smaller and smaller, the expense of the firing circuits does not decrease, and finally the cost of this auxiliary is so high in comparison with the rest of the rectifier that the over-all result is not economically sound. At the present time this lower limit for an economical design of sealed pool tube rectifiers is at about 100 amperes per anode. This situation is a problem confronting engineers active in the development of tubes of this general type for wider applications.

Considerable thought and effort, therefore, are being given to the development of ignitors that require much less current than the present ones that take a maximum of about 25 amperes.[36] This is not an easy problem in view of the outstanding performance of present-day ignitors as regards life and reliability. Life of a modern sealed ignitron is measured in years rather than in a few thousand hours and it requires time to develop new devices with the assurance that these long life records will be maintained.

Most large steel envelope sealed ignitrons contain two separate ignitors. In view of the long average life obtained in modern tubes the question has been raised as to whether two ignitors are really necessary or advantageous. The concensus of opinion seems to be that two ignitors will be continued as a design feature. They represent low-cost accident assurance against ignitor breakage or burn-out resulting from trouble in the firing circuit. Designers of these tubes point out, however, that when a tube finally fails after many years of service it is usually from some other cause than ignitor failure and, therefore, it is seldom that the spare ignitor can be used to rejuvenate completely the tube and start it off on a second career of long life.

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Electrical Essay

Faraday's Law of Induction

If S is any smooth, continuous surface bounded by a single, smooth, continuous closed curve, then always the integral of the electric field intensity E around this closed bounding curve, $\int E_s.ds$ is equal to the negative rate of change of the integral, over the surface of the normal component of the magnetic flux density B.

$$\int E_s dS = -\frac{\partial}{\partial t}\int\int B_N dS$$

True or false?

Answer to Previous Essay

The author's reply to his previously published electrical essay (*EE, Apr '48, p 337*) is as follows.

Don't ask such questions! See Joseph Slepian's "Energy Flow in Electric Systems—the *Vi* Energy-Flow Postulate," AIEE *TRANSACTIONS,* volume 61, 1942, December section, pages 835–40, as to why such questions are without meaning.

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tive power we account for, by reflecting that the reactive power we account for, by reflecting that the reactive power associated with a given magnetic energy is proportional to the frequency and that therefore, because of its lower frequency, sf, the smaller reactive power, $e_2 i_2 = s e_1 i_1$, of the rotor corresponds to just as much magnetic energy as the larger reactive power of the stator.

The rotor might be loaded by connecting its slip rings to a static impedance, $\mathcal{Z} = R + jX$. Then the load taken from the line will be the same as if an impedance $\frac{1}{s}\left(\frac{n_1}{n_2}\right)_2 (R+jX)$ were connected to the line. We note again that the line reactive power is of the same sign as the rotor power, lagging if the latter lags, and leading if the latter leads.

Let us now run the rotor at above synchronous speed, that is, with a negative slip, which we shall denote by $-s$. Now the rotor induced voltage will be *opposite* in phase to the stator induced voltage, $e_2 = -s\frac{n_2}{n_1}e_1$. The stator and rotor currents, however, continue to be in opposite phase relationship, $i_1 = -\frac{n_2}{n_1}i_2$. Thus, as compared with running below synchronism, with positive slip, s, we see that above synchronism, the relative phases of the stator and rotor voltages are reversed, whereas the relative phases of the stator and rotor currents are unchanged. We conclude then, that above synchronism, the stator power will be opposite in sign to the stator power below synchronism.

Consider again the case where the rotor is loaded by a static 3-phase impedance, $\mathcal{Z} = R + jX$, across its slip rings, and compare the operation at slip $-s$ above synchronism, with slip s below synchronism. The rotor frequencies will be the same in the two cases; namely, $f_r = sf_o$. Hence the static impedance $\mathcal{Z}$ will have the same value, $R+jX$, in the two cases. The rotor voltages in the two cases, E'_2 and E_2 will be the same in magnitude, but opposite in phase, $E'_2 = -E_2$. The rotor currents, therefore, will be opposite in phase in the two cases, $I_2' = \frac{E_2'}{\mathcal{Z}} = \frac{-E_2}{\mathcal{Z}} = -I_2$. The stator, or line voltages, are of course the same in the two cases, $E_1' = E_1$. The stator currents however, which must be opposite in phase with the rotor currents, will be opposite in phase in the two cases. $I_1' = \frac{n_2}{n_1}I'_2 = +\frac{n_2}{n_1}\frac{E_2}{\mathcal{Z}}$; $I_1 = -\frac{n_2}{n_1}I_2 = -\frac{n_2}{n_1}\frac{E_2}{\mathcal{Z}}$; therefore, $I_1' = -I$.

