

PREDETERMINATION OF SPARKING IN DIRECT-CURRENT MACHINES.

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Speaking generally, dynamo design did not become an art until after the old two-pole smooth-core Siemens and Edison machines came into extensive use for lighting. The original design of these machines was more or less guesswork; but after a few machines had been made to run satisfactorily the designer was able to lay out a complete line of machines, designing them partly by eye and partly by some empirical rules, which he decided on as he built successive machines. The armatures were designed more from a mechanical than from an electrical standpoint, the length being limited by the stiffness of the shaft rather than by questions of commutation. The armatures were not ventilated and the output was necessarily limited by heating. The armatures being of the smooth-core type, the self-induction of the armature coils was so small, even with the length of armatures in general use, that usually it was not necessary to consider it in connection with the sparking of the machine. It was, however, generally recognized that if the magnets were too weak the machine was likely to spark, so the length of the air-gap was usually determined by some empirical rule obtained by experiment. When slotted armatures were adopted extensively they were designed along the same lines as smooth-core armatures. These armatures were so badly ventilated that the output was limited by heating to about one half that of a modern armature; but in spite of this it was found necessary to use carbon brushes to obtain good commutation.

To economize in dies several different lengths of armatures were frequently built on the same diameter, and to economize

space the armatures were often built smaller in diameter and longer than they otherwise would be. Experience with these different forms of armature made it very evident that a long armature had a greater tendency to spark than a short one; this became especially noticeable as the ventilating of armatures was improved and the output increased, so as to take advantage of the cooler running.

Up to this time a great deal had been written on the theory of commutation in dynamos, but had been ignored by the practical designers who had more faith in experimental results. This bad behavior of long armatures as regards sparking called attention to the theoretical work, and designers began to consider whether or not the self-induction of the commutated coil did not, after all, decide the amount of current the machine would carry without sparking. In the first attempts to take into account the self-induction of the commutated coil, the self-induction of a one-turn coil was considered as being simply proportional to the length of the armature core; that is, the shape and size of the slot, the number of coils per slot, and the self-induction of the end connections—all were neglected. This gave a very simple formula for the self-induction:

$$L = ln^2.$$

Where l = length of armature

n = number of turns per coil,

And the self-induction e.m.f. of commutation (the reactance voltage as it was called) which is an estimate of the difficulty of commutating the current, was given by

$$E = l n^2 I f$$

I being the current per coil and f the frequency of commutation.

This formula gave good results when applied to machines designed along the same general lines. The allowable value of the reactance pressure could be obtained from experiment on one machine and used in the design of other machines. But, if applied to machines which were designed differently, the formula showed wide discrepancies; so it soon became recognized that the formula was at best only a rough approximation.

Early slotted machines were designed with one coil per slot; two coils per slot obviously saved insulation space and was soon tried, but it was found that generally every other bar on the commutator became badly marked.

As it was imperative to save space in car motors, three coils

per slot were adopted, and in extreme cases four, or even five coils per slot were used. It was generally found, however, that whenever more than one coil per slot was used some of the commutator-bars were marked, and that it was possible to count the number of coils per slot by the recurrence of the marking on the commutator. This marking was attributed to the inequality caused by using a small number of slots, and so the general rules were adopted—to use as many slots as possible and to make small machines with one coil per slot and large machines with two coils per slot.

It was also noticed that the dead coils necessary in certain multipolar wave-windings often caused some of the commutator-bars to be marked; this was naturally attributed to the dissymetry produced in the winding, and it became generally recognized that anything tending to produce inequality in the commutation conditions, such as few slots or many coils per slot, or dead coils, tended to make perfect commutation more difficult.

