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HIGH VOLTAGE[1]

By Dr. KARL T. COMPTON

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WHILE there is much truth in the statement that necessity is the mother of invention, it has often been pointed out that it is far from true that necessity is the mother of discovery. Discoveries come often most unexpectedly, in the pursuit of knowledge by the curious and observant. The great background of natural phenomena which have thus been discovered form an immense reservoir from which may be drawn natural laws or combinations of phenomena which can be made to work for the solution of men's needs or desires when necessity arises.

One of the most excellent examples of the fact that necessity is the mother of invention is found in the great number of applications of science which were made during the past war to cope with situations which never before had challenged the ingenuity of man. Such situations were the detection and location of submarines or of airplanes flying by night. There were also the location of underground mining operations or of enemy artillery by sound, or the direction of counter-battery artillery fire, also by sound. Such examples could be multiplied almost indefinitely, but the interesting feature of them all is that every one was handled by the application of some scientific phenomenon which had been known in the laboratory for many years. The necessities of war brought forth the means of applying these phenomena for particular purposes.

It is to a very recent example of this natural sequence of events that I will call your attention tonight, an example taken from the field of electricity, the chosen field of Joseph Henry, in whose honor this lecture has been named. It is a modern application of one of the oldest branches of electricity, a branch so old that some ultramodern text-book writers have advocated omitting it entirely from text-books

[1] The third Joseph Henry lecture delivered before the Philosophical Society of Washington on March 11, 1933.

on account of the academic and impractical character of its subject-matter. But let me first lay the groundwork for this new development in the field of high-voltage electricity.

While electricity can be produced in a variety of ways, and it was some time in the history of the subject before it was realized that the electricity was the same kind of thing in all these cases, nevertheless there are but three principal means of generating electricity. The first is static electricity, first discovered by Thales of Miletus as early as 600 B. C. Thales found that amber, when rubbed against other substances, had the power of attracting fragments of straw or leaves or feathers. In fact, the word electricity is derived from the Greek word electrum meaning amber, and was first so used by William Gilbert in about 1600.

The second great step in the production of electricity was the invention by Volta of the Voltaic cell in 1799, and from that time until the time of Faraday in 1831, the great development of electricity was in the production of batteries of various kinds. Volta was able to generate several hundred volts by piling up alternate layers of copper and zinc, separated by paper which had been moistened with acid, thus creating, in effect, a battery with a large number of cells in series.

When in 1831 Faraday made the discovery of electromagnetic induction and about the same time Joseph Henry discovered self-induction and independently repeated a number of Faraday's discoveries in mutual induction, the modern science of electricity and art of electrical engineering were born.

It is a striking fact, which perhaps we do not stop to think about, that this so-called electrical age has grown up during a period of one working lifetime, since men like Elihu Thomson are still living and men like Edison have just died, who built upon these scientific discoveries of Faraday and of Henry the modern art of electrical engineering.

With the development of electromagnetic devices, dynamos, motors and transformers, the use of batteries except for very special cases has largely been discontinued. Static electricity, which had been developed from the study of frictional charges and charges of conductors by induction, was relegated almost to the field of scientific but useless curiosities. The efficiency of electromagnetic generating apparatus has been developed to a remarkable degree, so that, for the practical purposes of our industrial needs and our home needs, the modern science of electricity has appeared to be eminently satisfactory.

It is true that there have been some other new developments of first importance in the electrical field, notably electronic devices, such as radio tube detectors, amplifiers and transmitters or devices which operate with ionization of gases, such as the mercury-arc rectifier and the glow discharge tube. These things, however, are more in the nature of electrical instruments or electrical control devices and it still remains true that the production and distribution of electricity are basically carried on by means of the electromagnetic induction devices developed from the work of Faraday and Henry.

Let us first follow the development of high voltage by electromagnetic induction. In this as in all other fields the first developments were crude, as was necessarily the case because instruments and methods had not been developed and everything had to be taken up *de novo*. When Joseph Henry wished to build his great magnet with several coils of wire, he had first to invent insulated wire, which he did by wrapping strips of his wife's dresses and petticoats with shellac around the wire. When Henry wished to measure the voltage of the current produced in a step-up transformer, he had no ammeter or voltmeter capable of detecting the small current at high voltage and had to substitute for them the students in his class, judging the voltage by the number of students who could be shocked when connected hand to hand in series across the terminals of the secondary of his transformer. Thus a voltage that would shock thirty students he estimated to be twice as high as one which would shock fifteen students, and in this way he was able to arrive at a very crude but correct idea of the relationship between the number of turns of wire in the secondary of a transformer and the voltage which was produced therein.

