of the nature of things.—**Editor.**

To all of us who are interested in the use of electric energy the nature and characteristics of electric energy are of importance; as on their understanding depends our success in the economic use of this energy, and our ability of guarding against the difficulties, troubles and dangers which it may threaten when out of control.

The uses of electric energy are familiar to all of you, and form the subject of numerous papers; the study of the troubles and dangers is in the hands of the Committee on High Potential Disturbances, and therefore only a general discussion appears appropriate here.

Electric energy is industrially used as direct current and as alternating current, that is, as steady flow and as wave motion, usually of 25 or 60 cycles. Electric disturbances are of various character, and, where they are periodic or wave motions, are often of very high frequencies.

It can not well be doubted that electric disturbances in our systems are increasing in number. The reason therefore is found in the increasing size and energy of modern electric systems. Just as in a pail of water even a gale will not cause an appreciable disturbance, or, as a small pond is usually quiet while the ocean is never at rest, but continually traversed by undulations from small ripples to big waves, so in a small isolated plant high voltage disturbances are practically unknown; are rare in smaller central stations; while in the huge modern systems waves continuously traverse the circuits, from minute high frequency ripples of negligible energy to occasional high power surges of destructive energy.

The nature and form of disturbances met in electric systems are as variegated as those of any other form of energy. Single electric waves or impulses may appear as magnetic discharges, analogous to the snap of a whip in acoustics. Oscillations appear as waves which start suddenly and gradually die out, like the waves produced by throwing a stone in water; such are the disturbances caused by switching, synchronizing, etc. Then there are travelling waves, analogous to the ocean waves, of various size and wave length; such for instance as the disturbances caused by arcing grounds, by lightning, etc. Standing waves or stationary oscillations, like those of a tuning fork or violin string, may appear; and occasionally also, the most dangerous of all disturbances, cumulative oscillations, like the resonance of a tuning fork, namely, oscillations which gradually build up, increase in intensity until they finally limit themselves and become stationary, or die down again, or increase until something happens. Such for instance are the hunting of synchronous machines, certain internal transformer oscillations, etc.

Disturbances may affect the system by their quantity, or by their intensity. Electric power can be resolved into the product of two terms, quantity (or current) and intensity (or voltage), just as most other forms of energy are resolved into the product of two terms. Hydraulic energy is quantity of water times head or pressure; heat energy is entropy times temperature, etc. Instances of current disturbances are the momentary short circuit currents of alternators, the very high frequency currents of arcing grounds, etc. Voltage disturbances appear wherever an electric wave breaks at a barrier in a circuit, as at a reactance, or in the end turns of a transformer.

A wave in the water, as a big ocean wave, may cause damage by its bulk, by over-

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turning a structure. So a current wave may cause damage by its volume: the momentary short circuit current of an alternator may tear the windings to pieces, twist off the engine shaft, etc. Again, waves in the water too small of themselves to do any harm, may still do harm by the continuous pounding—by undermining and washing away the shore. In such manner a continuous oscillation—a continuous surge—may destroy. Each individual electric impulse would not have sufficient energy to do damage, but when they follow each other successively, in thousands and millions, as coming from an arcing ground, then finally they cause destruction. Again, the damage may be done by the pressure or voltage. Just like an ocean wave, not high enough in itself to overtop the shore, when stopped at the beach, when breaking in the surf, throws the water up to heights that are much greater than the height of the wave, so in the same manner a voltage impulse in an electric distribution system, when it breaks at the entrance to another circuit, at a reactance, or the end connections of the transformer or generator, or the series coil of a potential regulator, may pile up high voltage and rise to values far beyond those which the wave has in its free path in the cable or the line; and there, at the point where it breaks, where the wave is abruptly stopped by reactance, the voltage may rise to destructive values.

Disturbances may enter the electric system from the outside, as by lightning; or they may originate in the system, as by switching, synchronizing, etc.; or again, they may originate in the circuit by outside interference, as by an arcing ground, a spark discharge to an isolated conductor, etc.