Thus again we conclude that the stator power at the slip $-s$, above synchronism, is equal to but opposite in sign for the stator power at the slip s below synchronism.

In an actual motor, of course, the rotor will have a resistance and a leakage reactance which should be added to the slip ring impedance in the previous example. If the slip rings are short-circuited, then the total effective rotor impedance is just this rotor resistance and rotor leakage reactance.

We conclude then that an induction motor with short-circuited winding, at an oversynchronous speed, slip, $-s$, will take power from the line very nearly equal and opposite to the power taken at below synchronous speed, slip s. Below synchronous speed the motor takes positive true power from the line, and also positive (lagging) reactive power.

Hence above synchronism, the motor will deliver true power to the line and also deliver reactive power to the line. That is, the induction motor above synchronsim operates at leading power-factor.—*True* or *false?*

Answer to Previous Essay

The author's reply to his previously published electrical essay (*EE, Jun '48, p 530*) is as follows.

Take a long rectangular strip of paper. Give the strip a half-twist, that is, turn one end 180 degrees relative to the other, then overlap the two ends and glue together. As may be seen from a model or the figure, the strip now constitutes a smooth, continuous surface bounded by a *single*, smooth, continuous, closed curve. Nevertheless, Faraday's law is not true for this surface bounded by this curve.

The statement of Faraday's law should have included the restriction that the surface is two-sided. Of the books on the library shelf in this laboratory dealing with vector analysis or electromagnetic theory, only Stratton's "Electromagnetic Theory" mentions this condition.

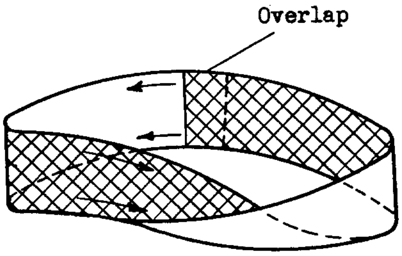

Figure 1

The necessity for this two-sidedness becomes evident when we consider how the sign of the integrals occurring in Faraday's law are to be determined. We may take one particular sense of going round the bounding curve as positive. If then the surface is two-sided, we may use a right-hand rule or some equivalent to determine which side shall be regarded as having the positive normal direction. If the surface is one-sided, however, as in the Figure 1, it becomes impossible to determine a positive normal direction related in some definite way to the direction along the bounding curve which is chosen as positive.

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Measuring Leakage Reactance

To demonstrate and measure leakage reactance, the two windings of a 230-230-volt transformer were connected in series bucking. A reduced voltage sufficient to circulate rated current of 22 amperes was applied. To measure the voltage, a 6-volt a-c voltmeter having a resistance of 24 ohms was connected. The deflection was slightly more than full scale so it was decided to measure the voltage across one winding and double that value to obtain the total voltage. When the voltmeter was connected across either winding there was no observable deflection of its pointer from a zero reading. Why is such a result obtained?

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stress "has little meaning . . .," whereas in 1948 he presented a paper in which all of the data on dielectric strength were given in terms of maximum stress and there was even no reference to average stress.[1]

We owe something to Del Mar for his quotation of Pupin's "I do not believe in theories—I use them." That quotation deserves much repetition.

Gemant has made an important contribution in pointing out that the views of K. W. Wagner concerning the ionization mechanism of breakdown, expressed in writings later than the one to which I referred, are identical with those I have expressed.

Some confusion has resulted from my likening of the first incipient ionization by collison to an avalanche. Initially this incipient discharge is stopped after a travel of only the thickness of a tape, by the tape against which it impinges. It is the cumulative damage due to these relatively minor occurrences which gradually breaks down successive tapes and results in the major avalanche of complete failure. In any attempt to explain dielectric performance it seems most important to emphasize these initial stages which tend to be obscured by the later developments of the failure.

