Chapter.5 Design of field windings

The poles are wound with preformed copper, which is typically of rectangular shape, although round shaped coils are also used. In both cases, varnishing is the most common insulation method. First, a layer of insulation is assembled on the pole and then the winding is wound on it. The cross section of the field winding conductor may be round or rectangular.

Field coils placed on the poles are connected generally in series and designed for 80 to 85 % of excitation voltage. The rest 15 to 20% is reserved across the field rheostat or regulator to vary the excitation current and hence the emf induced or terminal voltage.

Voltage across each field coil $V_f = (0.8 \; to \; 0.85)\,\frac{V}{P}$

where V is the applied voltage in case of motors and terminal voltage in case of generators.

$$Since\ V_f = I_f R_f = I_f \frac{\rho L_{mt}}{a_f} T_f, cross\ sectional\ area\ of\ the\ field\ winding\ conductor$$

$$a_f = \frac{\rho L_{mt} I_f T_f}{V_f}$$

Field or excitation current $I_f = a_f \delta_f$

where the current density δ_f lies between 1.5 and 2.0 A/mm^2

$$Number\ of\ \frac{turns}{pole} T_f = \frac{I_f T_f}{I_f}$$

The number of turns can also be calculated by loss or temperature rise consideration.

$$Loss = V_f I_f = \frac{V_f I_f T_f}{T_f} = \frac{\text{loss}}{\text{m}^2} \times \text{dissipating area in m}^2$$

If all the surfaces i.e. inner, outer, top and bottom are considered to be equally effective in dissipating heat, then the total dissipating area $= 2L_{mt}(h_f + d_f)$.

If only the inner and outer surfaces are considered then the dissipating area $\approx 2L_{mt}h_f$

If only the outer surface is considered then the outer dissipating area,

$$= External\ perimeter\ or\ periphery \times h_f$$

$= \left[2\left(L_P + b_p + 4t_i\right) + 2\pi d_f\right]h_f$ in case of rectangular or square poles

$= \left[\pi\left(d_i + 2t_i + 2d_f\right)\right]\mathrm{h_f}$ in case of round poles

The temperature rise can be calculated from the folowing expression.

$$\text{Temperature rise } \theta = \frac{(0.14\ to\ 0.16) \times \text{field copper loss i.e} I_f^2 R_f}{\text{Total coil dissipating surface}}$$

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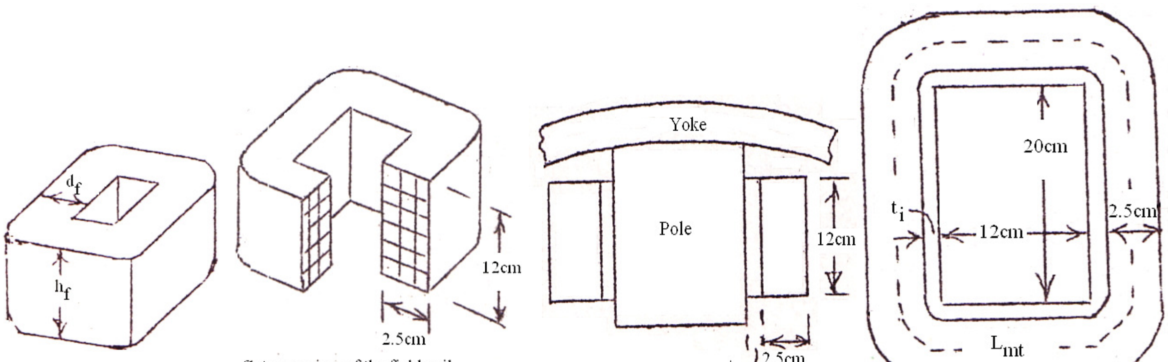
Solved Problems on Field windings

a)**Shunt field windings**

Example .1

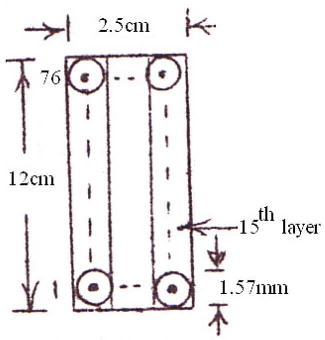
An 8 pole, 500V, dc shunt generator with all the field coils in series requires 5000ATs per pole. The poles are of rectangular dimension 12cm x 20cm and the winding cross-section is 12cm x 2.5cm. Determine the cross-section area of the wire, number of turns and dissipation in watts/cm^2 based on the outside and the end surfaces of the coil.