With increased competition came the necessity of cheapening the cost of building these machines; designers then returned to the construction of several coils per slot. In reducing the amount of copper on the armatures to save in the cost of material, it naturally happened that shallow slots were used. And it was found that with these wide and shallow slots it was possible to obtain good commutation with several coils per slot, under conditions where it would be quite impossible with the old deep and narrow slots. Obviously this was due to the lesser self-induction of a wide slot compared to a narrow one, and it was soon acknowledged that the shape of the slot should be considered in calculating the self-induction of the commutated coil.

When designing an armature for small self-induction it would be natural to make it large in diameter and short in length; that is, with a large pole-pitch. But in carrying this to an extreme it was found that it did not give the good results expected. It was suggested that this result was due to the fact that the self-induction of the end connections had been neglected and that in armatures with large pole-pitch and short length of core, the self-induction of the end connections was comparable with that of the conductor embedded in the slots.

In the light of these experiences it is evident that the design of a direct-current machine in regard to sparking is a compromise

between a number of conflicting conditions. It is not possible to obtain a formula which will give a strict measure of the commutating qualities of all machines; but by taking into consideration the more important conditions which effect the sparking it is possible to obtain a formula which will give fairly accurate results when applied to machines similarly designed, and which will give some idea of the sparking when applied to machines of widely different design. Such a formula, when it has been applied to a number of machines of different types, so that the allowable values for the sparking constant have been determined, can be taken as a fair working formula, and can be placed in the same category as empirical formulas for determining the regulation of alternators. Such formulas are not intended to reduce the designing of machines to mere slide-rule work, but are intended simply to give an idea as to the experimental results to be expected from individual design.

As outlined above, the most important conditions to be taken into consideration are the self-induction pressure of the commutated coil and the inequalities introduced by the conditions of commutation.

I.—SELF-INDUCTION PRESSURE.

This is given by the formula; V = self-induction of one coil times number of coils commutated in series times current in coil times frequency of commutation.

The self-induction of one coil = (self-induction of one conductor embedded in the slot + self-induction of one end connection) times (number of turns per coil)².

The self-induction of one conductor embedded in the slot = $l k$. Where l is the length of the core and k is a constant depending on the dimensions of the slot.

By determining the self-induction of a large number of slots we find that this constant k can with sufficient accuracy be taken as a function of the ratio

$$r = \frac{\text{width of slot.}}{\text{depth of slot.}}$$

A curve can be plotted connecting r and k , determined experimentally from tests on a number of armatures; such a curve is shown in Fig. 1.

Take the self-induction of the end connections = length of end connections times constant c' . And as the length of end connection is approximately proportional to the pole-pitch this can be written with sufficient accuracy = $p c$.

Hence the self-induction of one coil = $n^2 (l k + p c)$.

The number of coils commutated in series, N , is, of course, one in a parallel or lap-wound armature, and equal to the number of pairs of poles in a series or wave-wound armature.

The current per coil I in a series or wave-wound armature is equal to one half the total current in the machine, while in a parallel or lap-wound armature it equals the total current divided by the number of poles.

