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Appendix

Mathematical Development

1. Initial Voltage Distribution in a Winding for Steep Wave Fronts.

If voltage is suddenly applied to a system of inductances in multiple with a system of capacitances, the initial voltage distribution will be determined by the capacitances. At the instant of impact, the condensers short-circuit the steep wave front. If the wave is maintained, the condensers become charged, and the voltage rises. The voltage distribution, when the condensers are charged, is the same as that when an alternating voltage is applied to the system of condensers with the inductances disconnected. Considering the system of internal and ground capacitances by themselves (Fig. A), and assuming an alternating voltage of frequency f, ($f \neq \frac{w}{2\pi}$), applied, the following relations will be evident.

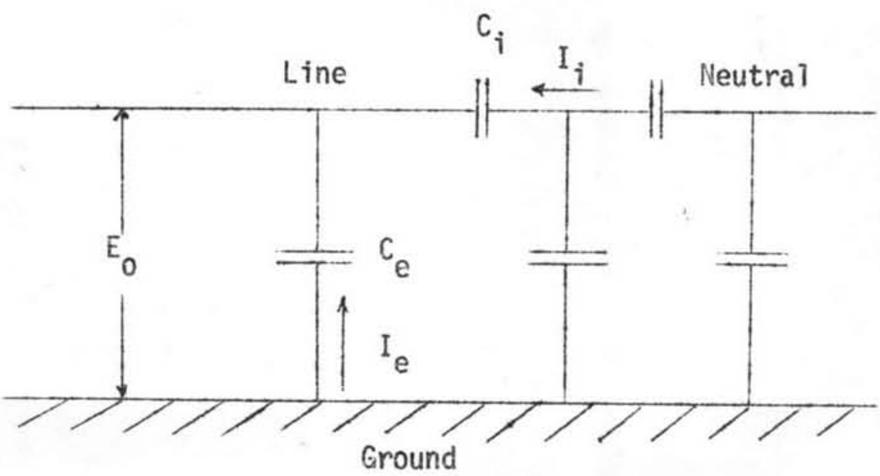

Fig. A

Let C_i = Capacitance between line end of coil and neutral

C_e = Capacitance between winding and ground for a coil length of line to neutral.

l = Coil length line to neutral

lC_i = Capacitance between portions of winding unit distance unit

$\frac{C_e}{l}$ = Capacitance to ground per unit length of coil

e_x = Voltage to ground at any point

$\frac{de_x}{dx}$ = Voltage gradients, volts per unit length of coil

E_o = Impressed voltage line to ground

w = $2\pi f$ = angular velocity

I_i = Current in the coil capacitance C_i

$$= wC_i l \frac{de_x}{dx} \qquad (1)$$

I_e = Current in ground capacitance C_e

dI_e = Current in ground capacitance per unit length of coil

$$= w \frac{C_e}{l} e_x \qquad (2)$$

The increase per unit distance in the current of the shunt capacitance is the current supplied by the ground capacitance per unit length, that is,

$$\frac{dI_i}{dx} = \frac{dI_e}{dx} \qquad (3)$$

2. Calculations of C_i and C_e

Assuming that the ends of the winding are electrically connected to clamping plates or end rings and C_i is the capacitance between these plates[2].

$$C_i = \frac{\epsilon_r \times A}{4 \quad d \times 9 \times 10^5} \ \mu f$$

where $_r$ = dielectric constant of oil = 2.2

A = area of plate = $\pi.\frac{(29)^2}{4}$ sq.cm.

d = distance between plates = 42.16 cm.

Therefore
$$C_i = \frac{2.2 \times \pi \times (29)^2}{4\pi \times 42.16 \times 4 \times 9 \times 10^5} \ \mu f$$

$$= 3.0475 \times 10^{-12} \quad \text{farads}$$

The capacitance of the surface of transformer winding to ground is given by

$$C_e = \frac{0.0388\ \epsilon_r}{\log_{10}(\frac{R_2}{R_1}) \times 1.609 \times 10^5} \ \mu f/cm.$$

where R_2 = 29.0 cm.

R_1 = 11.7 cm.