The story is told of a striking lecture demonstration given by Henry while at Princeton. He hung a secondary coil of a large number of turns of wire on the inside wall of his classroom and had the students of his class join hands in series across the terminal of the coil. The primary coil of this transformer was concealed from the students, being suspended on the outer wall of the building from wires passing out through an attic window and connected with a large Voltaic battery in the attic. When Henry rapped against the wall his assistant in the attic plunged the copper and zinc battery plates into the acid, thus sending a current through the primary, which induced a high voltage in the secondary and shocked the students of his class.

It is probable that Henry, burdened as he was with administrative duties and the difficulties of finding the means wherewith to carry on his experiments, did not realize so clearly as did his contemporary, Faraday, the ultimate practical value of these things which he was doing. Faraday, when once asked by the King, "What is the use of these things?" replied, "Your Majesty, of what use is a baby?" And another time when he was asked by the Prime Minister this same question, "Of what use are these things which you are doing?" he replied, "Your Excellency, some day you may be able to tax these things." Henry, however, was so wrapped up in his scientific pursuits that he gave little thought to the possible practical application of his work. It is said that when he was once urged to press his claim as inventor of the telegraph and other instruments, he replied that there were far too many interesting things to be done in the laboratory to permit him to take time with such matters.

There has been a practical urge for the development of high voltage power from three different points of view. The first and most important of these is for the transmission of electric power over large distances. It is much more economical to transmit power at high voltage and small current than at low voltage with large current because the resistance losses depend upon the current and not the voltage. For this reason, the voltage of high power transmission lines has continually risen from first a few hundred volts, then a few thousand, not many years ago sixty thousand, and now upwards of two hundred thousand volts. The losses of power due to heating of the wire from the flow of current are such that, according to a practical rule, it is not economical to transmit electrical power farther than one mile for every thousand volts. From this we see that a modern two hundred thousand volt transmission line could be economically used to transfer power from the power generating station to distances of about two hundred miles, but beyond these distances such transmission of power is not economical. For that reason, in any area requiring the use of electricity, power generating stations must be located at distances of not more than two hundred miles from each other.

The question may be asked as to why the voltage is not raised still higher than two hundred thousand volts, and the answer to this is found in the fact that with higher voltages the electric field in the air surrounding the wire becomes so intense as to ionize the air, causing a leakage of electricity from the wire into the air in the form of an electric discharge known as a corona. It is this phenomenon of corona which sets the practical upper limit to the voltage which can be used for transmission.

It is not feasible to generate directly voltages in the range of several hundred volts because the difficulty of insulation becomes too great, and an electric dynamo with insulation adequate to withstand even several thousand volts would have to be so large, to include the necessary insulation, as to be unwieldy and inefficient. Consequently, the power is generated at relatively low voltage, usually a few hundred volts in alternating current and this is sent through a step-up transformer insulated in oil in which the secondary has a hundred or a thousand times more turns of wire than the primary. In this secondary coil the very high voltage is generated for transmission over the power lines. Then at the other end of the line the power is fed through a similar transformer in the reverse order and comes out of that secondary as a very large current at relatively small voltage.

There has been no really fundamental difficulty to be overcome in these power transmission lines, although there have been very many interesting problems of science and engineering to be solved. The proper design of a transformer to be efficient and to be sufficiently well insulated is one problem. Perhaps the most difficult problem has been that of proper switching devices so that these high-voltage currents can be started and stopped without excessive arcing at the switches. It is such developments as these which have made the great generating stations at Niagara Falls and the many other hydroelectric or steam-electric generating stations such an important feature in our present industrial life.

The second thing which has stimulated high voltage developments of the electromagnetic type has been the x-ray. For ordinary purposes, from thirty thousand to one hundred thousand volts are adequate for either diagnostic or therapeutic purposes. Of recent years, however, in the endeavor to find the most effective methods of treating internal cancerous growth there has been an increasing desire to go to much higher voltages, and consequently x-ray tubes operating on as much as a million volts have been developed at the General Electric Company, at the California Institute of Technology and elsewhere.

