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The Precision of Electrical Engineering — Source link

Francis B. Crocker

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little honor to our late honorary member, Moses G. Farmer. He represented what I consider to be the ideal electrical engineer, because he combined the two branches of that subject, the theoretical and the practical. Dr. Barker has just pointed out that most of his work was done on the borderland between what we call pure physics and applied electricity. It would seem as if this combination of the two was most perfect and that either alone, without the other, is incomplete. The electrical engineer could not be a pure scientist, and while the latter might be a member of our body he would not represent the title in the most perfect manner. But in Prof. Farmer we have an ideal example of that well-balanced combination of pure science and useful application. Therefore we can do full homage to him, and the INSTITUTE will always cherish, I feel sure, not only his name but also it will be elevated by the example which he set to its members.

In taking up the subject of the evening, "The Precision of Electrical Engineering;" it occurred to me as Dr. Barker was speaking, that Prof. Farmer's mind had that very exactness which I am going to attempt to bring out. On several occasions his friends have spoken of the exact measurements which Prof. Farmer employed in his work, and Dr. Barker has just cited a case in which Prof. Farmer was able to predict the exact amount of current required to fuse a certain piece of platinum. It is that very precision, that very power of prediction, that I claim for our profession, and it seems therefore especially appropriate that I should now attempt to set forth this accuracy which characterized Prof. Farmer's work. The subject is obviously not a popular one. Nevertheless it is, I think, of general interest and the popular mind, as well as the scientific, is never tired of hearing of the wonderful achievements of electricity. It is a fascinating subject which never seems to lose its charm, and therefore I hope that some of the points will interest those present who are not electricians, although this address was of course prepared from the professional point of view. I may also state that I have not been able to do justice to the subject or to the occasion, owing to poor health during the last few months; but this theme is so powerful in itself that it simply requires to be started and it will carry itself along.

President Crocker then gave his address as follows:

THE PRECISION OF ELECTRICAL ENGINEERING.

BY FRANCIS B. CROCKER.

There still exists quite a general idea that electricity is so imperfectly understood that its laws and actions are little more than matters of chance or guesswork. The experience of the electrical engineer is supposed to consist of a series of surprises and shocks to his mind as well as to his body. This notion is not confined to the ignorant, but is believed by many educated persons, even including our brother civil and mechanical engineers; indeed, some members of our own profession hear this opinion expressed so often that they partly accept it as true, or at least they have no ready arguments with which to refute it.

The existence of this popular error concerning electricity is perfectly natural, and arises from the novelty of the subject and the fact that its development has been so great and so rapid that no one but a few specialists has been able to keep pace with it.

The subtlety, extreme rapidity of action, and the astonishing achievements of this modern agency make it appear most mysterious and occult in comparison with the ordinary forms of energy, such as heat and mechanical power. Possessing such transcendental powers, it is looked upon as something not only unknown, but unknowable, an irresponsible power for great good, or great evil. This idea has sometimes been the cause of actual harm to the progress of electrical engineering. The profession has been considered to be hardly legitimate, those who practised it being regarded as either wizards or charlatans, or a combination of the two. During the present year, the president of a large steam railroad system, on which electric propulsion is being tried, publicly expressed his opinion that electrical engineers know

little or nothing of their subject. In legal decisions in this country and abroad, judges have stated that electricity was so vaguely understood, that testimony concerning it was of no practical value.

It has also been held by many courts, that electricity being intangible, has no real existence, so that the tapping of current from the wires could hardly be considered as a theft, except in an imaginary sort of a way. The production of electrical energy in central stations has been decided by metaphysically inclined judges to be a totally different kind of business from the manufacture of gas. In point of fact, the differences are all in favor of the practical character of electricity. More useful operations can be performed by it; it can be more easily transmitted and distributed; the percentage of leakage is less, and its measurement is far more convenient and accurate.