A characteristic of most of these disturbances (which usually are comprised by the name of transients) is that they easily pass from circuit to circuit across space by magnetic or static induction, but frequently do not travel along the circuit for any considerable distance. The cause thereof is found in their nature, particularly the frequency.

When an electric current passes through a circuit, there is in the space surrounding the conductor which carries the current an electric field: lines of magnetic force surround the conductor, and lines of electrostatic or dielectric force radiate from the conductor. In a direct current circuit, if the current is continuous, the field is constant; there is a condition of stress in the space surrounding the conductor, which represents stored enegy, magnetic energy and dielectric energy, just as a compressd spring or a moving mass represents stored energy. In an alternating current circuit, the electric field also alternates; that is, with every half wave of current and of voltage, the magnetic and the dielectric field start at the conductor, and run out from the conductor into space with the velocity of light, or 188,000 miles per second. Where this alternating field of the conductor, this electric wave, impinges on another conductor, a voltage and a current are induced therein. The induction is proportional to the intensity of the field (the current and voltage in the conductor which produce the field) and to the frequency. Thus, where the frequency is extremely high, intense induction occurs; that is, considerable energy is transferred from the conductor which produces the electric wave (the primary or sending conductor) to any conductor on which the wave impinges (the secondary or receiving conductor). The result is, that a large part of the energy of the primary conductor passes inductively across space into secondary conductors, and the energy decreases rapidly along the primary conductor. In other words, such a high frequency current does not pass for long distances along a conductor, but rapidly transfers its energy by induction to adjacent conductors. This higher induction, resulting from the higher frequency, is the explanation of the apparent difference in the propagation of high frequency disturbances from the propagation of the low frequency power of our alternating current systems: the higher the frequency, the more preponderant become the inductive effects, which transfer energy from circuit to circuit across space, and therefore the more rapidly the energy decreases and the current dies out along the circuit; that is, the more local is the phenomenon.

The flow of electric power thus comprises phenomena inside of the conductor, viz., the dissipation of electric energy by the resistance of the conductor through its conversion into heat; and phenomena in the space outside of the conductor—the electric field—which, in a continuous current circuit, is a condition of steady magnetic and dielectric stress, and in an alternating current circuit is alternating, that is, an electric wave issuing from the conductor and traveling through space with the velocity of light. In electric power transmission and distri-

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bution, the phenomena inside of the conductor are of main importance, and the electric field of the conductor is usually observed only incidentally, when it gives trouble by induction in telephone circuits, or when it reaches such high intensities as to puncture insulation, cause mechanical motion, etc. Inversely, in the use of electric power for wireless telegraphy and telephony, it is only the electric field of the conductor, the electric wave, which is of importance in transmitting the message; the phenomena in the conductor, the current in the sending antenna, are not used.

The electric waves of commercial alternating current circuits usually have the frequencies of 25 and 60 cycles. With a velocity of propagation of 188,000 miles per second, 25 waves per second give a wave length of $\frac{188,000}{25} = 7500$ miles. The distance to which the field of a transmission line extends is, therefore, only an insignificant part of the wave length, and the phase difference within the field of the transmission line thus is inappreciable. With the alternating fields of transmission lines, the effect of the velocity of propagation of the field is therefore negligible and is always neglected. Not so with the alternating field of a wireless telegraph station. Using frequencies from one hundred thousand to a million cycles, the wave length is from $\frac{188,000}{100,000} = 1.8$ miles to $\frac{188,000}{1,000,000} = 0.188$ miles, or about 1000 feet. With a wave length of from 1000 feet to 2 miles, the electric wave extends over hundreds of cycles within the operative radius of a wireless telegraph station, which may be hundreds or even thousands of miles. It is appreciable also in long distance telephone lines. The average frequency of the sound waves—500 cycles—gives a wave length of 376 miles, and a 1000 mile telephone line thus comprises over 2½ waves. That is, at the moment when one half cycle of telephone current arrives in Chicago from New York, five succeeding half waves have already left the New York terminal and are on the way.