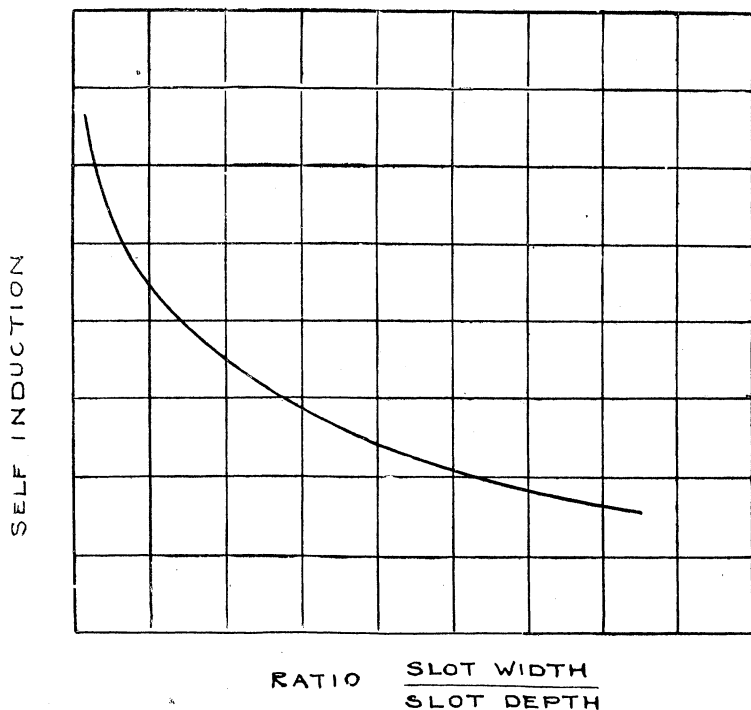


FIG. 1.

The self-induction pressure of the commutated coil is then given by

$$V = n^2 (l k + p c) N I f$$

Where f = frequency of commutation = number of commutator-bars times speed in rev. per min.

The width of the brush is neglected in calculating the frequency of commutation, since it is found by experiment that within the ordinary limits of practice the thickness of the brush has no effect on the operation of a machine, unless the current

density is excessive. The probable explanation of this is that a thicker brush gives more time for commutation to take place; but it means that more coils are commutated at the same time, thus increasing the self-induction effect. These two effects apparently counterbalance each other to a great extent.

II.—INEQUALITIES DUE TO CONDITIONS OF COMMUTATION.

These are due to the use of a few slots; more than one coil per slot; and to dead coils.

If there is only one coil per slot the use of few slots does not in itself affect commutation, unless the number of slots is extremely small; for though the slot may move through quite an appreciable arc while the coil is being commutated, the conditions are exactly the same for every coil when it is commutated. So there is no tendency to inequality in the conditions, and if the brushes can be set so that one coil can be commutated satisfactorily then commutation will be satisfactory all round the armature.

But if the number of segments is extremely small, say less than six per pole, then the coils will move in such a widely varying magnetic field, and will come so close to the strong field under the pole-tip while it is being commutated, that the local currents under the brush are liable to produce marking of the commutator-bars even if the brushes apparently do not spark. Of course this is only important in very low-pressure machines; it need not be taken into account in the sparking constant. It is sufficient to say that the number of commutator-segments in the polar-gap; that is, the arc between the two pole-shoes, must never be less than two and should generally be three or more.

With several coils per slot inequalities are introduced:

1. Due to the different self-induction of the different coils;
2. Due to commutation under different conditions.

The self-induction of all the armature coils will be the same when there are only two coils per slot, as it is obvious that the configuration of the conductors and neighboring iron is the same for both coils. But when there are three or more coils per slot the self-induction of the various coils will vary, as they occupy different relative positions in regard to the iron; the self-induction of the center coil will be less than the self-induction of the outer coil. Investigating conditions at the point of commutation in a modern generator by means of a pilot-brush, it is found that in practically all cases commutation goes on at a point where there

is no resultant magnetic field; that is, at a point where the armature field just counterbalances the field due to the magnets. In other words, there is resistance commutation; the armature current is commutated by the varying resistance of the brush, rather than by a reversing e.m.f. due to passing through a magnetic field. This being the case there is need to consider

