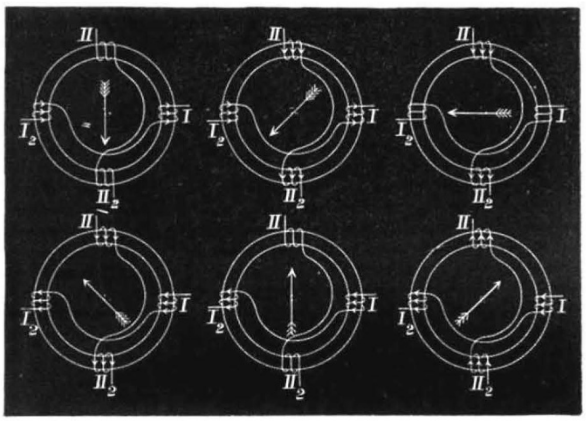
SOME NOTES ON THE FRANKFORT INTERNATIONAL ELECTRICAL EXHIBITION.[1]

V.

The Evolution of the Multiphase Alternate Current Motor.

THE two-phase alternate current motor described in Part IV. has the disadvantage that, not merely does the magnetic field rotate, but it also varies in strength: this causes the driving force to fluctuate, and diminishes the power that the motor would otherwise give out. That there is this variation in strength of the magnetic field



[FIG. 12 (repeated).—Rotating magnetic field produced by two alternating currents, differing by 90° in phase.

may be seen from Fig. 17, where the continuous curves I and II show at any moment the strengths of the currents in the coils I and II, Fig. 12 (repeated for reference from the last article); while the dotted curves I_2, II_2, in Fig. 17, give the values at any moment of the currents in the coils I_2, II_2, in Fig. 12. For example, when the time equals *a* (Fig. 17), the currents flowing in the coils I and II have respectively their maximum value and nought; whereas when the time equals *b*, the currents flowing in each of these coils is the same, being equal to 2 × sin 45° into the maximum value.

Now if each of the four coils occupies only a small portion of the ring, as shown in Fig. 12, the currents in all the four coils will always help one another to magnetize the iron ring, hence the magnetizing force at any moment will be approximately proportional to the number of convolutions in one of the coils multiplied by the *arithmetical* sum of the ordinates of all the four coils I, II, I_2, and II_2, that is, multiplied by twice the ordinate of the upper or summation curve.

If the maximum ordinate of either of the curves I or I_2 be called H, the ordinate of the upper or summation curve is equal to H when the time is *a*, *c*, or *e*, corresponding with the illustrations marked *a*, *c*, and *e* in Fig. 12; whereas the ordinate of this summation curve is $\frac{2}{\sqrt{2}}$ H, or 1·414H, when the time is *b*, *d*, or *f*, corresponding with the illustrations marked *b*, *d*, and *f* in Fig. 12.

Hence, if K be the number of convolutions in one of the coils, the sum of the products of the current into the number of convolutions, or the *number of ampere-turns*, as it is called, will vary between two values proportional to HK and 1·414 HK—that is, will vary by 41·4 per cent. The variation in the magnetism produced by such a change in the number of ampere-turns will be less than 41·4 per cent., and much less if the magnetic induction be considerable; still, the fluctuation in the strength of the rotating field may be greater than is desirable.

If in place of the two pairs of coils (Fig. 12) there be three, I, I_2, II, II_2, III, III_2, as in Fig. 18, and if the alternating currents passing through these three circuits be of the same maximum altitude and periodic time, but differ by 60° in phase, the variation in the number of ampere-turns will be much less than if only two alternating currents be employed. For on examining the sum of the ordinates of the three continuous curves, I, II, III (Fig. 19), which are the curves of three such currents, we see that the sum, or the ordinate or the top curve, varies between 2H sin 60°, when the time equals *t*, and H + 2H sin 30°, when the time equals *t*. Hence this sum varies between $\sqrt{3}$H and 2H, corresponding with a change of only 14 per cent. in the magnetizing force, and with less than 14 per cent. in the magnetism produced.

Such a system, however, would require six wires, whereas the same reduced maximum variation of the number of ampere-turns can be practically attained by employing only three wires conveying three alternate currents differing by 120° in phase, and by joining up the motor as shown in Fig. 20.

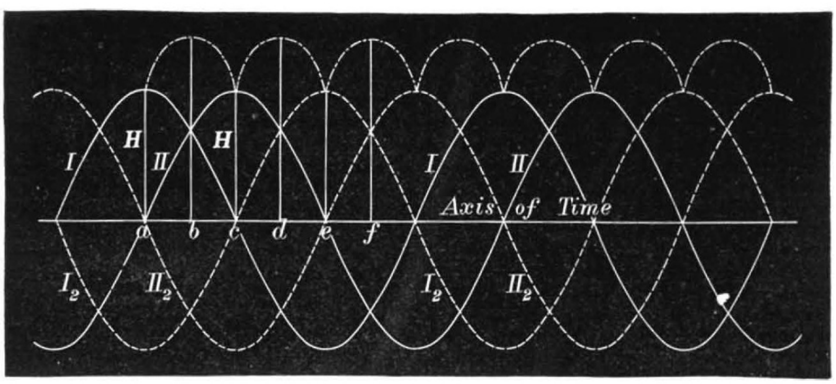


FIG. 17.—Two harmonic alternating currents of the same period and maximum amplitude, but differing by 90° in phase.

