A Method of Predetermining the Effect of Field Distortion in Continuous Current Generators.

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In spite of the numerous Papers which have been published on the subject of armature reaction in continuous-current machines, some doubt still appears to exist among dynamo designers as to the exact nature of the effect produced on the total flux per pole by the cross-magnetising ampere-turns of the armature. That such is the case will be evident by reference to pp. 10 and 11 of Hobart's "Electric Motors" (second edition), where this subject is discussed, as also by the appearance of two recent Papers—one by E. J. Brunswick,* the other by C. F. Guilbert†—on the same subject. None of the authors referred to seem to be aware of the very exhaustive treatment of this subject in the fifth (1909) edition of Hawkins and Wallis's "The Dynamo"‡—a treatment which leaves little to be desired, whether regarded from the point of view of the strict legitimacy of the method employed, or that of the accuracy of the results obtained, and whose only disadvantage probably lies in the fact of its being somewhat too elaborate and cumbersome for ordinary use. As regards the two recent Papers referred to above, E. J. Brunswick uses the somewhat doubtful expedient of the vectorial composition of magnetomotive forces and fluxes, and C. F. Guilbert employs a very elegant graphical construction. The method which forms the subject of the present communication differs from those already described, and should be easily followed by readers interested in the problem.

As a certain amount of obscurity appears to surround this subject, it will be well to clear the ground by considering briefly the nature of the distortion brought about by the armature

* "La Lumiere Electrique," Vol. XXI., p. 355 (March 22, 1913).

† "La Lumiere Electrique, Vol. XXII., p. 69 (April 19, 1913).

‡ Vol. II., pp. 564-577.

current. If we suppose that the permeabilities of the various media composing the magnetic circuit remain unaltered, then the main field and the armature field may be simply superposed, and since by supposition the aramature field is a crossfield pure and simple, the flux per pole will remain unaltered. In any actual case, however, the permeabilities will not remain constant, and there will be greater or less local changes of permeability in the various parts of the magnetic circuit, and especially in the teeth. We may imagine the final magnetic state to be arrived at by an imaginary process consisting of the following two stages. During the first stage the armature field is superposed on the main field without change of permeability in any part of the magnetic circuit; during the second stage the corresponding local changes of permeability are allowed to take place. During the first stage, as already explained, the flux per pole remains unaltered; while during the second, the flux per pole is reduced.* It is therefore obvious that *the reduction in the flux is due entirely to changes in the permeability, and is thus only a secondary and not a primary effect of field distortion.* This result does not appear to be very clearly realised by some writers, but is given due prominence in Messrs. Hawkins and Wallis's book.

We are now in a position to consider an approximate method of calculating the additional ampere-turns which are required to counteract the effect of decreased permeability in the teeth. It is true that the permeabilities of the pole-shoe and part of the field core, as also that of the armature core below the teeth, are affected by flux distortion. The change of reluctance resulting from this is, however, so slight in comparison with that arising from the drop in the average permeability of the teeth (which under normal conditions are highly saturated) that we may neglect it.

In order to fix ideas we shall explain the method in connection with a concrete example, the results for which have been verified by actual experiment. The machine in question is a six-pole, 40 kw., 220-volt generator, one of whose magnetic

* The reason for this reduction in the total flux may not at first sight appear to be very obvious. Since the permeability is in some parts of the magnetic circuit increased, while in others it is decreased, it might perhaps be expected that the one effect counterbalances the other. Such, however, is not the case, as under the conditions prevailing in ordinary practice, the increase of permeability in the less saturated portions of the circuit is numerically less than the decrease in the more highly saturated portions.

circuits is shown in Fig. 1. The machine is provided with interpoles, and the brushes are in the neutral position, so that we have merely to deal with the cross-magnetising effect of the armature current, the direct demagnetising effect being entirely absent. We shall calculate the additional ampere-turns required to compensate for decreased permeability in the teeth when the total armature current is 141 amperes, and the E. M. F. 239