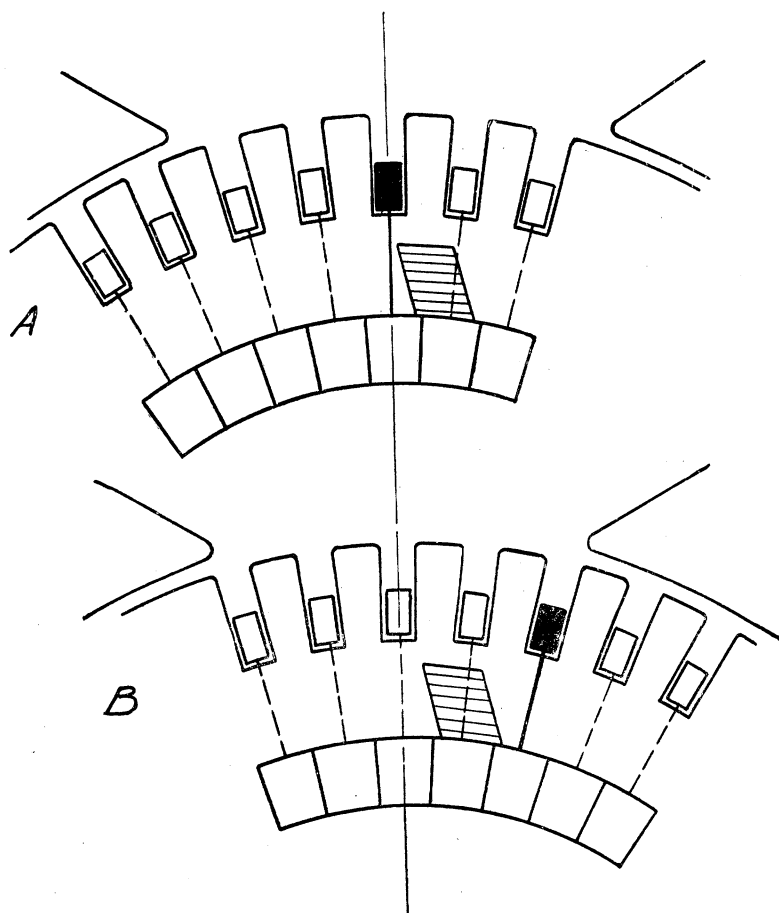


FIG. 2.—Showing position of armature at beginning and end of commutation period.

only the self-induction of those coils which have the greatest self-induction. If these are commutated satisfactorily by means of the varying resistance of the brushes, then those coils which have a smaller self-induction will also be commutated satisfactorily. Hence the variation in the self-induction of the coils

need not be considered and in the formula all that needs to be considered is the self-induction of those coils which have the greatest self-induction.

The chief inequality introduced into the commutation by having more than one coil per slot is due to the various coils in the slot commutating when they are in different magnetic fields. This is evident from Fig. 3, which shows the position of the armature when the first and the last coil in the slot are commutating.