That it is possible to use only three wires, so that either wire always acts as the return wire for the currents in the other two, arises from the fact that the algebraical sum of three harmonic alternate currents of the same period and maximum amplitude but differing by 120° in

[1] Continued from vol. xliv. p. 619.

phase is always nought. This may be easily proved thus: the values of three such currents are given at any moment by projecting on a stationary line, POQ (Fig. 21), the three equal limbs of the three-legged figure $O\alpha$, $O\beta$, $O\gamma$, as it rotates with uniform velocity round the point O. $O\alpha$, $O\beta$, $O\gamma$, are, therefore, the maximum values of the three currents, and the actual values of the currents for the position of the figure shown are OA, OB, OC, respectively, corresponding in relative magnitude with the lengths of the arrows which are attached to A, B, C, in Figs. 18 and 20, and in direction with the arrows attached to the latter figure, on the assumption that a current is regarded as positive when it circulates round the iron ring in such a direction as to tend to send a north pole counter-clockwise round the iron ring. Now the sum of the projections on POQ of any three lines $O\alpha$, $O\beta$, $O\gamma$ (Fig. 22) is simply the projection of $O\zeta$ found by drawing $\alpha\epsilon$ and $\epsilon\zeta$ parallel and equal to $O\beta$ and $O\gamma$ respectively. But if such a construction be made for Fig. 21, ζ and O will always coincide, therefore the sum of the projections of $O\alpha$, $O\beta$, and $O\gamma$, Fig. 21, must be always nought.

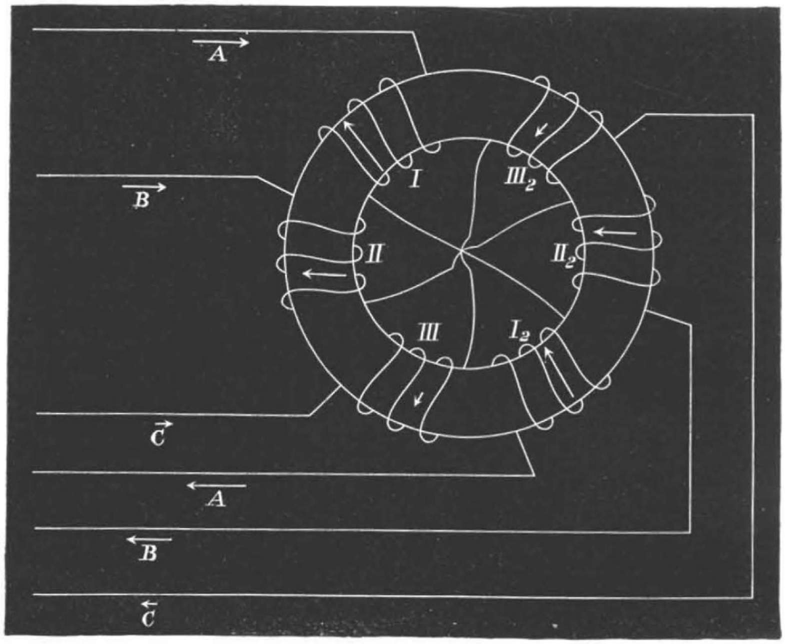


FIG. 18 —Currents differing by 60° in phase, and represented in direction and magnitude by the direction and length of the arrows.

Fig. 23 shows three curves, I, II, III, drawn so as to give the values at any moment of three harmonic alternating currents each of the same altitude, H, and periodic time, but differing by 120° in phase, and it is seen that the sum of the three ordinates—that is, the ordinate of the top curve—varies from H + 2H sin 30°, when the time equals t, to 2H sin 60°, when the time equals t', so that the ordinate of the summation curve varies from 2H to $\sqrt{3}$H, corresponding with a variation of 14 per cent. But this is exactly the variation that we obtained in Fig. 19, hence if there be twice as many convolutions in each of the three coils of Fig. 20, as in each of the six coils of Fig. 18—that is, the same total number of coils in the whole ring—and if the three equal harmonic alternating currents differing by 120° in phase have each the same