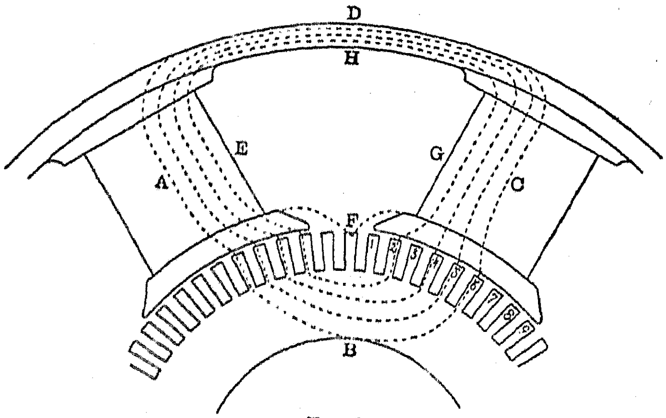

Fig. 1.

volts. By well-known methods of calculation the mean induction at the top of the teeth corresponding to this voltage was found to be 14,470. The first step in the solution of the problem consists in drawing a curve which connects the ampere-turns required for a single air-gap and tooth with the induction at the top of the tooth,* values of the induction both above and below B=14,470 being considered. The methods of calculating the ampere-turns in such a case are well known, and need not here be further referred to. The results for the machine under consideration are shown in Fig. 2. From this curve we find that in an undistorted field an induction of 14,470 at the tops of the teeth is obtained with a magnetic potential drop per single gap and tooth of about 3,260 ampere-turns.

Now when the armature is loaded with 141 amperes the field undergoes a distortion, and the value of B at the top of a tooth varies from tooth to tooth. We shall calculate the values for the various teeth approximately by assuming that the reluctances in the pole-shoe and armature core (offered to the flux

* Instead of referring everything to the induction at the top of a tooth we might equally well have referred it to that at the base of a tooth, or to the average induction in the air-gap.

due to the armature current) are negligible in comparison with those of the air-gaps and teeth.

The armature considered is provided with a simple wave

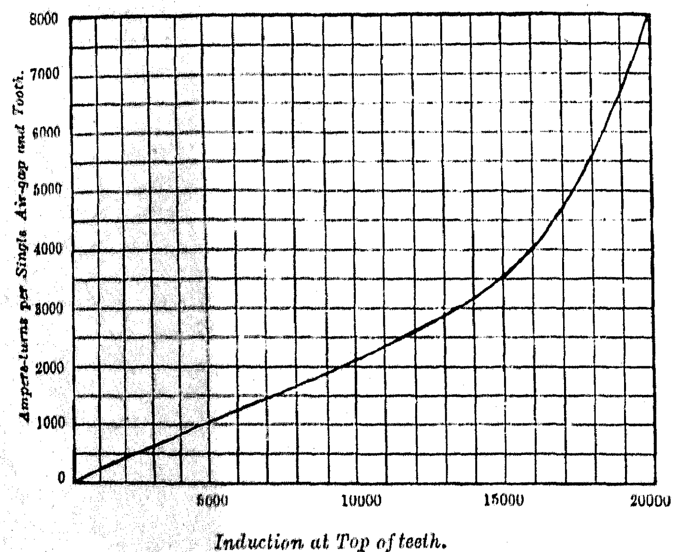

FIG. 2.

winding, so that the current in each conductor is $\frac{1}{2}\times 141=70{\cdot}5$ amperes. There are eight conductors per slot, giving $8\times 70{\cdot}5=564$ ampere-conductors per slot. As will be seen by reference to Fig. 1, there are nine teeth under cover of each pole-shoe. The ampere-turns acting on the gap and middle tooth 5 are con-contributed by the field winding alone.* Those acting on the gap and tooth 4 in the weakened region of the field are equal to the ampere-turns acting on the gap and tooth 5, *less* the ampere-conductors contained in the slot between the two teeth. Similarly, the ampere-turns acting on the gap and tooth 6 in the strengthened region of the field next to the middle tooth 5 are the ampere-turns acting on the gap and middle tooth 5, *plus* the ampere-conductors per slot. Considering the next pair of teeth, 3 and 7, symmetrically situated with regard to the middle tooth, we see that the ampere-turns are weakened and strengthened respectively, by the ampere-conductors in two slots; and so on.