A conductor of circular cross-section is to be used. The resistivity is 0.021Ω/m/mm^{2}and the insulation increases the diameter by 0.02cm. Allow a voltage drop in the field regulator of 50V.



field coil

Cutaway view of the field coil



Details of field coil showing layers and turns /layer

Cross sectional area of the wire$a_f = \dfrac{\rho L_{mt}(I_f T_f)}{V_f}$

Mean length of the turn $L_{mt} = 2(L_P + b_P + 4t_i) + \pi d_f$

If the thickness of insulation t_i *is assumed as* $1.0cm$ *then*,

$L_{mt} = 2(20 + 12 + 4 \times 1_i) + \pi \times 2.5 = 79.85cm$

$$Voltage\ across\ each\ coil\ V_f = \frac{500 - 50}{8} = 56.25V$$

$$a_f = \frac{0.021 \times 0.7985 \times 5000)}{56.25} = 1.49cm^2$$

$$Bare\ diameter\ of\ the\ conductor = \sqrt{\frac{4a_f}{\pi}} = \sqrt{\frac{4 \times 1.49}{\pi}} = 1.37mm$$

$$Diameter\ of\ the\ conductor\ with\ insulation = 1.37 + 0.2 = 1.57mm.$$

Number of turns/layer in a winding height of 12cm $= \frac{120}{1.57} = 76.4$ and is not possible. Let it be 76.

Number of layers in a winding depth of $2.5cm = \frac{25}{1.57} \approx 15$.

Therefore, number of turns/pole $T_f = 76 \times 15 = 1140$.

$$Dissipation\ in\ watts/cm^2 = \frac{Copper\ loss\ in\ the\ field\ coil}{dissipatng\ surface}$$

Copper loss in the field coil $= V_f I_f$

Field current $I_f = \frac{I_f T_f}{T_f} = \frac{5000}{1140} = 4.38A$

Therefore, $V_f I_f = 56.25 \times 4.38 = 246.7W$

Dissipating area of the outside and two end surfaces of the coil $= L_{mt} h_f + 2L_{mt} d_f$

$= 79.85(12 + 2 \times 2.5) = 1357.5cm^2$

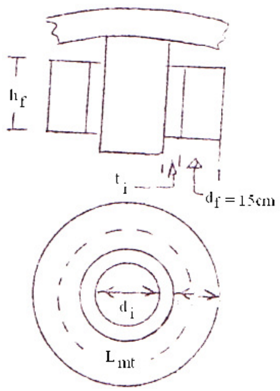
Dissipation in watts/cm$^2 = \frac{246.7}{1357.5} \approx 0.18$.

Example .2

Each pole of a dc generator is required to produce 19000 ampere turns. The gap flux/pole is 0.2Wb. The leakage coefficient for the pole = 1.2 and the flux density in the pole core of circular cross section is 1.5T. The field coil has a radial depth of 15cm and can dissipate 0.05W/cm^2 of the outside cylindrical surface without overheating. Determine the diameter of the wire, number of turns and height of the coil. Voltage across the coil may be taken as 60V and space factor 0.7.

Diamter of the bare wire$d_w = \sqrt{\frac{4a_f}{\pi}}$

$$a_f = \frac{\rho L_{mt}(I_f T_f)}{V_f}$$



Let the resistivity of copper $\rho = 0.021\Omega/m/mm^2$

$$L_{mt} = \pi(d_i + 2t_i + d_f)$$

Cross sectional area of the pole$A_P = \frac{\phi \times LC}{B_P} = \frac{0.2 \times 1.2}{1.5} = 0.16m^2$

Diameter of the pole body$A_P = \sqrt{\frac{4A_P}{\pi}} = \sqrt{\frac{4 \times 0.16}{\pi}} = 0.45m$

$L_{mt} = \pi(45 + 2 \times 1 + 15) = 194.7\text{cm}$ with the assumption that $t_i = 1.0\text{cm}$

$$a_f = \frac{0.021 \times 1.947 \times 19000}{60} = 12.94mm^2$$

$$d_w = \sqrt{\frac{4 \times 12.94}{\pi}} \approx 4mm$$

$$\text{Loss} = V_f I_f = \frac{V_f(I_f T_f)}{T_f}$$

$$= Loss/cm^2 \times \text{outside cylindrical surface } \pi(d_i + 2t_i + 2d_f)h_f \text{in cm}^2$$

$$= \frac{60 \times 19000}{T_f} = \pi(45 + 2 \times 1 + 2 \times 15)h_f$$

$$h_f T_f = 94252.8 \quad \ldots\ldots\ldots\ldots\ldots (1)$$

$$\text{Since space factor} S_f = \frac{a_f T_f}{h_f d_f}, \quad 0.7 = \frac{12.94 \times 10^{-2} T_f}{h_f \times 15}$$

$$or\ h_f = 0.0123 T_f \quad \ldots\ldots\ldots\ldots..(2)$$

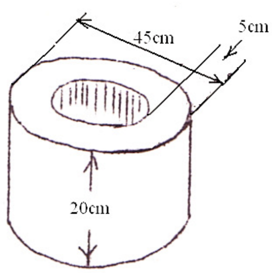
From equations 1 and 2, $0.0123T_f^2 = 94252.8$

$$\text{Therefore, number of } turns/pole\ T_f = \sqrt{\frac{94252.8}{0.0123}} \approx 2765$$