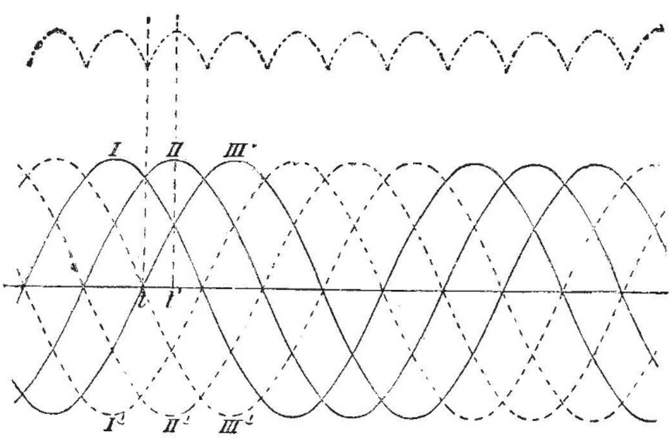


FIG. 19.—Three harmonic alternating currents of the same period and maximum altitude, but differing by 60° in phase.

maximum amplitude as the three equal harmonic alternating currents differing by 60° in phase, there will be the same maximum variation in the number of ampere-turns in the two cases.

Mr. Dolivo Dobrowolski, the designer of the three-phase motor employed in the Lauffen-Frankfort transmission, was the first to draw attention to this variation in the number of ampere-turns with a rotatory magnetic field motor, and the pulsation of the field thus produced. But we venture to think that in his deductions he lays too much stress on the mere variation in the number of ampere-turns, and too little on the fact that the variation in the number of ampere-turns only imperfectly indicates the variation in the strength of the rotating field. That the one variation does not alone measure the other arises first from the induction in iron not being, as is well known, proportional to the magnetizing force; secondly, from the magnetic leakage in the motor being different when the axis of the rotating field cuts the ring between two of the coils, and when it passes through a coil conveying a current, a case which cannot, of course, be neglected when each coil occupies a considerable portion of the ring, as in an actual three-coil motor.

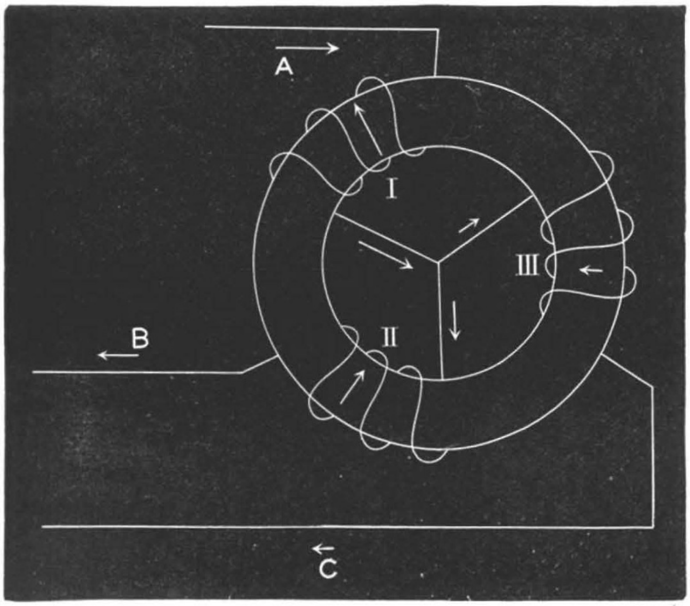


Fig. 20.—Three-phase alternate current motor (open winding); currents differing by 120° in phase, and represented in direction and magnitude by the direction and length of the arrows.

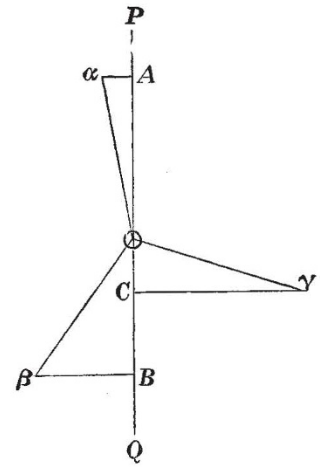


Fig. 21.

Hence we doubt whether it could be decided theoretically without experiment with which of the windings indicated in Figs. 12 or 20 the rotating magnetic field would undergo the greater variation in strength, if in both cases the windings occupied the whole of the iron ring.

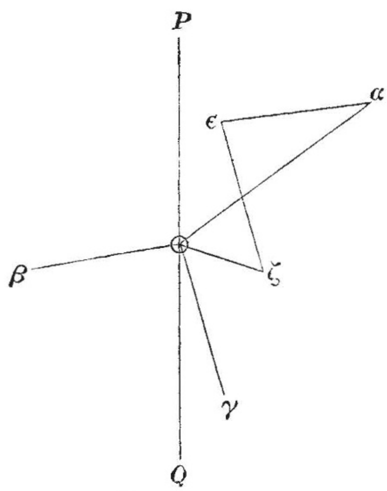


Fig. 22.