Therefore
$$C_e = \frac{0.0388 \times 2.2 \times 42.16}{\log_{10}(\frac{29.0}{11.7}) \times 1.609 \times 10^5} \ \mu f$$

$$= 55.226 \times 10^{-12} \quad \text{farads}$$

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2. L.F. BLUME and A. BOYAJIAN, Abnormal Voltages within Transformers. AIEE, 1919 Vol 38. p. 577

Substituting in equation (3) the value of $\frac{dI_i}{dx}$ from (1), and $\frac{dI_e}{dx}$ from (2), and simplifying,

$$\frac{d^2e}{dx^2} - \frac{1}{l^2}\,\frac{C_e}{C_i}\,e_x = 0 \tag{4}$$

The solution of this equation is of the form

$$e_x = A\,\epsilon^{px} \tag{5}$$

Substituting (5) and its derivative in (4), and solving for p,

$$p = \frac{1}{l}\sqrt{\frac{C_e}{C_i}} \tag{6}$$

and

$$e_x = A\,\epsilon^{px} + B\,\epsilon^{-px} \tag{7}$$

The constant A and B are determined by the terminal conditions as follows. If the neutral is grounded. The terminal conditions are at

$$x = 0\,,\quad e = 0 \tag{8}$$

and

$$x = l\,,\quad e = E_0 \tag{9}$$

Applying condition (8), to equation (7)

$$0 = A + B$$

$$A = -B$$

$$e_x = A(\epsilon^{px} - \epsilon^{-px}) \tag{10}$$

$$e_x = A' \operatorname{Sinh} px \tag{11}$$

Applying condition (9) to equation (11)

$$E_0 = A' \operatorname{Sinh} pl \tag{12}$$

Therefore,

$$e_x = E_0 \frac{\operatorname{Sinh} px}{\operatorname{Sinh} pl} \tag{13}$$

$$= E_0 \frac{\operatorname{Sinh} (\alpha \frac{x}{l})}{\operatorname{Sinh} \alpha} \tag{14}$$

where, $\alpha = pl = \sqrt{\frac{C_e}{C_i}}$ and the neutral is grounded.

3. Initial Voltage Distribution Curves.

$$C_i = 3.0475 \times 10^{-12} \quad \text{farads}$$

$$C_e = 55,226 \times 10^{-12} \quad \text{farads}$$

Therefore

$$\alpha = \sqrt{\frac{C_e}{C_i}}$$

$$\alpha = \sqrt{\frac{55.226 \times 10^{-12}}{3.0475 \times 10^{-12}}} \approx 4.0$$

The initial voltage distribution is, by equation (14)

$$\frac{e_x}{E_0} = \frac{\text{Sinh}\,(\frac{4x}{T})}{\text{Sinh}\,(4)}$$

and is plotted in Fig (8). From this curve, we can see that at $\frac{x}{T} = 0.875$ (approximately the first coil of H.V. winding) $\frac{e_x}{E_0} = 0.62$. If E_0 is equal to the rated output voltage.

Then, the voltage drop across the first coil $= (1.0 - 0.62) \times 100$

$= 38$ KV.

From the design of insulation for the high voltage winding in order to withstand this voltage drop. The pressphane insulations of 3.2 mm. thick and two oil ducts of 3.2 mm width were used to provide the insulations between coils.

The maximum voltage between layers of the first coil due to voltage drop $= \frac{38,000}{4318} \times 2 \times 110 = 1936$ volts