Abnormal electric waves in industrial electric power circuits vary from a few cycles per second (in the stationary oscillations of compound electric circuits) up to thousands, hundreds of thousands and millions of cycles per second. At frequencies of many thousand cycles per second, the ordinary measuring instruments, the oscillograph, etc., fail to record the wave; but such very high frequency waves can still be observed and measured through their inductive effects by bringing a conductor near them: the electric wave, impinging on this exploring conductor ("resonator" or "receiving antenna") then induces a current in it, and this is observed by a sufficiently delicate apparatus. In this manner, the telephone disturbances caused by alternating electric railway circuits have been studied by exploring antennae. A very intense wave, at short distance from its origin, may be observed by the spark across a small gap in the exploring antenna. Inversely, at hundreds of miles distance from the wireless sending station, the extremely weak wave is still observed in the receiving antenna by a change of the surface tension of a platinum hair wire dipped into an electrolyte, the change in resistance of which operates a relay. By exploring antenna, electric waves have been studied and observed up to frequencies of hundreds of millions of cycles per second—so-called "Hertzian waves,"—as they occur in industrial circuits between the end cylinders of high voltage multi-gap lightning arresters. There, they are the cause of the high sensitivity of the arrester for high frequency disturbances.[*]

We have to realize though, that light and radiant heat, the Hertzian waves, the waves of the wireless telegraphy station, the alternating fields of our transmission and distribution circuits, are one and the same phenomenon—electric waves traveling through space with the same velocity (188,000 miles per second) and exhibiting the same characteristics, but differing merely by their frequencies. This does not mean that electricity and light are the same, but that light is an extremely high frequency electric wave, an extremely rapid alternating electric field, while the electric field of the direct current is a steady stress in space.

From our knowledge of the identity of the alternating electric field and the wave of light radiation, we can derive a number of interesting relations between electric phenomena and the phenomena of light. To mention

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[*] Dr. Steinmetz here went on to point out that for frequencies of hundreds of thousands of millions, or millions of millions of cycles per second, the above method of observing the electric waves fails; however, they may be detected by placing a conducting body in their path, when they manifest themselves as "radiant heat." Frequencies of several hundred millions of millions are apparent to the eye as light, while frequencies of ten thousand millions of millions probably constitute the X-rays. For the full discussion of this subject, see Dr. Steinmetz's paper on "Arc Lighting" in the December, 1911, issue of the REVIEW page 568—EDITOR

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only one: the secondary current is repelled by the alternating magnetic field which induces it, that is, by the electric wave impinging upon it. This fact is made use of in the constant current transformer for constant current regulation. Applying the same phenomenon to the extremely high frequency light waves, means that the body which intercepts the light wave is repelled by the wave—the radiation pressure. Thus at extremely high frequencies the radiation pressure is the analogous phenomenon to the repulsion between primary and secondary circuits in our industrial circuits.

So far we have made no hypothesis, but merely recorded the facts: we can measure the waves and their frequencies, their velocity of propagation and other characteristics, and show their identity. We may now speculate on the nature of the electric wave, on the mechanism of its propagation, etc.; but must then realize, that as soon as we leave the facts and indulge in speculation, we submit to uncertainty, which every hypothesis has, no matter how well founded.

The velocity of propagation of the electric wave is incredible, but it is a finite velocity, and after the electric wave has left the sending antenna, a finite time elapses before it is observed by the receiving antenna. The energy sent out by the oscillator, the electric circuit, the sending antenna, is thus received by the receiving antenna at a later time. The finite speed of propagation of the electric wave implies that the energy during its motion from the starting point to the point observed must reside for some time in intervening space. This means that there must be something in the space which carries the energy; a carrier of the energy of radiation, of light. That carrier we explain by the hypothesis of the luminiferous ether. We assume that the ether permeates all space, is of extreme tenuity and fineness, and is the carrier of the electric wave. The question arises: Is the ether a mere hypothesis, or is it real? Is it a form of matter or not? We may speculate on that, but may come to one conclusion or to the opposite conclusion, depending on our definition of what matter is. After all, it is really not a question of speculation, but a question of definition—of what you define as matter.

We always speak of the phenomena of nature within the conception of energy and of matter. Energy we can perceive by our senses. All we know of nature, all that our senses give us as information, is the effect of energy—energy which reaches our body through the eyes, through the ear, through the sense of touch; and if I were to make a definition of energy it would be "that thing which reacts on, and is perceived by, or can be perceived by, our senses." This is probably the most consistent definition of energy.