Greenfield points out that secondary ionization does not occur at 100 volts per mil "in a much used type of oil-filled cable oil." Quite true, but electrical failures do not occur in such cables until stresses in the oil reach many times 100 volts per mil. Nor do I know of any reason to expect bubbles to be formed at that stress by a combination of electrical stresses and chemical action which he describes. Greenfield's other comments are with a different emphasis than the writer's but seem not inconsistent with them.

Wiseman expresses a "corona law" for breakdown in which a term is introduced containing the square root of the conductor radius in a manner similar to the law for corona initiation in air. There is a sound theoretical basis for the use of this term, but, since, before failure has set in, the free path of the ions is normally limited to the thickness of a tape, the magnitude directly explainable by it must be very small. However, in view of the fact that the practical results are in the direction predicted, this explanation of Dr. Wiseman's must be considered pertinent. He introduces a further term including the outer radius of the insulated conductor. This term scarcely can have a sound theoretical basis since one of his formulas which includes it gives infinity as the dielectric strength of insulation between flat plates. Thus, while the term might be used to express in mathematical form some observed data, it cannot help to explain the observations.

For the reasons stated by Robinson, it would be better usage, in all instances, to say "condensation" instead of "polymerization" to describe the process of wax formation in cables. Robinson suggests that even in a cable saturated in degassed oil (which avidly will dissolve gas bubbles) there still may be residual minute gas bubbles, and that ionization starts in these. While this thought is not easily accepted, it should not be discarded, especially since it makes a very helpful explanation of the dependence of the strength of such a cable upon the pressure. Very pertinent to this subject is the experiment of H. H. Race in which he produced visible corona in an oil bath, which continued for a time and then resulted in puncture, presumably when the oil became gas-saturated.

Here is a parting speculation. Can it be that when the highest stresses are reached in oil-filled paper insulation, the ions which begin the action are electrons drawn from the metal electrode by the electrical field? Can the freedom of extraction of these electrons from the metal be affected sufficiently by the hydrostatic pressure in the oil to explain the effect the hydrostatic pressure has upon the 60-cycle strength? This may be a useful seed for thought.

The discussions not mentioned herein contribute materially to the picture but call for no comment here.

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Electrical Essays

Faraday's Law of Induction II

A 2-Sided Surface Bounded by 2-Turn Coil

"If S is any smooth, continuous surface bounded by a single, smooth, continuous closed curve, then always the integral of the electric intensity, E, around this closed bounding curve, $\int E_s ds$, is equal to the negative rate of change of the integral over the surface, of the normal component of the magnetic flux density, B.

$$\int E_s ds = -\frac{\partial}{\partial t}\int\int B_n dS$$

"True or false?

"Author's answer: False."

The preceding is an electrical essay which appeared in *Electrical Engineering*, June 1948 (*p 530*).

In his answer the author gave as an example, the Moebius strip illustrated in Figure 1, and observed that such a strip is one-sided and that therefore Faraday's law cannot apply to it, since Faraday's law implies some criterion for determining a positive direction to the normal at any point of the surface, and this cannot be given for a one-sided surface.

The "single, smooth, continuous closed curve" which bounds the Moebius strip is shown in Figure 2 and is nothing more than the curve followed by the conductor of a plain ordinary 2-turn coil! Surely, Faraday's law applies to such a coil.

It then must be possible to construct a 2-sided "smooth, continuous surface," which is bounded by the "smooth, continuous closed curve" followed by the conductor of the 2-turn coil. Given such a surface, we may take, over it, the integral of the normal component of B and thus determine the flux linkages Φ of the coil, to which the equation $E = -\frac{\partial\Phi}{\partial t}$ may be applied. Without such a surface, no meaning can be attached to the idea of flux linkages of the coil.

Question! What does such a 2-sided smooth, continuous surface look like?

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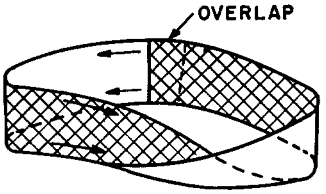

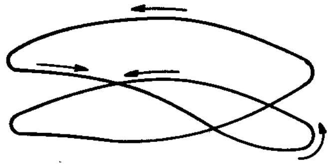

Figure 1 (left). Moebius strip bounded by 2-turn coil

Figure 2 (right). Two-turn coil

you started so that there might be some chance of your magnetic line closing.