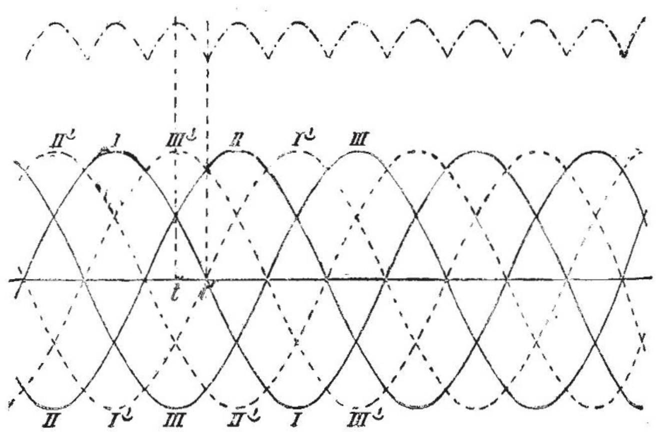


Fig. 23.—Three harmonic alternating currents of the same period and maximum altitude, but differing by 120° in phase.

Since, as we have proved, the algebraical sum of the three alternate currents in the coils I, II, III, Fig. 20, is always nought, Kirchhoff's second law suggests that these three coils, instead of being wound on the ring as indicated in Fig. 20, may be wound so as to form a closed circuit, as shown in Fig. 24. With this arrangement of coils it is easy to show that the current

$$\text{in I} = \frac{A+B}{3},$$
$$\text{,, II} = \frac{B-C}{3},$$
$$\text{,, III} = \frac{C+A}{3},$$

where A, B, and C represent simply the arithmetical values of the currents in the three main leads. And in Fig. 24 the arrows attached to the wires A, B, and C, and to the coils I, II, III, are drawn of such proportional lengths that the above connection between the currents in the three coils and the currents in the three mains is satisfied.

Next, to find the difference in phase, we draw three lines, so that their projections on POQ (Fig. 25) represent in direction and magnitude $\frac{OA+OB}{3}$, $\frac{OB-OC}{3}$, $\frac{OC+OA}{3}$, which is done by taking one-third of the diagonals of each of three parallelograms constructed respectively on Oα and Oβ *produced backwards*, on Oβ and Oγ *produced backwards*, and on Oγ and Oα *produced backwards*. In this way is obtained the three-legged figure, O1, O2, O3, with three equal sides making angles of 30° with Oα, Oβ, Oγ, respectively; then O I, O II, and O III, the projections of O1, O2, and O3 on POQ, give us the direction and magnitude of the three currents in the coils I, II, III (Fig. 24). Hence we see that the current in coil I lags 30° behind the current in A, the current in coil II 30° behind the current in B, and similarly the current in coil III 30° behind the current in C.

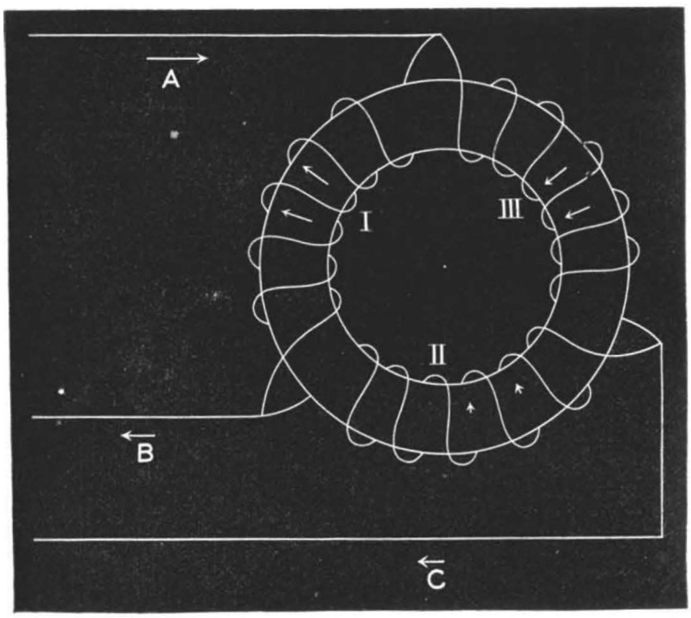


FIG. 24.—Three-phase alternate current motor (closed winding); currents differing by 120° in phase, and represented in direction and magnitude by the direction and length of the arrows.