Now, what is matter? We cannot see or get any knowledge of matter. If we see a thing, we do not see the matter, but we see the radiating energy from it which comes to us. We feel the mechanical energy of its momentum, but the matter we cannot perceive. All the conception of matter is as the carrier of energy; but if you define matter as the carrier of energy, then the ether which carries radiating energy—carries the energy of the electric wave—is just as much matter as the bullet which carries the mechanical energy that was supplied to it in the gun.

The question then arises: What are the properties of this ether, which is the carrier of the electric wave? The velocity of propagation of a wave in a medium depends on its density and elasticity. The velocity of propagation of the electric wave through the ether is nearly 200,000 miles per second, while the velocity of sound waves through the air is about 1000 feet per second, or the electric wave moves a million times faster than the sound wave. This means that the ether must be of a density inconceivably lower than that of air, though we speak of the air as being of low density, and realize this when trying to navigate it. Furthermore, through the ether all cosmic motion takes place: our earth rushes through it at high velocity, and still there is no appreciable friction. That means that the density of the ether must be so enormously low that even at very high velocity the frictional resistance is inappreciable.

We might then consider the ether as a gas of inconceivably low density.

However, the light wave or electric wave is a transverse vibration; that is, the oscillating ether particles oscillate at right angles to the direction in which the ray of light travels, and therefore in their oscillation come neither nearer nor recede further from the ether particles in front or behind in the direction of the beam of radiation. The oscillation cannot be transferred from ether particle to ether particle in the direction of the beam, by approach or recession of the ether particles, and the transfer of oscillation in the direction of the beam thus can occur only by some

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thing, some force, which holds the ether particles together, so that a side motion of one causes a corresponding side motion of the particle ahead, without approach. That is, the ether particles can not be free as in a gas, but must be held together with some rigidity. In other words, the existence of transverse vibrations precludes that the ether is a gas, and requires it to be a rigid body, a solid: transverse oscillations can occur only in solids, but are inconceivable in fluids. From the nature of the wave motion of light, we thus would have to conclude that the ether, through which the earth and all bodies rush with high velocity, and without appreciable friction, is a solid. This is physically impossible, and here we find a very common physiological phenomenon: if we attempt to carry any speculation or theory to its final and ultimate conclusion, we reach contradictions. This probably is not the result of the nature of the phenomena, but is in the nature of our minds, which are finite and limited, and therefore fail when attempting to reason into the infinite.

A speculative hypothesis on the nature of electrical phenomena has in the last years been developed in the *ionic theory.* Its starting point is the study of the phenomena of conduction, more particularly the conduction of gases and vapors. In this, we must not merely consider typical cases, but cover the entire field of conductors. On first sight, it appears easy to divide all electric conductors in two classes: metallic conductors or conductors of the first class, in which the resistance slightly increases with increase of temperature, and electrolytic conductors or conductors of the second class, in which the resistance slightly decreases with the temperature. Further investigation shows, however, that there are numerous conductors which do not belong in either class, such as gases, vapors, etc., and that there are all transition stages between the different conductors represented, so that we can not speak of classes any more, but merely of types. Thus there are solid conductors, such as metallic oxides (for instance magnetite) and elements and their alloys, as silicon, etc., which, with a change of temperature, gradually change from metallic conductors of positive temperature coefficient to conductors of metallic character, but with negative temperature coefficient; and which at still other temperatures have such high negative temperature coefficients that the voltage decreases with increase of current, thereby having the same characteristics as arc conductors; while at still higher temperatures they become electrolytic conductors. Such "pyroelectrolytic" conductors, to which the Nernst lamp glower belongs, are interesting because of the change of type of their conduction. Equally, if not more interesting, are gases and vapors as conductors, such as the arc, the Geissler tube, the static spark, etc. There seem to exist two classes of gas or vapor conduction: to the one belong the arcs, while to the other belong the Geissler tube and the electrostatic spark. Again, on first sight, it appears difficult to realize that the silent faintly luminous Geissler tube discharge, and the brilliant and noisy electrostatic spark, are one and the same phenomenon. However, the one changes gradually and without dividing line into the other by a change of gas pressure, and the differences, therefore, are due merely to the difference in the gas pressure. Furthermore, the usual noise and brilliancy of the static spark at atmospheric pressure is largely the result of the circuit condition under which it is produced: the passage of the spark closes the circuit and thereby starts a momentary more or less unlimited flow of electric energy. If however, this short circuiting effect of the spark is eliminated, as for instance by interposing between the spark terminals a glass plate which is not punctured, the electrostatic sparks appear as thin colored moderately luminous discharges which pass with moderate noise, the apparent difference from the Geissler discharge being then far less. With decreasing gas pressure, the electrostatic spark becomes less noisy, less brilliant, longer and thicker, and finally changes to the noiseless steady stream of the Geissler discharge, which traverses the space between positive and negative terminal with a glow, its color depending on the nature of the gas: for example, the glow is pink with air, orange-yellow with nitrogen, green with mercury vapor, etc. Going still to higher and higher vacua, the conductor which passes the current between the positive and negative terminal of the vacuum tube finally changes again and becomes a green discharge, which issues from the negative terminal in straight lines, like a beam of light, irrespective of where the positive terminal is located. It may not reach or come anywhere near the positive terminal, and if the positive terminal is located back of the negative terminal, the cathode ray, issuing from the latter, will really proceed away from the positive terminal.