The idea that "no one knows what electricity is, therefore we know practically nothing about it," is often expressed by those who want to excuse their own ignorance of the subject. They are glad to think that they are no more worse off in this respect than the rest of the world. Their deduction is quite natural, but is absolutely fallacious. While we must admit that we do not know the real nature of electricity, the same limitation of knowledge applies to all other fundamental facts. Gravitation is the most familiar of natural phenomena, yet we have no conception whatever of what it actually is. Our theories and mental pictures of the nature of electricity are much more definite than those concerning gravitation. In regard to the latter, little progress has been made since the time of Newton, while electrical knowledge has advanced and is now advancing with giant strides. There is every reason to believe that we shall "know what electricity is" and be able to explain the inherent mechanism by which electrical actions take place, before we understand how and why a stone is drawn to the earth. What we do know, however, are the laws of both electricity and gravitation, as well as the results that they produce, and it is very doubtful if our ability to control, measure and utilize these agencies would be improved even if we understood their exact nature. The laws and applications of hydraulics would be just as definite and successful even though the fact were not known, that water is composed of two atoms of hydrogen and one of oxygen. It is possible that methods of generating electricity may be advanced when its real character

is discovered, but it is not likely that this knowledge will greatly affect the methods of handling and using it.

The popular ignorance and doubt concerning electricity is rapidly disappearing in consequence of the remarkable results accomplished by it during the last ten or fifteen years, but it will not be out of place, I think, to consider at this time the remarkable exactness which electrical engineering has reached. A discussion of this question may serve to inform laymen who are not familiar with the facts, and may also be a matter of interest and satisfaction to ourselves. This profession has only very recently gained for itself a position of independence and equality among the branches of engineering, but it can now fairly claim to be an example for the others to follow, not only in the magnitude and rapidity of its results, but also in the exactness and certainty of its methods. Let us consider what are the principal facts upon which this strong claim is based.

The names connected with electrical science :—Gilbert, Franklin, Faraday, Ampere, Maxwell, Henry, Helmholtz, Kelvin, and a long list of other distinguished electricians, are not men whose ideas are vague or incorrect. Indeed, it is a significant fact that the ablest and most profound scientific men have been attracted by, and have performed some of their best work in the study of electricity.

The rapid progress of electrical science and its applications is an absolute proof of sure and exact knowledge. Uncertainty would necessarily cause delay, and error would involve repeated trials before success could be reached. The fact that the difficult arts of long-distance transmission of power, and electric traction have been developed to their present state of importance and success in about ten years, shows conclusively that electrical theories and designs agree very closely with the actual facts.

The great results accomplished by electrical engineering is probably its strongest claim. Many of these are so unique and astonishing that we still regard them with wonder even after we have become familiar with them. Among the most striking of these examples are the locating of faults on submarine cables, telephoning a thousand miles or more, transmitting power over one hundred miles, sending simultaneously a number of messages on the same wire, utilizing the power of Niagara, and producing the Röntgen ray. These and hundreds of other wonderful feats are not accomplished by chance, or by groping in the dark.

The close relationship between pure and applied electrical science is still another proof of the exactness and truth of both. If knowledge were complete, theory and practice would become identical. The agreement between theoretical and practical electricity is largely due to the small losses which occur in electrical apparatus and processes. Even quantities which correspond to friction in mechanics, such as electrical resistance and magnetic hysteresis, are capable of exact calculation. It is only the purely non-electrical factors, such as the friction of bearings and air resistance, that are uncertain in designing electrical machinery. The almost infinite rapidity of electrical action makes the time element so small that it can nearly always be neglected. This greatly simplifies calculations and renders their results more accurate. The fact that there is only one kind or quality of electricity also gives definiteness to our ideas and calculations. With coal we must know its quality, including both its physical and chemical properties, in order to make even approximate calculations concerning it. In the case of steam, pressure and volume are not sufficient data; the amount of moisture or superheating must also be known. The most accurate methods of the physicist are not any too good for, nor beyond the reach of the electrical engineer, and they are often employed by him. A notable example of this is Lord Kelvin's work in connection with laying the Atlantic cable, which was undertaken at about the same time that he began to publish his essays on the vortex theory of matter. When Werner Siemens first built his self-exciting dynamos, he also constructed the sensitive galvanometers, used in the researches of his friend Helmholtz. It was Siemens, the electrical engineer, who gave his money and influence to the Reichsanstalt, an institution where the most accurate physical work is now being carried on.

A historical example of the agreement between electrical theory and fact is the brilliant work of Ampere, who gave to the world a beautiful and complete theory of electro-magnetism within a few days after he heard of its discovery by Oersted. The work of Maxwell is another great example of the power of the intellect to deal with electrical problems.

