PRELIMINARY AND FINAL DESIGN OF A DIRECT-CURRENT MAGNETIZING COIL

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A direct-current magnetizing coil is a substantial part or element of most electrical machines and apparatus. It is exemplified as mounted on an electromagnet in Figs. 1 to 4 showing openings of rectangular, circular, and other forms. Usually the conditions or requirements which should be complied with or fulfilled by a designer are as follows.

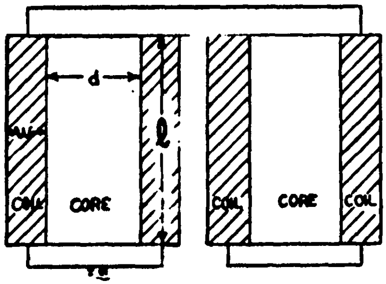

FIG. 1

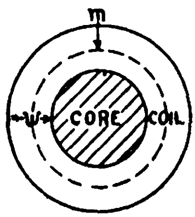

FIG. 2

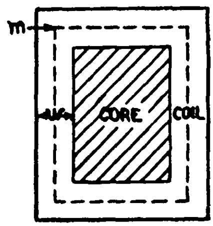

FIG. 3

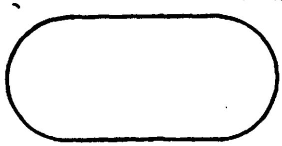

FIG. 4

1. A terminal voltage V; it may be determined by line voltage or otherwise.

2. A fixed number of ampere-turns (ni) where n is the number of winding turns and i the current in the winding.

3. A surface temperature rise T_r; in other words, an outside rise—a difference between the surface temperature of the coil and the ambient temperature.

4. Also, very often, a specific size and shape of coil opening.

5. Sometimes special requirements as to length and/or width of the winding space; we call them simply the length and width, or thickness, of the coil.

6. V is given as prescribed by the current source; (ni) and also the size and shape of the coil opening are usually predetermined on the basis of the magnetic-circuit specification and performance of the electrical machine or apparatus; the temperature rise T_r is mostly chosen within limits depending on the ambient temperature and *restrictions imposed by insulating materials at the hottest spot inside the coil*, or, in other words, an appropriate temperature T_h there is assumed.

There are given: number of ampere-turns (ni); outside temperature rise T_r; terminal voltage V; size and form of coil opening, p being the length of its perimeter.

There are sought: size of conductor, i. e., its cross-section area q; area of winding space indicated by l and w, its length and width respectively, which are at the same time the length and thickness of the coil; number of ampere-turns n.

The derivations are brought about by using auxiliary formulas, as follows.

The electrical losses or generated heat in watts:

$$W = i^2R = V^2/R \qquad (1)$$

The length of the mean turn:

$$m = p+kw \qquad (2)$$

where the value of k depends upon the form of the opening. For openings of circular form (Fig. 2), of rectangular shape with perfectly rounded corners, and of the type represented in Fig. 4, $k = \pi$; for the rectangular opening with square corners (Fig. 3) $k = 4$; for the rectangular opening having corners not perfectly rounded $\pi < k < 4$—the first plausible assumption in this case would be averagely to make $k = 3.57$.

The cooling surface:

$$A = 2mw+pl+ (p+2kw)l = 2(w+l)\ (p+kw) = 2m(w+l) \qquad (3)$$

The outside temperature rise:

$$T_r = W/cA \qquad (4)$$

where c is the cooling coefficient, A the area of the cooling surface, and W given by (1).

The total winding resistance:

$$R = \rho n(p+kw)/q \qquad (5)$$

where ρ designates resistivity at the *average* temperature of the coil wire.

The number of winding turns:

$$n = slw/q \qquad (6)$$

where s is the space factor which is computable or available from graphs if q and the mode of insulation of the conductors are known or determinable.

The current in the coil winding:

$$i = Vq/\rho n(p+kw) \qquad (7)$$

Further derivations are as follows.[1]

Because of (7)

$$(ni) = Vq/\rho(p+kw) \qquad \text{I.}$$

Referring to (4)

$W = cT_rA$ .... (8).

Again, because of (1),

$i^2R = cT_rA$ .... (9).

Referring to (2) and (5)

$R = \rho nm/q$ .... (10).

Then from (9) and (10)

$i^2R = i^2n\rho m/q = i(ni)\rho m/q = cT_rA$ .... (11).