Height of the field coil $h_f = 0.0123 \times 2765 \approx 34cm.$

Example .3

The outside cylindrical surface of a field coil can dissipate 0.1W/cm^2, its area is limited to an axial height of 20cm and an outside diameter of 45cm. If the radial thickness of the coil is 5cm, how many ampere-turns can be accommodated with a terminal voltage of 50 V. Specific resistance at working temperature is 2μΩ/cm^3,,space factor = 0.6.



Field coil

$$Number\ of\ turns\ that\ can\ be\ accommodated = I_f T_f$$

Loss $= V_f I_f = Loss/cm^2 \times$ outsidecylindrical surface $\pi(d_i + 2t_i + 2d_f)h_f$in cm^2

$50I_f = 01 \times \pi \times 45 \times 20$

$I_f = 5.65A$

Since $S_f = \frac{a_f T_f}{h_f d_f}$, $\quad 0.6 = \frac{a_f T_f}{20 \times 5}$ $\; or \; a_f T_f = \; 60 \ldots\ldots(1)$

$a_f = \frac{\rho L_{mt} I_f T_f}{V_f} = \frac{2 \times 10^{-6} \times \pi \times 40 \times 5.67 T_f}{50}$ as$L_{mt} = \pi \times$ mean diameter of the coil

$$a_f = 2.84 \times 10^{-5} T_f \quad \ldots\ldots\ldots\ldots(2)$$

From equations 1 and 2, $2.84 \times 10^{-5} T_f^2 = 60 \quad or \quad T_f \approx 1454$

Therefore$I_f T_f = 5.64 \times \; 1454 = 8212.3$

Example .4

A 440V, dc shunt generator develops 7200 ampere-turns/pole in the field winding and has 6 poles. Depth of the field coil 3.5 cm, mean length of the turn 120cm, field coil height 18cm, the resistivity is 2.1x$10^{-6}\Omega$ cm. If the cooling surface required is $15cm^2/watt$ and 15% of the voltage is absorbed in the field rheostat, find the number of turns and cross-sectional area of the field winding conductor. Consider heat dissipation only from the inside and outside cylindrical surfaces of the coil.

Number of turns$T_f = \frac{\text{ampere turns} I_f T_f}{\text{field current} I_f}$

field current $I_f = \frac{field\ copper\ loss\ V_f I_f}{voltage\ across\ each\ coil\ V_f}$

$Inside\ and\ outside\ cylindrical\ surface\ \approx 2L_{mt}h_f = 2 \times \; 120 \; \times 18 = 4320cm^2$

Since 15 cm^2 is dissipating 1.0 W, 4320cm^{2}dissipates $\frac{4320}{15}$=288W

Voltage across each coil$V_f = \frac{0.85V}{P} = \frac{0.85 \times 440}{6} = 62.33$V

Therefore$I_f = \frac{288}{62.33} = 4.62A \quad and \;\; T_f = \frac{7200}{4.62} \approx 1558$

$$a_f = \frac{\rho L_{mt} I_f T_f}{V_f} = \frac{2.1 \times 10^{-6} \times 120 \times 7200}{62.33} = 0.028\text{cm}^2$$

Example .5

The field coil of a 6 pole, 440V, DC shunt generator is to supply 4000 ampere turns. The length of inside turn is 74cm. The length available for the winding is 13cm. The space factor of the winding is 0.52, permissible dissipation of external surface excluding the ends is 0.12W/cm^2. Calculate the size of the conductor and number of turns of the coil. Solution should not be attempted by assuming a value for the depth of the winding.