Hertz said, in regard to Maxwell's electro-magnetic theory of light: "It is impossible to study this wonderful theory without feeling as if the mathematical equations had an independent life and an intelligence of their own; as if they were wiser than our-

selves, indeed, wiser than their discoverer; as if they gave forth more than he had put into them. And this is not altogether impossible; it may happen when the equations prove to be more correct than their discoverer could with certainty have known."

It can hardly be admitted that there is anything in Maxwell's equations that he did not put into them, but the remarkable experimental corroboration of Maxwell's theories many years after they were evolved, shows that from a few fundamental truths almost the whole theory of electricity may be deduced.

This power to solve problems successfully by *a priori* reasoning demonstrates the perfection of electrical science. We can arrive at the facts by reasoning out what they ought to be; hence we may say that electrical science is ideal. In other branches of applied science, as for example in civil engineering, the corrections, factors of safety and other allowances are often much greater than the original quantity itself. In such cases it is obviously impossible to go very far from an experimental fact, by any process of reasoning. The errors would immediately become so magnified that the truth would be greatly distorted or lost entirely.

To take a concrete example, the losses in transforming electrical energy are only two or three per cent., and if an error of ten per cent. is made in calculating these losses, the actual error is only two- or three-tenths of one per cent. It would, therefore, be possible to design a system in which electrical energy was transformed many times, and yet the final error would only be one or two per cent. If, on the other hand, the losses in mechanical engineering are ten or twenty per cent., or even fifty per cent., as is often the case, an error of ten per cent. in calculating these quantities would soon become multiplied to a large figure.

Exactness in electrical units and terms is another strong point of electrical engineering, because definiteness in terms and ideas go hand in hand. The system of electrical units is complete and scientific, being based directly upon the c. g. s. system, and is the only example of a set of units which are universally adopted. The metric system is not in use in the United States, Great Britain and her possessions and many other countries, but the same electrical units are accepted by all nations. This avoids the great confusion which arises from the use of several different units for the same thing, as is the case in steam engineering, in which at least four different heat units are commonly employed.

In electrical engineering the distinction between the various quantities are usually more clearly understood, as for example the difference between force, work and power. In other branches these quantities were often confused, and the fact that mistakes of this kind are not more often made at present, is largely due to the influence of electrical engineering in the accurate use of terms. The useful word torque has been introduced through electrical engineering although it is a purely mechanical quantity. The adoption of such terms as impedance and reactance gives a nicety of expression which is rarely found in other applied sciences.

The facility and accuracy of electrical measurements contributes greatly to the precision of electrical engineering. Volts and amperes can be easily, quickly and accurately measured by means of convenient portable instruments. The product of these volts and amperes gives the watts or power which is the most important quantity.

If desired, a single instrument—the wattmeter—can be used to combine the two quantities. Electrical resistance can also be measured easily and quickly, and with still greater accuracy. Even the less common electrical quantities, such as capacity and inductance, can be measured without much difficulty and with reasonable exactness. The magnetic quantities are also quite easily and correctly determined. As already stated, the most doubtful factors in electrical engineering are the mechanical ones.

The enormous range in electrical engineering is still another proof of its precision. The same laws and principles which apply to the almost infinitesimal galvanometer current are equally applicable to the current from an electric light station. The former may be only a hundred billionth of an ampere and the latter reaches ten thousand amperes, which is a thousand million million (10^{15}) times greater.

An even greater ratio than this represents the range of resistance measurements. In the case of large copper bars, a determination to within .000001 ohm is often required, and for insulation testing 10,000 megohms is not an unusually high figure. This gives a range of measurement of ten thousand million million (10^{16}).

An electrical instrument, the bolometer of Professor Langley, is used to measure the heat received from the fixed stars, and electricity is also the agent selected when 100,000 horse-power are to be distributed from Niagara. Instead of saying that elec-

tricity is selected for these extreme uses, it would be more correct to state that it must be employed, just as it is the only means of transmitting speech a thousand miles, or performing the many other miracles of which it alone is capable.