So, there you are! A magnetic line, without the axial current gives only one linkage, but with my axial current it gives thousands of linkages. Thus the electromagnetic induction is intensified or multiplied thousands of times.

For the practical application of my invention, whenever and wherever you want to use electromagnetic induction in a coil, always use two coils, connected as shown in Figure 4. Then each coil will act as an intensifier of electromagnetic induction for the other, and you will get the induction you want multiplied thousands of times.

I am writing up this invention as an electrical essay to get prompt publication, but now I have to ask a question.

Question. Is my invention any good?

J. Slepian, Alter Ego

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Low-Voltage Winding

Two identical transformers have a low-voltage winding that is rated at 115 volts and 60 cycles per second and is provided with 50 and 86.6 per cent taps. With a sinusoidal voltage of 115 volts at 60 cycles per second applied to the full winding the exciting current has rms components of 1 ampere fundamental, 0.4 ampere third harmonic, and negligible higher harmonics. The two windings are connected in *T* to a 115-volt 60-cycle-per-second 3-phase sinusoidal supply, one line connection being made to the 86.6 per cent tap on the teaser transformer. Will the three exciting currents have identical wave forms? Will they have equal rms values?

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Answers to Previous Essays

Faraday's Law of Induction II. The following is the author's answer to a previously published essay of the foregoing title (*EE, Jul '49, p 613*).

The surface in question is shown in Figure 1 of this answer. It is 2-sheeted. Students of the theory of functions of a complex variable will recognize it as portion of a 2-sheeted Riemann surface containing a single branch point. The surface apparently crosses itself at a line of intersection of the two sheets. However, this line of intersection is not to be regarded as common to the two sheets, but the apparent points of this line are to be regarded as two distinct sets of points, one set being reached if the line is approached on the upper surface from the left and on the lower surface from the right, and the other set of points being reached if the line is approached on the lower surface from the left, and on the upper from the right.

This surface is 2-sided. If, for example, we start on the upper side of the upper sheet, and move about, as we will, on the surface, we return always on the upper side of the upper sheet. This is not true for the Moebius strip.

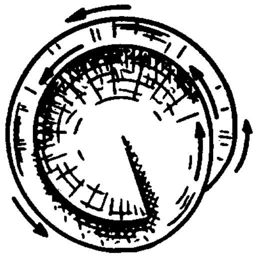

Figure 1. Two-sided surface bounded by 2-turn coil

Faraday's law then applies for this 2-sided surface of Figure 1. The integral of the normal component of B over this surface,

$$\int\int B_n dS = \Phi$$

has a meaning. Such an integral over such a surface is the only definition of the flux linkages Φ, which can be given in terms of operations which refer only to the coil in question, even though other electric circuits and sources of magnetic fields may be present.

A surface suitable for application of Faraday's law may be generated as follows. From any point fixed in space draw a straight line, radius vector, to a variable point on the bounding circuit curve. The surface generated by this moving radius vector, as the variable point traces out the bounding circuit, will be a smooth (except at the vertex) 2-sided surface to which Faraday's law may be applied.

Students of electromagnetism probably will recognize that if a layer of normally magnetized material with surface density of magnetization i, is placed uniformly along the surface of Figure 1, it will produce the same magnetic effect as a current i, flowing in the bounding circuit.

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The Steinmetz Network. The following is the author's answer to a previously published essay of the foregoing title (*EE, Jul '49, p 614*).

The Steinmetz network contains no internal electromotive force and must be energized by an external source of voltage. When the secondary terminals are open-circuited and the secondary current output is zero it follows from equation 1 of the essay that the primary voltage must be zero. This means that the network is a short circuit on the system to which the primary terminals are connected. The primary current therefore will be E_1/z (where z is the system impedance) and from equation 2 the open circuit voltage is

$$E_0 = xE_1/z \qquad (3)$$

Similarly, the impedance to be placed in series with this voltage is found to be

$$Z = x^2/z \qquad (4)$$

When the young engineer assumed a sustained primary voltage *and* an open-circuited secondary side of the network, he thereby introduced into the problem a system of infinite capacity having an impedance zero. Substitution of zero for z in the foregoing equations of voltage and impedance demonstrates that the results obtained, if not practical, are at least consistent with his assumptions.

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