Again, denoting current density by Δ, it obtains that

$i = q\Delta$, $\Delta = (ni)/swl$, and $i = q(ni)/swl$ .... (12).

Substituting (12) for i and (3) for A we derive from (11) the fundamental equation:

$\rho(ni)^2/swl = 2cT_r(w+l)$ .... II.

Then

$\rho(ni)^2/2wscT_r = lw+l^2$ .... (13).

Let

$Q_w = \rho(ni)^2/2wscT_r$ .... III.

Now (13) transforms to the quadratic equation:

$l^2 + wl - Q_w = 0$ .... IV.

From this it follows that

$l = -w/2+\sqrt{w^2/4+Q_w}$ .... V.

Equation V gives l in terms of the assigned or known data, w being among them.

Likewise from equation II we get finally (if l is known or assigned):

$w = -l/2+\sqrt{l^2/4+Q_l}$ VI

where

$Q_l = \rho\ (ni)^2/2lscT_r$ .... VII.

Both equations III and VII are practically important although only auxiliary.

Expressions for Q_w and Q_l can be given other forms. Let us substitute for (ni) its value in equation I, then finally

$Q_w = qV^2/2wsR_m(p+kw)cT_r$ .... III_a

$Q_l = qV^2/2lsR_m(p+kw)cT_r$ .... VII_a

where R_m stands for resistance of a mean turn at average temperature of the coil.

Likewise substituting from (4), it obtains that

$cT_r = 1/A_1$ and $A_1 = 1/cT_r$ .... (14)

where A_1 stands for A/W and denotes area of the cooling surface per 1 watt dissipated; formulas III and VII, also III_a and VII_a, transform to

$Q_w = \rho A_1(ni)^2/2ws = qA_1V^2/wsR_m(p+kw)$ .... III_b

$Q_1 = A_1(ni)^2/2ls = qA_1V^2/2lsR_m(p+kw)$ .... VII_b.

[1] Roman numerals are used to indicate practically important formulas or fundamental equations.

Raising equation (6) to the rank of practical importance we write:

$$n = swl/q \quad \text{VIII.}$$

There are now three fundamental equations, namely, I, V (or VI), and VIII to determine four basic magnitudes pertaining to the coil, i. e., q, w, l, and n. This is practically advantageous because it permits a design to be adapted to other requirements arising from structural and economical considerations.

Suggestions and remarks. There are cases in which w must or can be estimated on the basis of some conditions or considerations; for example, the field coils of a machine may call for this estimation. With the shape and size of the opening known or assigned and the average temperature T_a of the winding reasonably assumed or estimated, equation I makes it possible to compute q for an assigned number of ampere-turns; then if necessary it is rounded to a wire-table figure. A more accurate value for w should then be computed from equation I substituting there the above table value. Now by using equations III (or III_b) and V, l becomes computable.

Denoting ambient temperature by T, outside and inside temperature rises by T_r and T_i respectively, and hottest spot and average temperature by T_h and T_a respectively, it obtains that

$$T_h = T+T_r+T_i \quad (15)$$

and also with sufficient accuracy that

$$T_a = T+T_r+T_i/2 \quad (16).$$

T_i usually varies from 5° to 30° C as ampere-turns change within the range 500 to 18,000. For a continual load in the absence of exceptional conditions it is suggested that $95° \text{ C} \leqq T_h < 100° \text{ C}$. It is understood that if a load is intermittent or space limitations are stringent higher values of T_h are allowable, but in the latter case this would of necessity shorten the life of the coil. The cooling coefficient c usually varies from 0.005 to 0.010 depending on the nature of the ambient medium, conditions of ventilation, etc. Substituting values for T, T_h, and T_i in equations (15) and (16) one finds T_r and T_a which in combination with chosen c and w will set the system of fundamental equations and their auxiliaries to work. T_a can usually be chosen beforehand within the range 85° to 95° C if there are *no* exceptional conditions such, for instance, as drastic limitations of winding space.

Another approach to the development of a design is to begin with a reasonable assumption of A_1 instead of the temperature and cooling coefficient; then equations III_b and VII_b should be used. Usually A_1 varies within the range 2 to 3.3, being about 2.65 for average cases. Also there are situations which require that l should be estimated first and then w determined from equations VI and VII. Since q is not yet known in this case, the space factor s should be estimated and checked afterwards.

The half-empirical formula

$$T_i = 5\sqrt{(ni)/500} \quad (17)$$

for an estimation of T_i in degrees C at the beginning of work on a design is offered as helpful and adequately accurate.