The directness and high efficiency with which electrical energy can be converted into other forms is another fact which gives exactness to our work. It can be transformed into heat, light, magnetic, mechanical or chemical energy, by the simplest means, and conversely, the latter forms, with the possible exception of light, can be readily changed into electrical energy. In most cases the conversion is almost perfect, the efficiency of an electric motor or dynamo being usually over 90 per cent. and often 93 or 94 per cent. The chemical energy in a storage battery represents nearly 90 per cent. of the watt-hours applied to it, assuming the losses in charging and discharging to be about equal. The storage of magnetic energy may be effected at an even higher efficiency of 97 or 98 per cent. and the conversion of electrical energy into heat is complete, the efficiency of an electric stove actually reaching the ideal figure of 100 per cent. The production of light cannot be accomplished so economically, nevertheless the arc lamp has a far higher efficiency than any other artificial source of light, although it is usually stated to be only 8 or 10 per cent. It is also more than probable that the long-sought-for high efficiency lamp will be an electric one when it is finally invented. This facility and economy of transformation puts electricity directly in touch with the other sciences and their applications, avoiding the chances for error which round-about processes necessarily involve. None of the other forms of energy possesses anything like the same convertibility. The one serious difficulty in connection with electricity is the fact that its generation requires a boiler, engine and dynamo, bringing in heat and mechanical power as steps in the process. If this complication could be avoided, and electrical energy produced directly from the chemical energy of the coal, the only limitation would be removed. This has already been done in an experimental way, and by the substitution of water-power for steam, one piece of apparatus and one form of energy are eliminated, but the complete independence of electrical engineering and the realization of all of its possibilities will be secured when the direct conversion of fuel energy into electrical energy is accomplished practically.

It has been shown that there are no less than eight substantial

grounds upon which the precision of electrical engineering is based. The consideration of these has incidentally brought out several concrete examples, but it will be well to cite a few other special instances which demonstrate electrical exactness.

The one which first claims our attention not only on account of its historical precedence, but also from its wonder-compelling results, is the locating of faults in ocean cables. In this connection I quote from information kindly furnished me by one of the vice-presidents of the INSTITUTE, Dr. A. E. Kennelly, who has had a long and successful experience in this branch of the profession. He states that "In the case of cable coiled in a tank and which has been taken into the tank over a measuring drum without being subjected to any considerable tension, the precision with which a fault in the gutta percha can be located is sometimes very considerable. I have known one or two cases in which a fault has occurred in a length of say thirty miles of cable immersed in water and maintained at practically one temperature in the tank, and in which, by means of the Varley loop test repeated many times and under various conditions to eliminate constant errors, the electrical position of the fault has been determined to within a probable error, representing about twenty feet of length. On turning the cable over from one tank to another by a seven foot drum on which the cable makes three turns, and cutting the cable when the computed distance has been run over, the fault has been found on the drum, that is, in the sixty feet or so of cable then lying on the drum."

"As regards the location of faults in submarine cables on the ocean bed, the precision depends upon a variety of circumstances, and in general is necessarily much lower than in the case of a cable coiled in a tank. The average error in practice, or the difference between the true electrical and computed positions, is perhaps about fifteen ohms, or about one mile and a half of cable having the common resistance of ten ohms per mile. Under favorable circumstances a complete break in a cable developing a fair extent of surface exposure to the sea water at the end of the copper conductor, the electrical position can be determined within five ohms in a total conductor resistance of 1,000 ohms. In the case of a fault in the insulator, sufficiently serious to interfere with signalling, specially favorable cases will occur in which the electrical position of the fault can be determined to within one ohm when a loop test is obtainable and when the total conductor

resistance of the loop does not exceed 3,000 ohms." "I have known a case of total loss of continuity in the conductor, accompanied by perfect insulation. It occurred in lifting a cable for repairs and was within half a mile of the ship. A measurement of electrostatic capacity enabled the distance to be determined within a few yards." Other cases are given by Dr. Kennelly, and many may be found in various works and journals, but these are sufficient to show the astonishing results that are possible, as well as those that are obtained in regular practice.