To generate the high voltage power for these x-ray tubes, recourse has been had to transformers connected in series, the primary of one transformer being connected with the secondary of the other, and all transformers after the first being insulated. By such means, large power can be delivered and high voltages obtained, although a million volts appears to be about the practical limit because there are parasitic currents known as charging currents which drain a great deal of energy uselessly from the system when an alternating or varying current is used at such high voltages. Furthermore, the equipment becomes tremendously expensive on account of the requirements for insulation.

The third thing which has led to high voltage developments of the electromagnetic induction type has been the study of the effect of lightning on transmission lines and the desire of electrical engineers to duplicate as nearly as possible the effect of lightning by means of high-voltage sources for laboratory study. For this purpose there has been developed the impulse generator, in which a series of condensers capable of storing electric charge at high voltage are charged in parallel from a high-voltage transformer and are then connected in series so that the overall voltage which is delivered is the sum of the voltages across the separate condensers. By such means impulsive or momentary voltages of ten or fifteen million volts have been obtained. These are exactly right for studying transient effects like those of lightning, but the impulse generator is inherently incapable of serving properly any purpose which requires a steady and reasonably constant source of high voltage. The discharge in this impulse generator lasts only a few hundred thousandths or millionths of a second.

This impulse generator represents the peak of high voltage accomplishment by the electromagnetic method, and you will notice that this is accomplished by combining with the electromagnetic device, namely the step-up transformer, a series of condensers which are essentially electrostatic instruments.

Let us return now from the high-voltage developments, based on principles of electromagnetism, to the historically earlier type of electric generation which falls within the general field known as electrostatics. The characteristic of these devices has been the relative ease of producing high voltages, but with an exceedingly minute quantity of electricity.

The first electrical machines of which we have any knowledge were frictional electrical machines constructed about 1663 by Otto von Guricke. They consisted of globes of sulfur made to rotate about an axis so as to rub against the hands of persons held against them. In this way the globe of sulfur became electrically charged and the charge of the opposite sign appeared on the person who touched the globe. Isaac Newton appears to have been the first person to use a glass globe instead of sulfur, but it was Ramsden in 1768 who really constructed the first object which might really be called an electrical generating machine.

The Ramsden machine consists of a glass plate which can be rotated by a winch, and which passes with rubbing contact between two leather pads. By friction the glass becomes positively charged and the pads negatively charged. These positive charges are taken off the glass disk as it passes in rotation between combs of sharp points. Similarly, the negative electricity from the pads is collected from them and delivered to another terminal. For a number of years the only development of the art of electrical generation consisted in finding various materials which might be put on the glass or on the leather pads to increase their effectiveness in separating frictional electricity.

A later development of a frictional machine is that invented by Lord Armstrong, of Newcastle, England, in 1841. Lord Armstrong was experimenting with steam boilers. By accident one of his assistants received an electric shock when he touched a piece of metal against which a jet of steam from a leaky boiler was striking. This led Lord Armstrong to further experiments leading to the steam electrostatic generator. The action of this generator consisted in blowing drops of condensed steam, by the steam pressure, out through a series of nozzles against a neighboring metal plate. The droplets of water were charged by frictional contact against the walls of the nozzles. The electrical power was created by the work done in moving the charged droplets against the electric field which developed between the nozzle and the plate on which the droplets struck, and of course this power was in turn derived from the driving power of the steam which carried the droplets out and away from the nozzle.

Another whole series of electrostatic generators was built upon the principle of electrostatic induction. Perhaps the simplest of these was the Belli doubler, which was devised in 1831 and operated on the same principle as a later device designed by Lord Kelvin and better known as the Kelvin Replenisher, described by him in 1872. This action is shown schematically in Fig. 1. When the rotating member with the insu-

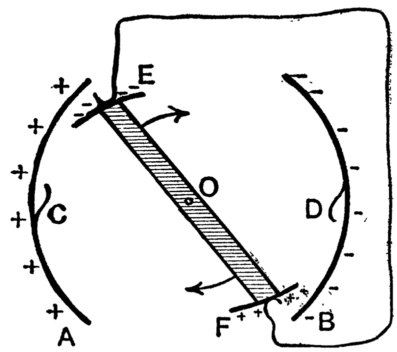

FIG. 1. Schematic diagram of Kelvin Replenisher

lated plates *E* and *F* is at the position shown, positive and negative charges are separated from the connecting wire, which brushes lightly against *E* and *F*, by means of the electrostatic forces arising from the charges on the neighboring metal armatures *C* and *D*. As the rotating arm turns and breaks contact with these brushes the charges are carried on *E* and *F* and, when they touch the springs *C* and *D*, respectively, these charges are communicated to the armatures, thus increasing the charge already existing on these armatures. Then at the next contact with the brushes at *E* and *F* the process is repeated. Consequently, the charge on the armatures continually builds up until it reaches such magnitude, or rather until the voltage rises so high that the charge leaks away as fast as it is produced, leaking away either through the insulation or by a corona discharge produced by breakdown of the surrounding air.