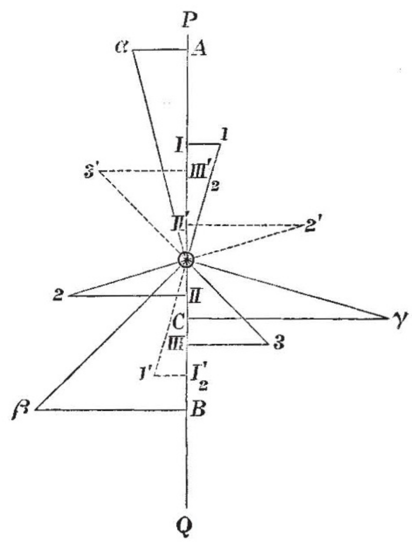


FIG. 25.—Projections of Oα, Oβ, Oγ give direction and relative magnitude of currents in the mains A, B, C of Figs. 20, 24, 27, 29, and 31, and of currents in coils I, II, III of Fig. 20. Projections of O1, O2, O3 completely represent currents in coils I, II, III of Fig. 24; and projections of O1, O2', O3 completely represent currents in coils I, II, III of Fig. 27.

Since the three coils both for the open and the closed methods of winding (Figs. 20 and 24) are connected together, and since the current in any one coil varies like the current in the preceding coil, with a lag of 120°, each value of the current may be regarded as travelling round the ring from each coil to the next. This idea has led Mr. Dobrowolski to call such a motor a rotatory current or "*drehstrom*" motor.

In joining up a three-phase *drehstrom* motor, we have to decide whether we shall adopt the arrangement shown in Fig. 20 or that illustrated in Fig. 24. The latter, or closed winding, would be employed when we desired that the maximum potential difference between the terminals of any one of the three coils should be equal to the maximum potential difference between any two of the mains; while with the open method of winding (Fig. 20) the maximum difference of potential between the terminals of any one of the three coils would be only $\frac{1}{\sqrt{3}}$, or 0·5744 times the maximum potential difference between any two of the mains. The open method has the further advantage that the middle point where the single current branches into two (Fig. 20) can be permanently connected with the earth; so that, while the maximum potential difference between each pair of mains may be, say, 20,000 volts, the potential of no point of the whole system can ever differ from that of the earth by more than 10,000 volts, a result which of course enables the insulation of separate aërial conductors to be more easily carried out.

The open method of winding has therefore been adopted for the transformers at Lauffen and at Frankfort, as well as for the motor at Frankfort; but, for the reasons which follow, the actual winding employed is more complex than that indicated in Fig. 20.

In addition to the defect possessed by the two-phase alternate current motor arising from the variation in the strength of the rotating magnetic field, there is another defect caused by the rotation of the field not proceeding at a uniform rate, so that the driving force is intermittent. Both these defects, however, can be much lessened by subdividing up the coils wound on the iron ring of the motor, a result that can be attained without increasing the number of main wires beyond three by employing the following device. Imagine one half of each of the three coils of the motor in Fig. 24 to be wound in the opposite direction; then an arrangement, symbolically indicated in Fig. 26, would be obtained, where the six halves of the former three coils, I, II, III, are now called I, I_2, II_2, II, III, and III_2, as we go round the triangle, Fig. 26. If now, without separating any of the connections, the coils I_2 and II be made to change places, as well as II_2 and III, we obtain the arrangement of winding shown on the motor in Fig. 27.

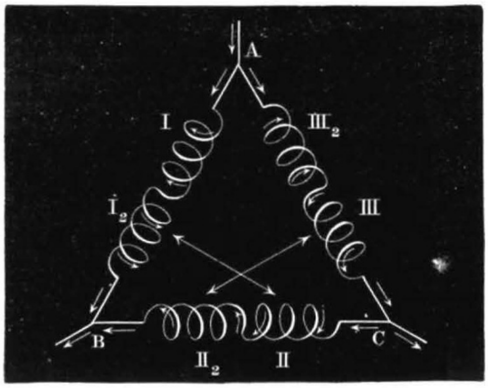


FIG. 26.—Transformation of a three-phase alternate current motor (closed winding), with currents differing by 120° in phase, into a six-phase motor, with currents differing by 60° in phase.

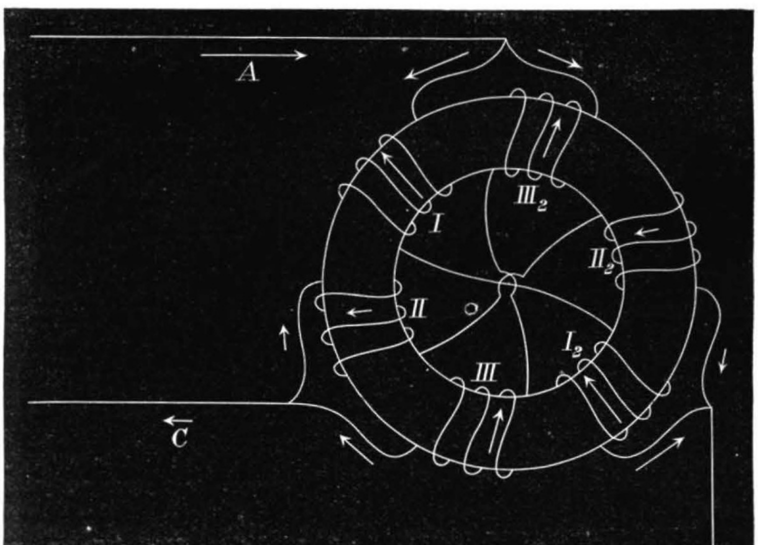


FIG. 27.—Six-phase alternate current motor (closed winding); currents differing by 60° in phase, and represented in direction and magnitude by the direction and length of the arrows.