The methods employed in locating faults in underground conductors are quite similar to those used for submarine cables, but the results are less striking and important. Mr. William Maver, Jr., who is an authority on this subject, cites a case in which the calculated position of a fault was 2,343 feet from the testing end of an underground cable 4,200 feet long. The defect was found at the exact point indicated. The alternative would have been the tearing up of the street and cutting through a heavy iron pipe until the fault was found, as the conduit was not provided with manholes. One way to locate a ground connection, which illustrates the simplicity and certainty of electrical testing, consists in sending a current through the conductor to the ground through the fault in the insulation. A compass carried along over the cable will indicate by its deflection or non-deflection when the fault is reached. The facility of overcoming distances and obstacles impassable to other agencies is characteristic of electricity and magnetism.

The writer has had occasion to test the resistance and position of faults ("grounds") on a very large system of underground conductors for electric lighting. Although the problem was complicated by the fact that it was a three-wire system which extended several miles, it was found possible to determine the insulation resistance of each of the three conductors. The position of a "ground" is shown by the potential difference between the conductor and the earth, being a minimum at that point. For example, if a ground connection exists on the positive wire and a considerable current flows through it into the earth, the potential of the earth at that point will be raised above its normal value. The potential difference existing between the wire and the earth is actually less near the ground connection. This may be measured from the station by using the "pressure wires" ordinarily laid with the feeders, and special wires which connect to the ground at various points of the system.

The paper on "The Alternating Current Induction Motor," presented by Vice-President Charles P. Steinmetz at this meeting of the INSTITUTE, affords an excellent example of the marvelous precision of electrical engineering. In Figs. 1 and 2, two curves are shown which give the efficiency, speed, power-factor and other characteristics of a three-phase induction motor under various conditions. These curves were all predetermined by calculation. In the same figures the results obtained by actual test are also marked by small crosses. The agreement in all cases is so close that curves plotted from the actual results of tests would practically coincide with those predicted by calculation. This is all the more remarkable when it is remembered that the three-phase motor is one of the newest of electrical machines, and is a difficult problem from a theoretical standpoint. It has long been possible in designing direct current machinery to predetermine the results with almost as great accuracy as that shown in the curves of Mr. Steinmetz, but of course that is a much older problem. Nevertheless, the predetermination of results in direct current machinery is fully as difficult as in the case of alternating current apparatus, because permeability is the most doubtful factor in such calculations and is especially so at the high flux densities used in the former. It is to be observed, however, that any error in the permeability data can be corrected by increasing or decreasing the ampere-turns on the field magnet. This is easily accomplished by providing five or ten per cent. greater *m. m. f.* than the calculations require, which may be reduced, if necessary, by the introduction of resistance. Since the energy used for the field is a very small percentage of the total amount, it may be considerably varied without materially affecting the other factors in the machine. Sparking at the commutator brushes is an additional and by no means simple question which confronts the designer of direct current apparatus. I remember, however, being informed by Mr. Gano S. Dunn several years ago that he had found by experience in many cases that the efficiency of a direct current dynamo or motor can be predetermined from the drawings before the machine is built, within a fraction of one per cent.; in fact, he relied more upon his calculations than upon an actual test of the completed machine, even when performed by skilled men. In one case the calculated efficiency was 93 per cent. and the result obtained by test was 92.7 per cent., and in another case the total flux was found to be 1.38

per cent. greater than the computed value. This agreement is somewhat closer than is found in every day practice, but is not accidental and can usually be approximated by careful work.

We naturally suppose ourselves to be familiar with mechanical energy and heat; but as soon as we convert these well known forms of energy into that extremely subtle and mysterious agent—electricity—it immediately becomes far more definite and convenient to control, measure, transmit and utilize. In becoming intangible, it forthwith acts as the most reliable and matter-of-fact tool in the hands of those familiar with it. For example, the quickest, neatest and most exact method of making a test of mechanical friction, or the power required in any given case is by the use of an electric motor. In this way, for example, we can determine the friction of different bearings or lubricating oils under various conditions of pressure and speed, or the power consumed by fans, pumps and other machines.