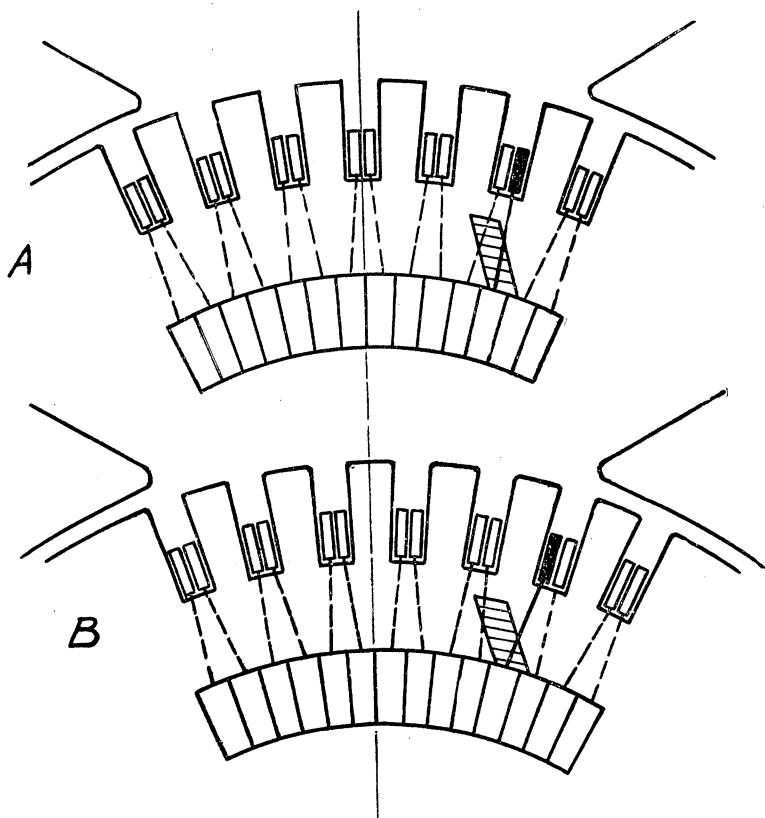


FIG 3.--Armature with two coils per slot showing positions of armature when the two coils are being commutated.

If the brushes are set so that the magnetic field is right for the first coil it will be wrong for the last one, and vice versa. So whenever the machine is loaded to its limit the commutating conditions will be so bad for some of the coils that in time some of the commutator-bars will become pitted and there will be that well-known regularly recurring marking of the commutator-bars.

The question now is how to take this inequality into account in the sparking formula. To do this, make the assumptions that the magnetic field varies uniformly from the neutral point to the pole-tip, and that in order to obtain perfect commutation

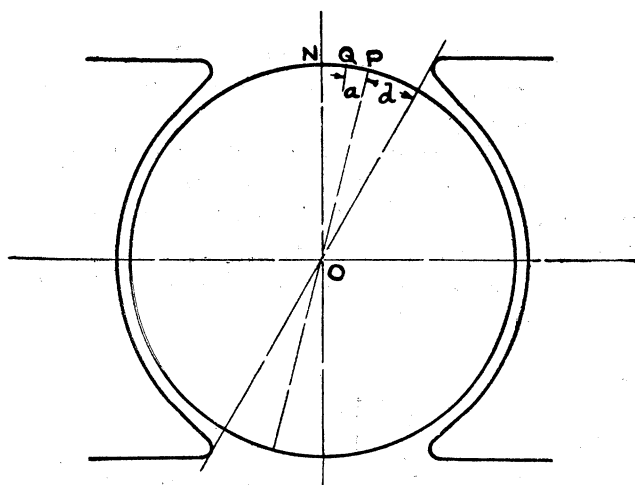


FIG. 4.

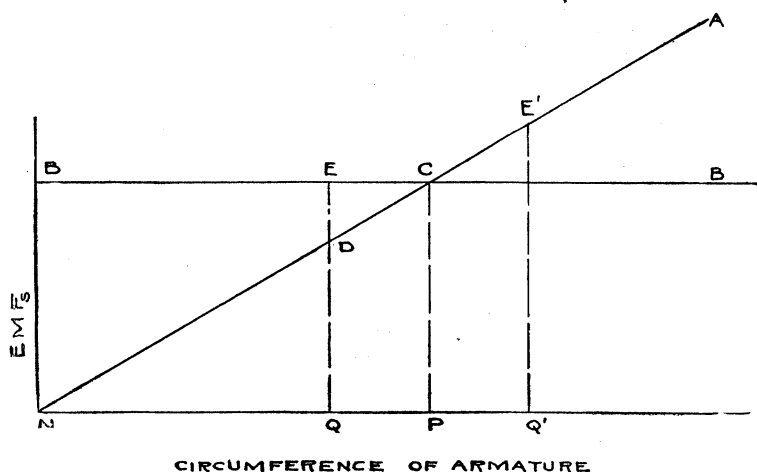


FIG. 5.

it is necessary to move the brushes from a position at the neutral point at no load to a position half-way between the neutral point and the pole-tip at full load. Calling the distance between the neutral point and the pole-tip $2d$, and assuming

the brushes fixed on the line OP half-way between the pole-tip and the neutral point, then if any coil is commutated when it is at Q distant " a " from P , then it will only commutate perfectly a load $l - \frac{a}{d}$.

Just what this assumption means can be seen from Fig. 5.

Abscissa represent positions along the polar-gap corresponding to Fig. 4, and ordinates e.m.fs.