Now it is to be observed that since the coils I and I_2 (Fig. 27) are in series, being in fact simply parts of the same coil I of Fig. 26, the current in the one must be, of course, exactly the same as the current in the other; but as one-half of the coil is wrapped one way round the iron ring, and the other half the other way, the currents, as far as sending a north pole round the ring is concerned, will have diametrically opposite effects—that is, will differ by 180° in phase. Hence, while the currents in the three coils I, II, III, in Fig. 24, differed by 120° in phase, the currents in the six coils I, II, III, I_2, II_2, III_2 (Fig. 27) will differ by 60° in phase, so that, as far as the magnetization of the iron ring is concerned, we have arrived at exactly the arrangement of currents shown in Fig. 18. There is, however, this important difference—that, whereas in Fig. 18 six main wires were required, in Fig. 27 only three are needed.

The difference in phase between the currents in the six coils (Fig. 27) and the currents in the mains can be at once obtained from Fig. 25. For it is easy to show that the current

$$\text{in } \quad \text{I} = \frac{A + B}{3},$$

$$,, \quad \text{II} = \frac{B - C}{3},$$

$$,, \quad \text{III} = \frac{C + A}{3},$$

where A, B, and C represent simply the arithmetical values of the currents in the three main leads. Arithmetically, then, for the same currents in the mains A, B, C, the currents in the three coils I, II, III of Fig. 27 are the same as the currents in the three coils I, II, III of Fig. 24. But while, as far as sending north polarity counterclockwise round the iron ring is concerned, the current in coil II of Fig. 24 was negative, that in coil II of Fig. 27 is positive. Hence, while it was the projection of O2 (Fig. 25) that gave the current in coil II of Fig. 24, it will be the projection of O2′ that will completely represent the current in coil II of Fig. 27, &c.

Hence, in Fig. 27 the current in the coil I will be O I, the projection of O1; the current in the coil II will be O II′, the projection of O2′; that in coil III will be O III, the projection of O3; that in coil I_2 will be O I_2', the projection of

OI′, &c. And the various arrows attached to the various parts of Fig. 27 are all drawn so as to represent, in direction and by their proportional lengths, the currents as determined from Fig. 25.

If, instead of starting with the closed circuit three-phase motor (Fig. 24), we deal in the same sort of way

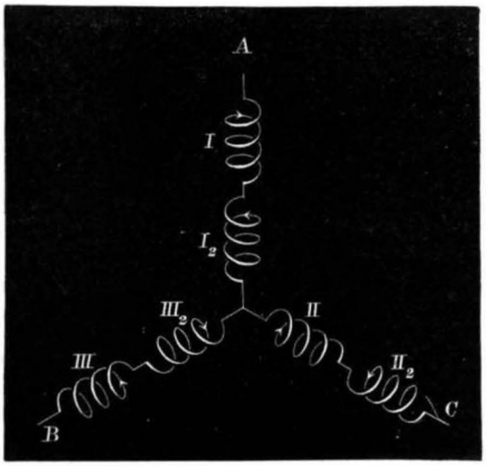


FIG. 28.—Transformation of a three-phase alternate current motor (open winding), with currents differing by 120° in phase, into a six-phase motor, with currents differing by 60° in phase.

with the open circuit three-phase motor (Fig. 20), we obtain Fig. 28, by supposing each coil to consist of two coils in series oppositely wound; and then, by interchanging the positions of the coils without breaking any of the connections, we arrive at the six-phase motor seen

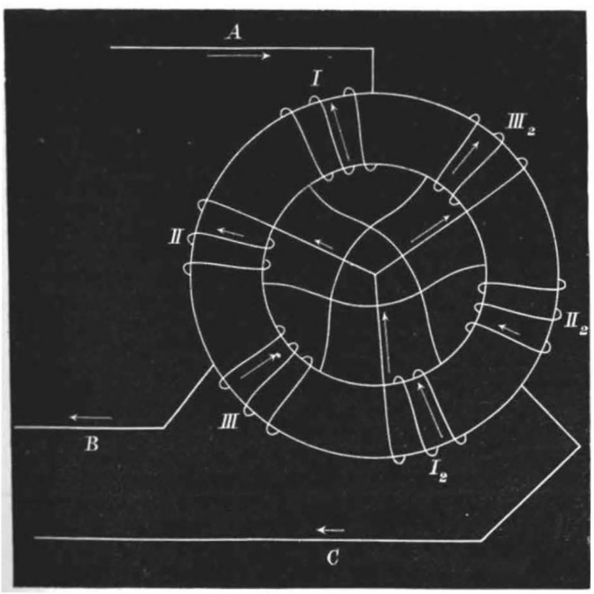


FIG. 29.—Six-phase alternate current motor (open winding); currents differing by 60° in phase, and represented in direction and magnitude by the direction and length of the arrows.

in Fig. 29, where the current in coil I is completely represented by Oa (Fig. 25), that in coil II by the projection of Oγ *produced backwards*, that in coil III by the projection of Oβ, &c.