Quite a striking example of the possibilities of electrical measurement is the determination of the *E. M. F.* of a dynamo machine without running it, which I saw successfully carried out more than ten years ago. All that is necessary is to measure the torque exerted by the machine with a given current in its armature. This may be accomplished by simply clamping a stick of wood to the pulley and weighing the pull at a given radius by means of a spring balance. If the same machine were run as a dynamo and had no losses, it follows that

$$\frac{EI}{746} = \frac{2\pi r SP}{33,000},$$

whence

$$E = \frac{r SP}{7.04 I},$$

in which r is the radius at which the pull is measured, S is the speed in revolutions per minute at which the dynamo is to be run, P is the pull in pounds at the given radius and I is the current in amperes. The field strength is supposed to remain the same. This method is correct whatever the efficiency of the machine may be. The electrical and magnetic losses due to the $I^2 R$ effect in armature, field current, eddy currents and hysteresis do not enter this problem. Even the mechanical losses arising from friction of bearings, brushes, etc., may be eliminated by measuring the pull plus the friction and then minus the friction, the actual pull being one-half the sum of these two results. The

effect of friction may also be gotten rid of by tapping the shaft when the measurement is made. It certainly strikes one as strange that E. M. F., which depends upon cutting lines of force, can be determined while the machine is standing still.

In electro-chemistry and electro-metallurgy quantitative relations are particularly precise. The ampere being defined as the current which deposits .001118 grammes of silver per second, the weight of any other substance is by Faraday's laws proportional simply to its chemical equivalent. This definition eliminates any error in passing from the electrical to the chemical data, or vice versa. The volt is also defined electro-chemically in terms of the E. M. F. of a Clark cell.

The author presented before the INSTITUTE, in May, 1888, a paper on "The Possibilities and Limitations of Chemical Generators of Electricity,"¹ in which the weights of materials, E. M. F. and other data were given for various voltaic combinations. Some of the figures were obtained by experiment and some by calculation. The paper also gives the E. M. F. produced by combinations of thirteen of the most important metals with chlorine, bromine and iodine, respectively. The average difference between the calculated and tested values was less than one-tenth of a volt. Even this small error is practically eliminated when the results are corrected by the equation of Helmholtz, that is, by adding the quantity $\pm T \frac{dE}{dT}$, in which T is the absolute temperature and E is the E. M. F. of the cell. Since the weights of materials liberated or consumed by a given current in a given time can be definitely predetermined and the voltage due to a certain chemical combination can also be accurately calculated, almost any problem in electro-chemistry or electro-metallurgy is susceptible of being quite easily and correctly solved. That branch of electro-chemistry and metallurgy which employs electrical heating methods is also very definite, the exact amount of heat in gramme-degrees produced per second by an electric current being always given by the simple expression, $.24 I^2 R$, or $.24 E I$.

In support of the proposition advanced in the title of this address, I am able to produce most interesting personal testimony. Mr. Edison and Mr. Tesla have independently expressed to me their opinion that electrical knowledge had become so definite and general that almost anyone could apply it, and comparatively

1. TRANSACTIONS, vol. v., p. 227.

little opportunity was left for invention. They believed that chemistry and thermodynamics were far more uncertain and therefore offered a much better field for improvement. These views were expressed several years ago, and subsequent events have shown that they contain a great deal of truth. It is a fact that electrical engineering has advanced along the lines laid down by these and other great inventors, and it is also true that much of the work has been done by the rank and file of the profession. The trails blazed by the pioneers have since become broad highways with many branching roads, built for the most part by common workmen. On the other hand, the discovery of the Röntgen ray has since been made; and both of these investigators have given much valuable time to it. It would seem, therefore, that the electrical principles and laws of to-day are true for all time, and afford a firm foundation for unlimited future progress, but that there are also many additional facts yet to be discovered that are well worthy of the efforts of the greatest genius.

In conclusion, the following quotation from the preface of Maxwell's great work on Electricity and Magnetism is appropriate. "The important applications of electro-magnetism to telegraphy have also reacted on pure science by giving a commercial value to accurate electrical measurements, and by affording to electricians the use of apparatus on a scale which greatly transcends that of an ordinary laboratory. The consequences of this demand for electrical knowledge and of these experimental opportunities for acquiring it, have been already very great, both in stimulating the energies of advanced electricians and in diffusing among practical men a degree of accurate knowledge which is likely to conduce to the general scientific progress of the whole engineering profession."

These words were written in 1873, and yet they show strong confidence in the accuracy of electrical methods and full appreciation of the close relationship between electrical science and engineering, as well as their beneficial effects upon each other. At that time the telegraph was the only practical application of electricity. What language would express Maxwell's wonder if he were alive to-day!