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Now this form of electric conduction (and to a considerable extent the conduction of the Geissler tube at lower vacuum) looks very much like electric convection: it looks as if the electric energy were carried across the terminals by luminous material particles, which are shot off, in straight lines, from the negative terminal with great energy, producing luminosity where they strike; and after losing their luminosity have to find their way to the positive terminal. The transfer of electric energy by the cathode ray would then have the same relation to the transfer of electric energy by a copper wire as the transfer of kerosene by a series of tank cars has to the transfer of kerosene by a pipe line.

Assuming then the hypothesis that the cathode ray is the transfer of electric energy by convection by material particles, we will see what conclusions we can derive therefrom.

A material particle containing electric energy is acted upon by an electrostatic field, in a direction depending on the polarity of the electric energy, whether positive or negative against surrounding space. The cathode ray, if consisting of material particles, thus would be deflected by an electrostatic field by an amount depending on the intensity of the field and on the energy, mass and velocity of the material particles. This is the case: the cathode ray is deflected, and measurements of the deflection of this ray by the electrostatic field thus give us a relation between electric energy, mass and velocity of the cathode ray particles. Moving electric energy, whether flowing through a metal conductor or carried by a moving particle, is acted upon by a magnetic field. The cathode ray thus should be deflected by a magnetic field by an amount depending on the electric energy, mass and velocity of the moving cathode particles. This is the case. From these two relations, given by the deflection of the cathode ray by the electrostatic and by the magnetic field respectively, we can calculate the mass and the velocity of the moving cathode ray particles. If the masses of the cathode ray particles, calculated by this assumption, were found to be of the same magnitude as masses of other particles, calculated by other means, such as the chemical atoms or molecules, —if their velocities were comparable with other known velocities,—this would be a strong confirmation of the hypothesis of electric convection by the cathode ray, that is, of the ionic theory. However, this is not the case, and the experiment therefore neither confirms nor contradicts the ionic theory. The calculation shows that, if the conduction of the vacuum tube is by convection of electric energy by moving particles, these particles, called electrons, must be very much smaller than the chemical atoms, or of a magnitude of one thousandth the size of the smallest chemical atom, the hydrogen atom. Their velocity of motion must be inconceivably high—comparable with, though smaller than the velocity of light. They carry electric energy at a negative potential against surrounding space, that is, the electron may be considered as the negative terminator of a line of dielectric force, while the positive end of this line of dielectric force terminates at the positive terminal of the vacuum tube, or at a positive electron, where such exists.