Note: Since the type of the pole, rectangular or round,has not been specified, the problem can be solved by assuming either a round or rectangular pole.

$$a_f = \frac{\rho L_{mt}(I_f T_f)}{V_f}$$

Let $\rho = 2.1 \times 10^{-6} \Omega$ cm

Mean length of the turn $\text{L}_{\text{mt}} = 2(L_P + b_P + 4t_i) + \pi d_f$ in case of rectagular pole

$$= \text{Length of inside turn} + \pi d_f$$

$$= \pi(d_i + 2t_i + d_f) \text{ in case of round poles}$$

$$= \pi(d_i + 2t_i) + \pi d_f$$

$$= \text{Length of inside turn} + \pi d_f$$

$$= (74 + \pi d_f)cm$$

$V_f = (0.8 \; to \; 0.85)\frac{V}{P} = \frac{0.8 \times 400}{6} = 58.7V$ with the assumption that the drop across the regulator is 20%.

$$a_f = \frac{2.1 \times 10^{-6} \times (74 + \pi d_f)4000}{58.7} = 1.36 \times 10^{-4}(74 + \pi d_f) \quad \ldots\ldots\ldots..(1)$$

Since $S_f = \frac{a_f T_f}{h_f d_f}, \quad 0.52 = \frac{a_f T_f}{13 \times d_f} \;\; or \;\; d_f = 0.148 a_f T_f \quad \ldots.\ldots\ldots.(2)$

$$Loss = V_f I_f = \frac{V_f(I_f T_f)}{T_f}$$

$$= \frac{loss}{cm^2} \times external\ dissipating\ surface[2(L_P + b_P + 4t_i) + 2\pi d_f]h_f$$

$$or\ \pi(d_i + 2t_i + 2d_f)h_f$$

$$\frac{58.7 \times 4000}{T_f} = 0.12 \times (74 + 2\pi d_f)13$$

$$(74 + 2\pi d_f)T_f = 150512.8 \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

From 3 *and* 2,

$$\frac{(74 + 2\pi d_f)T_f}{0.148 a_f T_f} = \frac{150512.8}{d_f}$$

$$(74 + 2\pi d_f)d_f = 22275.9a_f \ldots\ldots\ldots\ldots..(4)$$

$(74 + 2\pi d_f)d_f = 22275.91.36 \times 10^{-4}(74 + \pi d_f)$after substituting equation 1 in 4

$$2\pi d_f^2 + 74d_f - 3\pi d_f - 222 = 0$$

$$2\pi d_f^2 + 64.6d_f - 222 = 0$$

$$d_f = 2.72cm$$

$$a_f = 1.36 \times 10^{-4}(74 + \pi \times 2.72) = 0.11cm^2$$

$$T_f = \frac{d_f}{0.148a_f} = \frac{2.72}{0.148 \times 0.011} \approx 1671$$

Example..6A rectangular field coil is to supply 7000 ampere turns when dissipating 200W at a temperature of 60˚C. The inner diameter of the coil is 20cm x 12cm. The height of the coil is 12cm. The heat dissipation is not to exceed 0.005W/˚C rise in temperature/$cm^2$of the outside surface, neglecting top & bottom of the coil. Temperature of the ambient air may be taken as 25^oC . Calculate the depth of the coil, space factor & current density.

$$Loss = V_f I_f = \frac{V_f(I_f T_f)}{T_f} = \frac{loss}{cm^2} \times Outside\ \ dissipating\ area[2(L_P + b_P + 4t_i) + 2\pi d_f]h_f$$

$$= Loss\ in\ watts\ /^{0}C/cm^2\ of\ dissipating\ surface\ \times rise\ in\ temperature$$
$$\times\left[2(L_P + b_P + \quad 4t_i) + 2\pi d_f\right]h_f$$

$$200 = 0.005 \times (60 - 25) \times [2(20 + 12 + 4 \times 0.5) + 2\pi d_f]12$$

$$200 = 0.005 \times (60 - 25) \times [2(20 + 12 + 4 \times 0.5) + 2\pi d_f]12$$

$$Therefore\ d_f = 4.34cm$$

$$Since\ \ S_f = \frac{a_f T_f}{h_f d_f} = \frac{\frac{a_f}{I_f}\left(I_f T_f\right)}{h_f d_f} = \frac{I_f T_f}{\delta_f h_f d_f},$$

$$therefore\ current\ density\ \delta_f = \frac{I_f}{a_f} = \frac{V_f I_f}{a_f V_f} = \frac{Loss\ in\ watts}{\rho L_{mt} I_f T_f}\ \ as\ a_f = \frac{\rho L_{mt} I_f T_f}{V_f}$$

$$L_{mt} = 2(L_P + b_P + 4t_i) + \pi d_f = 2(20 + 12 + 4 \times 0.5) + \pi \times 4.34 = 81.6cm$$

$$\delta_f = \frac{200}{2.1 \times 10^{-6} \times 81.6 \times 7000} = 166.7A/cm^2$$

$$S_f = \frac{7000}{166.7 \times 12 \times 4.34} = 0.806$$

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