The line NA gives the e.m.f. induced at various points by the conductor moving in the field due to the magnets.

CP , the ordinate of the line BB , gives the e.m.f. necessary to reverse the full-load current I in the coil.

If the coil is commutated at the position Q instead of at P

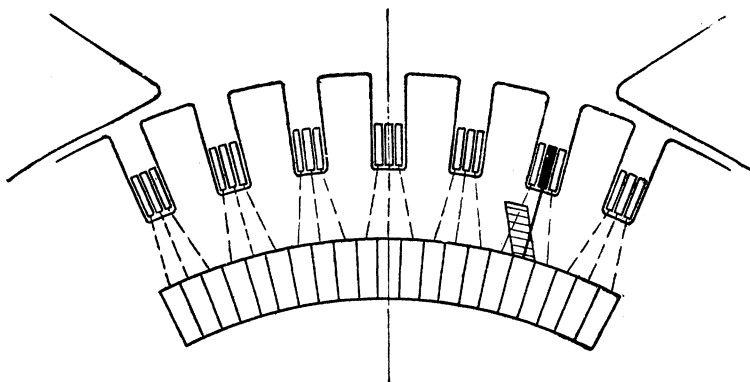


FIG. 6.—Armature with 20 slots per pole and three coils per slot.

then the commutation conditions will be perfect only for a current $\frac{DQ}{CP} \cdot I$. Hence we assume that if we have several coils per slot, and that in consequence of this we have to commutate some of our coils in a position EQ and $E'Q'$, then the current which the machine will carry without sparking is reduced in the ratio $\frac{DQ}{CP}$ that is $\frac{NQ}{NP}$.

It is very easy to figure out just what this inequality amounts to in any particular case. Take 20 slots per pole, 3 coils per slot, pole-face = 75% of pole-pitch.

There are 2.5 slots between the neutral point and the pole-tip. Assuming that the conditions are perfect for the center coil, the outer coils are 0.333-slot pitch out of this most favorable position.

And 1.25 slots corresponding to variation from no load to full load, hence an equality of 0.333-slot pitch gives an inequality factor $\frac{0.333}{1.25} = 0.26$. Hence the sparking constant should be multiplied by the inequality factor 1.26.

Curves can very easily be plotted for different numbers of slots per pole, and coils per slot, in order to facilitate the calculation of this inequality factor.

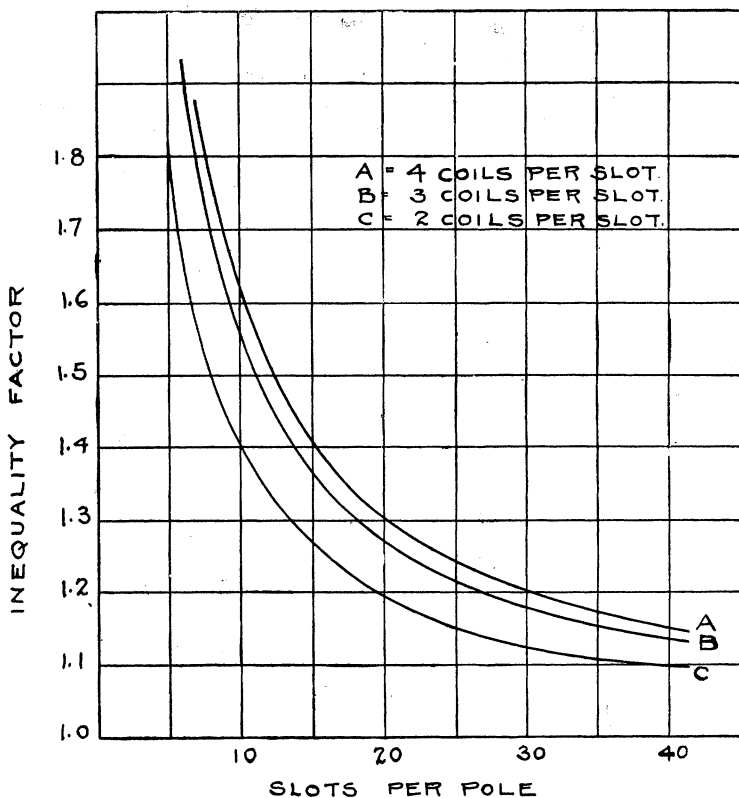


FIG. 7.