A large variety of instruments, some simple and some very complicated, have been developed to carry on the idea of the Belli doubler in a more efficient manner. Such devices were devised by Varley in 1860, by Toepler in 1865 and by Holtz between 1864 and 1880, but by far the most successful of these devices is the well-known Wimshurst machine, which was first invented in about 1878. This machine is well known to everybody, I think, as the "influence machine" whose action may be described as follows:

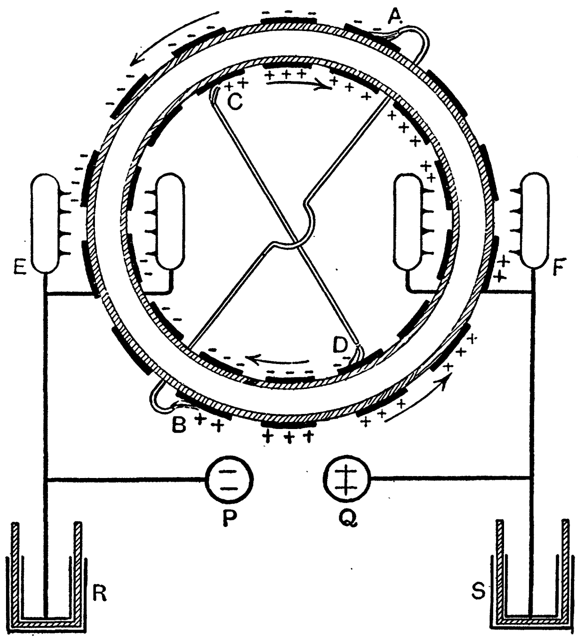

FIG. 2. Schematic diagram of Wimshurst influence machine

Imagine that, in some way or other, such as by friction, a small negative charge is located on the metal sector of the rotating disk opposite the point C of Fig. 2. This negative charge will induce the separation of positive and negative electricity in the metal rod CD, drawing positive charge to the point C and forcing negative charge to the point D. At these two points the charges are collected on the metal sectors of the second glass disk which is rotating in the opposite direction. Thus all the metal sectors to the right of C carry positive charge collected from C and they all deliver it to the sharp needle point at F.

At the same time, these positive charges on the metal sectors to the right of C will similarly induce negative charges in the metal rod AB, which charges will be deposited on the metal sector to the left of A and will in their turn be collected by the sharp point at E. Thus the process is a continuous one, E and F collecting negative and positive electricity, respectively, from the metal sectors on both of the revolving disks. By having a multiplicity of revolving disks these Wimshurst machines may be made to deliver a considerable amount of power and were in fact at one time quite largely used in the x-ray art until they were supplanted by the more powerful and much more convenient electromagnetic induction devices described previously, including step-up transformers, induction coils and the like.

One of the most ingenious types of electrostatic induction machines is the famous Kelvin water-dropper, which is shown in Fig. 3. Here perhaps more easily

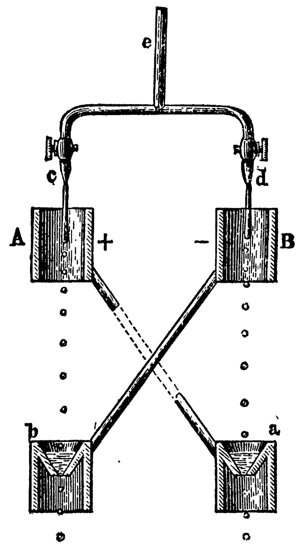

FIG. 3. The Kelvin water-dropper

than in any of the other induction machines can be seen the way in which a small charge once produced may result in the continual building up of an indefinitely large charge, if the arrangement of apparatus and connections are suitably arranged. Assume for a moment that for some cause, such as friction of the wind or anything else, there happens to be a small charge on the cylinder A. Every drop of water leaving the outlet in A will therefore carry a small induced negative charge which will be delivered to the cup below, thus raising the cylinder at B to a negative charge. All the drops of water which come from the outlet inside of B will therefore carry the positive charges which will be collected in the trap below and serve still further to increase the positive charge on A. So the process goes on, the charges building up until through leakage or through a corona discharge to the air, they leak away as fast as produced.