The question then arises: What is the electron? By the derivation of its hypothetical existence, it is a form of matter, since its mass has been calculated by the action of forces on its mechanical momentum. It thus would be a new form of matter, a new chemical atom, a thousand times smaller than the hydrogen atom. It has been called "an atom of electricity." As "electricity" is a vague term without physical meaning, which has loosely been used for "electric quantity" (and even "electric quantity" is a mere mathematical fiction, a component factor of electrical energy) no objection exists to giving the name "electricity" to this new hypothetical form of matter, represented by the electron. It naturally does not explain anything: The electron certainly is not electric quantity, nor is it electric energy, but it may be defined as that form of matter which is the carrier of electric energy. Then, however, the electron in its definition comes rather close to the hypothetical ether atom, which is the carrier of radiant energy, that is, the carrier of the energy of the electric wave in space.

The electron, however, can not be considered as electric energy, nor as representing or carrying a definite amount of electric energy, even when associated with a definite quantity of electricity, no more than the iron atom of a magnetic circuit can be considered as magnetic energy, or as carrier of a definite amount of magnetic energy. Energy comprises the product of quantity and intensity, and the electric energy carried by the electron is its electric quantity times the intensity of its electric field, that is,

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the potential gradient along the line of dielectric force, which starts at the electron, up to a reference point on this line of dielectric force—the potential of the positive terminal, of surrounding space, of the universe, or anything else. This disposes of the mistaken conception, occasionally expressed, that the electron represents a definite amount of electric energy, and leaves the amount of energy of the electron indefinite, that is, depending on an arbitrarily chosen reference potential, just as it is with any other form of energy: the amount of energy of any carrier of energy, such as a moving body, is always relative, depending on a reference point.

Obviously then, electric energy can not be measured by the number of electrons, and has no direct relation to it, but depends on the electric intensity, or potential difference.

In the last years, the ionic theory has been greatly strengthened by the discovery and investigation of phenomena similar to those of the cathode ray, though more general in nature, in the radiation of so-called "radio-active substances." A number of chemical elements, such as radium, thorium, uranium, etc., continuously send out rays of various kinds. Some of these, the β rays, are identical with the cathode rays of the vacuum tube, or, in other words, are deflected in the same manner by electrostatic and magnetic fields, and are therefore considered as electrons—terminators of the negative end of a line of dielectric force, of a mass about a thousandth that of the hydrogen atom, shot off by the radio-active substance with velocities approaching that of light. Other rays, the α rays, are deflected in an opposite direction by electrostatic and magnetic fields, and thus must be considered as carriers of electric energy of positive potential: positive electrons. Their mass, as calculated in the manner above described, is that of the helium atom (4 times the mass of the hydrogen atom), and they are therefore generally considered as helium atoms carrying electric energy of positive potential. They are shot off with velocities very much lower than the velocities of the negative electron, though still inconceivably high. When carrying electric energy, they contain the same quantity of electricity at positive potential that the negative electrons carry at negative potential, and if the latter are considered as terminators of the negative end of a line of dielectric force, the helium atoms as positive electrons are terminators of the positive end of a line of dielectric force.

A third class of rays, issuing from radio-active substances, are the γ rays. They have the same characteristics as the other rays, except that they are not deflected by electrostatic or magnetic fields. They are identical in their properties with the X-rays, discussed above as electric waves at the extreme end of high frequencies, and are usually considered as X-rays.

Here we come to one of those conclusions which do not appear rational: the α, β and γ rays are very similar in their nature, differing only by the direction and amount of their deflection, and it therefore does not appear reasonable to assume that the γ rays are ether waves, while the α and β rays are projectiles thrown off by the radio-active mass. The attempt of avoiding this dilemma by assuming the γ rays to be projectiles, which carry equal positive and negative electric quantity, and therefore are not deflected, appears forced and merely transfers the difficulty into the relation between X-rays and ultra-violet light. The latter is generally conceded—and corroborated by the phenomena of interference, etc.—to be ether waves. At the extreme ultra-violet, however, the properties begin to shade into those of the X-rays, and it again appears unreasonable to assume such an essential difference between ultra-violet and X-rays, as that the one are ether waves, the other projectiles.