The assumptions on which this calculation is based are to a great extent rational, and though we cannot pretend that the calculation has a rigid basis, yet it is probably as correct as the other sparking calculations, and used with discretion it gives fairly reliable results.

The inequality introduced by using a dead coil on the armature is similar to that due to several coils per slot. The dead

coil produces a break in the uniformity of the winding; and if the position of the brush is correct for commutation of the coil immediately on one side of the dead coil then it will be just one segment out of the correct position for the coil immediately on the other side of the dead coil. The inequality introduced can be calculated, and allowed for in the sparking constant exactly in the same way as we allow for the inequality due to

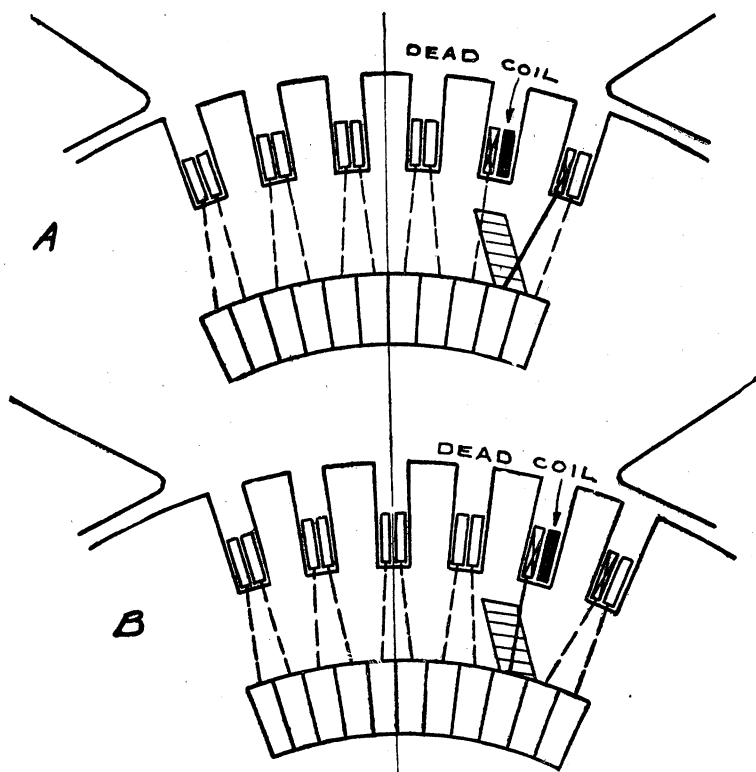


FIG. 8.—Armature with dead coil showing positions of armature when the two coils next to dead coil are being commutated.

several coils per slot. Assuming that the brush is in a mean position then it will be just half a segment out of position for the two coils which are next in position to the commutated coil.

Making the same assumptions as before; if there are n commutator-segments per pole, and if the pole face = 75% of pole-pitch then the inequality is equivalent to $\frac{8}{n}$. Thus if there are 20 segments per pole a dead coil produces an inequality equal

to 40% of the load, and the inequality should be introduced into the sparking constant by the factor 1.4. A curve can readily be plotted between the inequality factor and the number of coils per pole. Such a curve is shown in Fig. 9.