At this point I am minded to make a confession regarding my first experiment in physics. I conceived the idea of producing electrolysis by the use of gravitational energy alone, and set up a device somewhat similar to the Kelvin water-dropper. My device consisted of drops of copper sulfate coming from an outlet like that in the cylinder A and falling into a platinum funnel like that directly below A. I charged the cylinder A with a large negative charge from a static machine and this charge remained on the cylinder, which was well insulated. Consequently, every drop of copper sulfate which dropped carried an induced positive charge and delivered it to the funnel b, which was earthed. This excess positive charge would of course be in the form of copper ions which would be deposited on the platinum in the process of neutralization of the drop. After running the apparatus for an hour or so, I looked at the platinum cylinder to see whether I could see any copper deposited on its inside and finding none I set the apparatus going in the late afternoon and let it run automatically until the following morning. Again examining the funnel, I found no deposit of copper and, somewhat surprised, I sat down to figure. I soon discovered that the copper would be present in far too small a quantity to detect. In fact, if every drop were charged with the largest amount of electricity which it could carry without losing it by corona to the surrounding air, and if the drops had fallen as fast as possible beginning with the time of Christ, I would by this time have collected barely enough copper to be shown by the most sensitive known chemical test. This little experience illustrates the vast difference in magnitude between the kind of currents that we are accustomed to deal with in electromagnetic induction devices, dynamos and motors, and these relatively very feeble currents of electrostatics. These drops were charged with high electrostatic voltage and the device was a fairly efficient electrostatic generator, and yet two thousand years would have been required to deposit an amount of copper such as would appear in a fraction of a second with only a moderate current of the type which we ordinarily use in electromagnetic instruments.

In recent years an interesting development of the Kelvin water-dropper has been proposed by Dr. Swann, of the Bartol Research Laboratory, in which the water drops are replaced by steel balls which fall under the action of gravity, and in order to make the process continuous, there is the suggestion whereby these balls may be carried back again to the upper container by means of magnetic control. In this way, the succession of falling balls behaves somewhat like a continuous belt containing metal sections separated by insulated regions of air and driven by gravity. In the absence of leakage this kind of a generator should be capable of developing such a high voltage that the electrostatic attraction of the falling balls would just compensate gravity. This would be an extremely high voltage such as could be obtained only if the apparatus were operating in a vacuum, and in fact Dr. Swann suggests that it may be operated in this manner.

(To be concluded)

IN HONOR OF PROFESSOR ELIHU THOMSON

By Dr. HARVEY CUSHING

I HAVE been requested to speak in behalf of the professions other than Engineering. This is embarrassing for a doctor, for though Medicine has been said to be the mother of the sciences, they have usually left her, when grown up, to make their own independent way in the world. The best she can do under the circumstances is to breed more; and being prolific, this she continues to do. Meanwhile, being busily engaged in what is more an Art than a Science, she scarcely pretends to know how her scientifically minded descendents have grouped themselves, much less what mischief they are up to under their individual names.

There are those twins, for example, that have just been here, one terrestrially minded, the other stratospheric—but just which one is Auguste and which one Jean she is not quite sure. And then there are the Comptons whom she has learned to differentiate as H. V. and C. R.—High Voltage Compton and Cosmic Ray Compton—and this, after all, is not so difficult for her to remember. But when it comes to identifying all the Elihus, mostly surnamed Thomson but sometimes Thomson-Houston, that's another kettle of fish altogether.

What may be the relation of E.W. (Electric Welder) to E.L. (Electric Lighter) to C.T. (Current Transformer) to P.T. (Power Transmitter) to Q.F. (Quartz Fuser) and to Aurora B. and M.I.T. Thomson, to mention but a few of them, it's now impossible for almost any one to say. To one of this superfluous lot, sometimes known as H.F.A.C. Thomson, mention will subsequently be made if advancing time and contracting space permit. The only thing known about the Thomsons as a clan is that in memory of Roger Bacon's tutor, Peter Perigrinus, who is the family saint, every newborn child cuts his teeth on a loadstone or a spool of wire or both at the same time, and as a consequence the continued activity of the U. S. Patent Office is easily explained.

[1] Address at the dinner given in honor of Dr. Elihu Thomson on the occasion of his eightieth birthday, at the Massachusetts Institute of Technology, May 1, 1933.