Let us suppose that the field ampere-turns acting on the middle tooth and gap amount to 3,260, corresponding, as mentioned above, to the required value of B=14,470 at the tops of

* This statement is only approximately correct.

the teeth in the undistorted field. When the armature is loaded with 141 amperes the ampere-turns acting on the consecutive gaps and teeth are as follows :—

Tooth ...	1	2	3	4	5	6	7	8	9
Amp.-turns per tooth and gap	1,004	1,568	2,132	2,696	3,260	3,824	4,388	4,952	5,516

The above figures are obtained by first successively subtracting 564 (the ampere-conductors per slot) from 3,260, and then successively adding 564 to 3,260.

By referring to Fig. 2, we can read off the corresponding values of **B**, thus obtaining the following table :—

Tooth ...	1	2	3	4	5	6	7	8	9
B at top of tooth	4,850	7,520	10,170	12,700	14,470	15,650	16,560	17,270	17,900

By taking the sum of the inductions and dividing by 9 we obtain the mean value of **B** per tooth. This comes to 13,010. From this we see that field distortion reduces the mean value of the tooth top induction from 14,470 to 13,010.

Proceeding in the same way, we determine the mean values of the tooth top induction for consecutive ascending values of the field ampere-turns, thus arriving at the following results :—

Ampere-turns per pole ...	3,400	3,600	3,800	4,000
Mean induction at top of tooth	13,410	13,950	14,470	14,980

These results are plotted in Fig. 3. We see that in order to obtain a mean value of **B**=14,470, the number of ampere-turns required is 3,800. The inductions in the various teeth corresponding to this number of ampere-turns are as follows :—

Tooth ...	1	2	3	4	5	6	7	8	9
Amp.-turns per gap and tooth	1.544	2,108	2,672	3,236	3,800	4,364	4,928	5,492	6.056
Induction at top of tooth.	7,420	10,050	12,570	14,420	15.620	16,510	17,250	17,850	18,450

By making use of this table we can approximately determine the distribution of the magnetic flux. This is shown in Fig. 1, the total flux being divided into four large tubes of in-

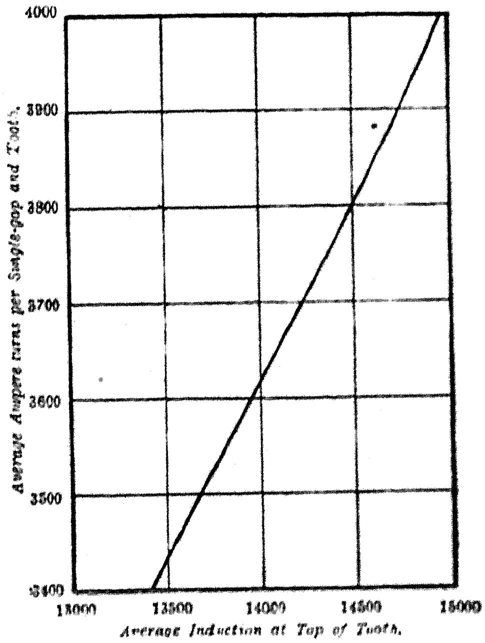

FIG. 3.

duction. It will be seen from Fig. 1 that the outermost useful line—ABCD—is linked with an effective number of armature-turns corresponding to the conductors contained in two slots, *i.e.*, with $2\times 564=1{,}128$ ampere-turns; while the innermost line—EFGH— is not linked with any armature ampere-turns at all. We shall assume the mean linkage of armature ampere-turns to be $\frac{1}{2}\times 1{,}128=564$ ampere-turns,* so that the added ampere-turns per pole will be $\frac{1}{2}\times 564=282$.

Since, therefore, the armature itself provides 282 ampere-turns per pole, and since the total ampere-turns per pole are required to be 3,800, the field coil must provide $3{,}800-282=3{,}518$ ampere-turns. But with an undistorted field a value of $B=14{,}470$ would be obtained (*see* Fig. 2) with 3,260 ampere-turns per pole. Thus the required increase in the ampere-turns per pole due to the decrease in the average permeability of the teeth (arising from field distortion) is $3{,}518-3{,}260=258$ ampere-turns. An actual test of the machine gave 212 for the additional

* This assumption is only approximately correct

ampere-turns per pole. This seems to indicate that the method outlined above is capable of giving results sufficiently correct for practical purposes.

The method was further tested in the case of a machine for which the calculated addition to the ampere-turns turned out to be negligible. In this case also the experimental result was in agreement with theory, no perceptible decrease of flux being observed when the armature was loaded.

R. P. B.—5-1914.—500.