In many instances, when we follow the reasoning of the ionic theory to its conclusion, we meet contradictions. For instance, the calculation of the mass of the electron shows that at very high velocities the mass is not constant, but increases with increasing velocity, becoming infinity; and therefore the kinetic energy of the electron becomes infinite, if its velocity equals the velocity of light. This is impossible, as it contradicts the law of conservation of energy: if we consider two electrons, moving in opposite directions at half the velocity of light, their kinetic energy against surrounding space would be finite. Their relative motion against each other, however, is at the velocity of light, and their kinetic energy against each other would be infinite. Since, however, they were set in motion by finite energy, their relative energy can not be infinite. To overcome this difficulty, a fictitious or apparent mass—the "electromagnetic mass"—has been attributed to the electrons, which is not the mass of mechanics. However, the calculation of mass and velocity of the electrons is based on the kinetic energy of the electron, that is, on its

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mechanical mass, and not a new kind of mass, which is not a mass in the mechanical sense.

These and other numerous contradictions to which the conception of the ionic theory leads, obviously do not mean that the ionic theory is fundamentally wrong in principle: we have also seen that the wave theory of radiation, in the properties of the luminiferous ether, lead to attributes that are contradictory and thereby impossible. We find the same thing in all theories—the chemical, the thermodynamic, etc. It simply means that our present formulation of the ionic theory, of the electromagnetic wave theory, and of all other theories are very far from final correctness, but are at best only very crude conceptions of the nature of things, which will have to be modified again and again with our increasing knowledge before we can expect to reach a moderately rational conception of nature's laws and phenomena, if we ever arrive there.

THE GROUND CONNECTION IN LIGHTNING PROTECTIVE SYSTEMS

PART I

By E. E. F. CREIGHTON
CONSULTING ENGINEERING DEPARTMENT, SCHENECTADY

Terminology

There is some confusion in the use of the word "grounded." It is not unusual to hear some one speak of a conductor as grounded to a cable sheath when the sheath itself is fairly well insulated from the earth. Again one hears of a phase being grounded to the iron case of a transformer when the case is insulated from the ground by, say, a 30-foot length of dry wooden pole. This length of dry pole would give an insulation of not less than a megohm.

Another important case, and not unusual use of the word "grounded", occurs in relation to lightning arresters. There are many cases where "grounded" must mean a connection to a conductor which is connected to earth in the near vicinity of the arrester. An arrester grounded to a water pipe, however, may not have an electrical contact to the earth within a hundred feet from the arrester. This is usually an inefficient condition of protection. Although the measured ground resistance may be acceptably low, the inductance of such a long path to ground is, usually, objectionable. The important thing to know may be the distance to the actual connection to *terra firma.*

Again, an entirely contrary case may be cited where the point of grounding of an arrester on a semi-insulated conductor is far more important than its connection to earth. This condition exists in the protection of apparatus on electrical railways. It is far more important to ground a line arrester to a rail than it is to connect it to earth. (Using the same language, we have the apparently inconsistent expression "to ground the lightning arrester to earth.")

The general use of the word "ground" is a natural growth, since the lower terminal of an arrester is called the ground terminal irrespective of whether it is to be connected to the earth or not. The loose usage of "grounded" is too well established to allow even a hope of making it definite. The word is convenient but its indefiniteness is to be deplored. Its indefiniteness becomes no insignificant matter when some one, at a distance of several thousand miles, wants advice regarding a failure of protective apparatus, and the deciding feature is the value of resistance in the so-called ground to *terra firma.* This feature of resistance to earth is nearly always important, and the engineers who are called on in such cases must choose between giving "snap" judgment, or causing a long delay in the mails in ascertaining what was meant by "grounded."

In 1907, it was proposed to accept the term "grounded to" as a particular equivalent to "connected to", and retain the older term "earthed" as meaning the actual connections to *terra firma.* After four years no improvement on this suggestion has been noted. To make the language definite and mutually comprehensible we would have such statements as the following: The arrester was grounded on the rail but the rail was not earthed; or, A line wire was grounded on the iron case of a transformer, or metal cross-arm, but these iron parts were not earthed—or were earthed through the high resistance of a wooden pole; and so on. Whether the

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