Lastly, if we combine the closed and open methods of winding, and consider each coil as consisting of two in series but wound in opposite directions, we arrive at the symbolical Fig. 30; then, by interchanging the positions of the coils without separating any of the connections, the twelve-phase motor shown in Fig. 31 is produced,

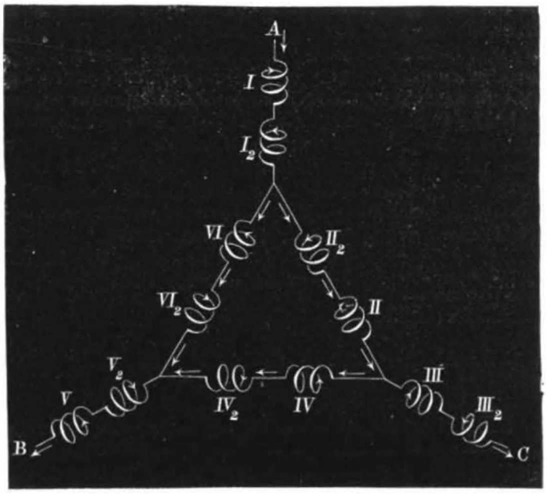


FIG. 30.—Transformation of an open wound combined with a closed wound six-phase alternate current motor into a twelve-phase motor with current differing by 30° in phase.

where the current in each coil differs from that in the preceding by 30° in phase.

In the twelve-phase motor (Fig. 31) the current in coil I is completely represented by the projection of Oa (Fig. 25), that in coil II by the projection of O3′, that in coil III by the projection of Oγ *produced backwards*, that in coil IV by the projection of O2, &c. The maximum currents then in the coils II, II_2, IV, IV_2, VI, VI_2, will

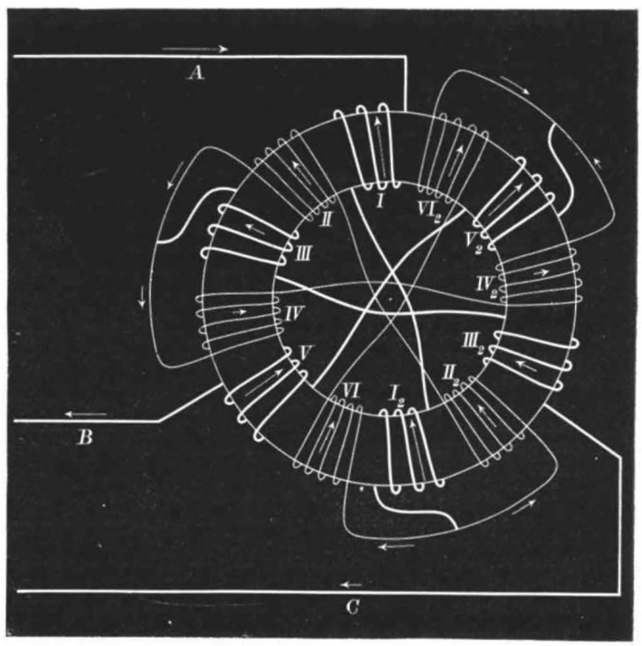


FIG. 31.—Twelve-phase alternate current motor; currents differing by 30° in phase and represented in direction and magnitude by the direction and length of the arrows.

be only $\frac{1}{\sqrt{3}}$, or 0·5744 times the maximum value of the currents in I, I_2, III, III_2, V, V_2. Hence the number of convolutions in each of the coils II, II_2, IV, IV_2, VI, VI_2 should be $\frac{2}{3}$rds of the number in each of the coils I, I_2, III, III_2, V, V_2, and the cross-section of the wire in each of the first six coils only $\frac{3}{2}$ths of that in the last six, both of which ratios are symbolically indicated in Fig. 31.

By still further following out the same general idea, an alternate current motor with twenty-four, or more, coils on it can be developed, requiring only three main wires to supply the current. And thus, thanks to the labours of Tesla, Bradley, Haselwander, Wenström, and last, but by no means least, to the striking ingenuity of Dolivo Doblowolsky, a practical alternate current motor can now be constructed, which will produce as steady a driving force as the best modern direct current motor.

W. E. A.

(*To be continued.*)

THE IMPLICATIONS OF SCIENCE.[1]

I.