Combining all the different factors which affect sparking we get our complete formula for a sparking constant.

$$C = n^2 (l k + p c) N I f P Q.$$

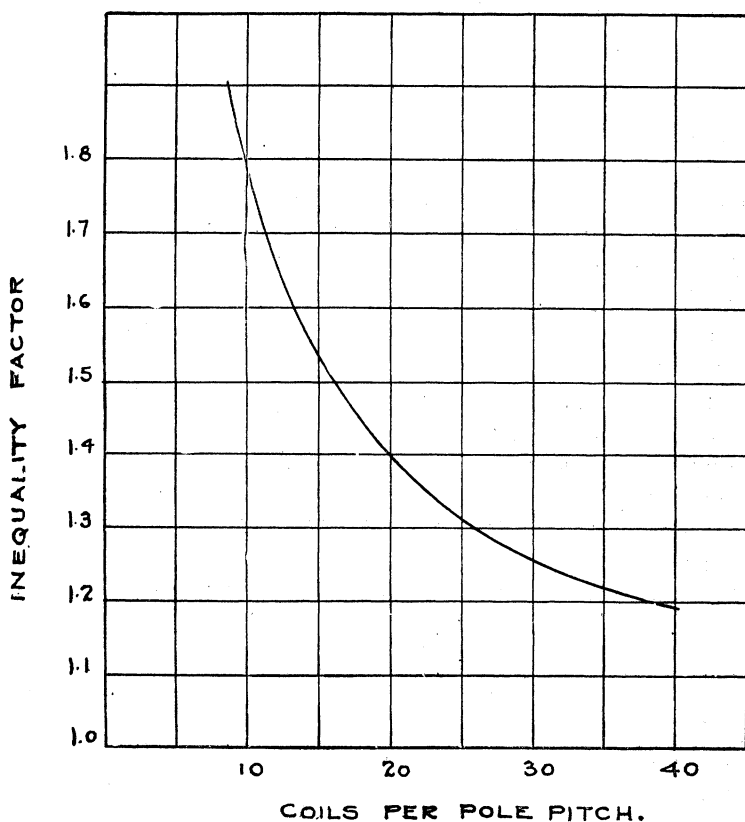


FIG. 9.

P being the inequality factor resulting from a number of coils per slot.

Q being the inequality factor resulting from a dead coil.

This formula is not put forward as being scientifically exact, but as an empirical formula which has gradually been built up as the result of experience, different terms having been added to the formula from time to time as it was found necessary to take different conditions into account. As the formula stands

it gives excellent results. When we know the value of C we can allow for the particular design of machine we are dealing with.

The relative values of C that have been found allowable in different cases are somewhat as follows:

2-pole	20
4-pole, series wound	35
6-pole, " "	50
4-pole, multiple wound	30
6-pole, " "	35
gradually increasing to	
24-pole, multiple wound	50

Of course, all the machines in each class are designed alike; that is, they have approximately the same densities in the teeth, and have the ratio of ampere-turns per pole on the armature (armature reaction) to the ampere-turns required for the teeth and air-gap approximately constant. If these vary much it is impossible to get consistent results.

The brush-gear and the current density in the brushes also play an important part in the sparking. If the brush-gear is weak mechanically, or if the commutator is in bad condition, the machine is sure to spark. And with ordinary-grade carbons the brushes will usually glow when the current density reaches 50 amperes per sq. in.

The shape of the pole-tips has some effect on the operation of the machine. But so long as they do not come too close together and so long as they are shaped so that there is a commutation field which varies gradually, the exact shape need give us no concern.

The density in the armature core (behind the teeth) has also a considerable effect on the allowable sparking constant. If the core is highly saturated it can be run with a constant considerably higher than if it is unsaturated.

Assuming that all these conditions are uniform and satisfactory, the variation in the allowable value of C shows that the formula does not take into account all the conditions that affect the sparking, so the formula must be used with considerable discretion. It cannot be claimed that the formula is in any way accurate, but it certainly is an empirical working formula, capable of giving very good results when carefully used, and as such it is put forward.

[For discussion on this paper, see page 443.]