WHEN I was honoured by an invitation to lecture here this evening, I felt much troubled as to the subject which I might most fitly select as my theme. During the forty years I have been a member of the Royal Institution, I have had the privilege of listening to lectures on many very different branches of science, and I know that all branches of science have few or many followers amongst the audience I am now addressing.

It has struck me, however, that for this single lecture it might be well not to confine myself to any subordinate department of scientific inquiry, but rather to invite your attention to certain questions which deeply concern them all. Thus, it has seemed to me, I might hope to interest a greater number of hearers than it would be possible for me otherwise to do.

I felt the more encouraged to take this course when I recalled to mind on how many previous occasions I had myself listened to discourses of a similar breadth of scope, given in this theatre by very distinguished men of science.

Foremost among them I may mention Prof. Huxley, who has here, as elsewhere, called attention to questions which underlie all physical science. I may also refer to that brilliant mathematician, Prof. Clifford, the sad and sudden ending of whose brief career we have good reason to deplore.

It would be easy to mention the names of other scientific celebrities who have here discoursed on matters beyond the scope of any one branch of science. These two, however, will, I think, suffice.

But before proceeding further I would feign say a few words as to the title of my lecture, so as at once to prevent any misunderstanding as to the object I have in view.

By "*the implications of science*," I mean nothing to which any section of my hearers can object, whatever their notions about "creed" or "conduct" may be. I desire carefully to eliminate all questions of either religion or morals, and I shall confine myself purely and simply to the consideration of certain propositions which appear to me to be latent within, and give force to, what we regard as well-ascertained scientific truths. They are propositions which must, I believe, be assented to by every consistent follower of science, who is convinced that science has brought to our knowledge *some* truths on which we can, with entire confidence, rely.

My appeal, then, is to the pure intellect of my hearers, and to nothing else. And indeed I desire to take this opportunity plainly to declare, before this distinguished audience, that not only here and now, but everywhere and always, I unhesitatingly affirm that no system can, or should, stand, which is unable to justify itself to reason. I possess no faculty myself, nor do I believe that any human faculty exists, superior to the intellect, or which has any claim to limit or dominate the intellect's activity. Feelings and sentiments have their undoubted charm and due place in human life, but that place is a subordinate one, and should be under the control of right reason.

But it is by no means only or mainly against those who would undervalue *reason* in the interest of *sentiment*, that I have this evening to protest. My object is to uphold what I believe to be the just claims of our rational nature against all who, from whatever side, or in the name of whatsoever authority, would impugn its sovereign claims upon our reverence, or unduly restrict the area of its sway.

As I have already intimated, I propose to fulfil this task by calling attention to some half-dozen far-reaching truths implicitly contained in scientific doctrines universally admitted, so that those doctrines cannot logically be maintained, if such implied truths are *really* and *seriously* doubted, and still less if they are *really* disbelieved and denied. These truths, then, are what I mean by "*the implications of science*." But what *is* science?

The word "science" is now very commonly taken as being synonymous with "*physical science*." There is much to be said against giving the word so narrow a meaning; nevertheless that meaning will sufficiently serve my purpose this evening. "Science," then, thus understood, is merely ordinary knowledge pursued with extreme care—most careful observation, measuring, weighing, &c.—together with most careful reasoning as to the results of observations and experiments, and also painstaking verification of any anticipations which may have been hazarded. In this way our thoughts are made to conform as accurately as may be with what we regard as the realities they represent.

The value and the progress of science are unquestioned. Many foolish discussions are carried on in the world about us; but certainly no one disputes or doubts the value of science or the fact of its progress. The value of carefully ascertained scientific truths will not at any rate be disputed in *this* theatre, which has witnessed the triumphs of the immortal Faraday, and which may justly claim to be a very temple of science. And certainly *I* have no disposition to undervalue it, who have loved it from my earliest years, and devoted such small powers as I possess to its service. I am profoundly convinced that, since I can recollect, biological science has made great progress, and I see grounds for absolute certainty now about many propositions in zoology which were doubtful or undreamed of when I was a lad.

We all, then, agree that science does advance. Nevertheless, it is obvious that such advance would be impossible if we could not, by observations, experiments, and inferences, become so certain with respect to *some* facts as to be able to make them the starting-points for fresh observations and inferences as to other facts. Thus, with respect to the world we live in, most educated men are now certain as to its daily and annual revolutions, as also that its crust is largely composed of sedimentary rocks, containing remains or indications of animals and plants more or less different from those which now live. No one can reasonably deny that we may rely with absolute confidence and entire certainty upon a variety of such assertions.

But our scientific certainties have been acquired more or less laboriously, and a questioning attitude of mind is emphatically the scientific attitude. We ought never to

[1] Friday Evening Discourse delivered at the Royal Institution by Dr. St. George Mivart, on June 5, 1891.