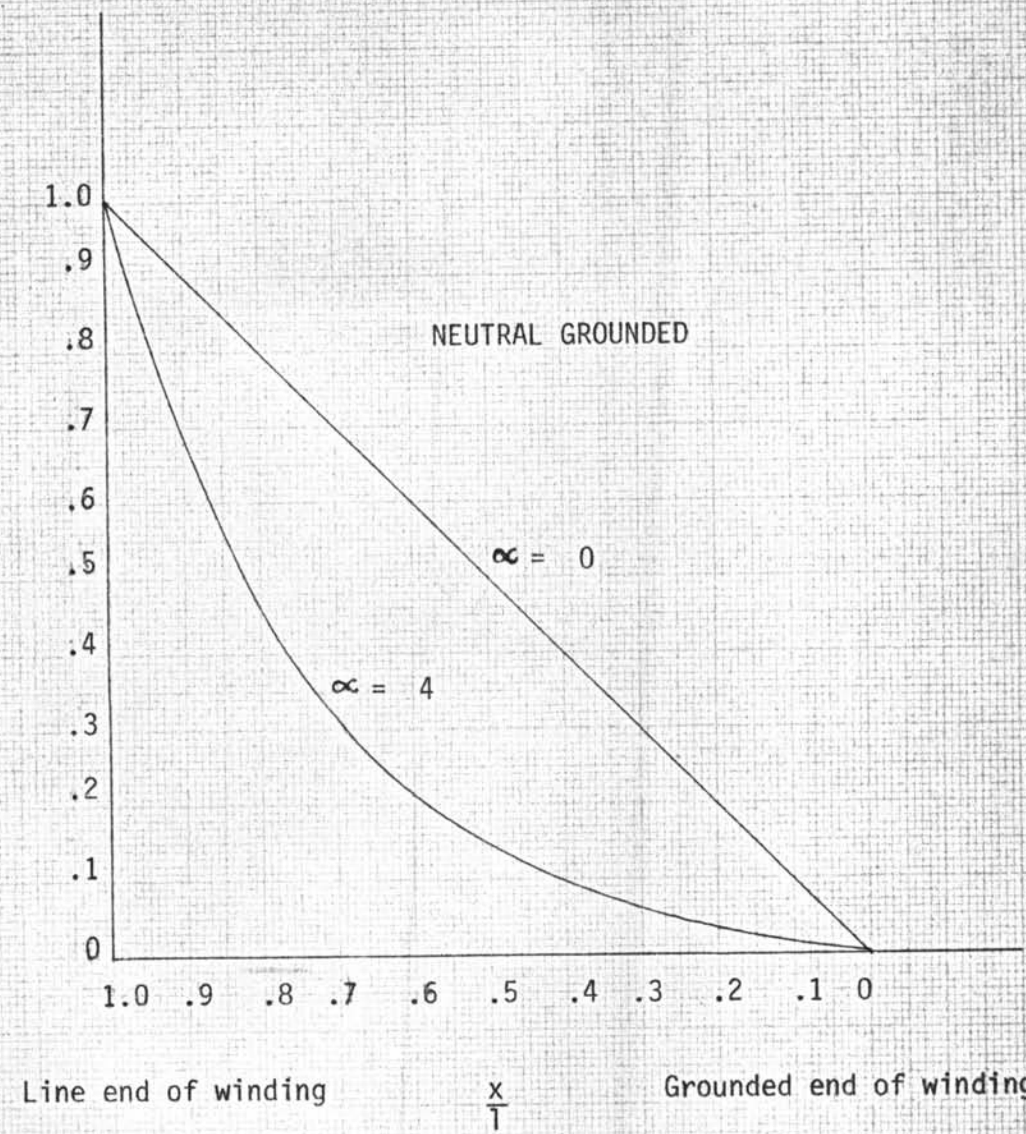

Fig. (B) Hyperbolic Voltage Distribution within Transformer Winding. Neutral Grounded.

4. Calculation of Highest Peak Value of Transient Overvoltage.

$$\hat{U}_1 = u_0 \left(1 + \epsilon^{-\frac{\pi}{2} \cdot \frac{R}{\sqrt{\frac{L}{c}}}}\right)$$

Where $\hat{U}_1$ = First and highest peak value of transient overvoltage.

u_0 = Rated output voltage = 100 KV

R = Total winding resistance = 41,880 ohms.

L = Total leakage inductance of coils

C = Total capacitance = $C_{eff} + C_t$

C_t = Capacitance of the test object

C_{eff} = Effective capacitance of the transformer

$$L = \frac{0.4\pi 1 N^2 L_h}{h \times 10^8} \quad \text{Henry}$$

$$= \frac{0.4\pi \times 42.16 \times (34546)^2 \times 80.4}{189 \times 10^8}$$

$$= 268.83 \quad \text{Henrys}$$

The effective capacitance of the transformer is approximately given by

$$C_{eff} = \sqrt{C_e \times C_i}$$

$$= \sqrt{55,226 \times 10^{-12} \times 3.0475 \times 10^{-12}}$$

$$= 12.97 \times 10^{-12} \quad \text{farads}$$

$$C_t = \frac{P}{2\pi f \times U^2 \times 10^{-9}} \quad \text{pf}$$

$$= \frac{5}{2\pi \times 50 \times (100)^2 \times 10^{-9}}$$

$$= 7960 \times 10^{-12} \quad \text{farads}$$

$$C = C_{eff} + C_t$$

$$= 12.97 \times 10^{-12} + 7960 \times 10^{-12}$$

$$= 7972.97 \times 10^{-12} \quad \text{farads}$$

$$\sqrt{\frac{L}{C}} = \sqrt{\frac{268.83}{7972.97 \times 10^{-12}}}$$

$$= 18.36 \times 10^{4}$$

$$= 183,600$$

Then $$\hat{U}_1 = 100(1 + \epsilon^{-\frac{\pi}{2} \cdot \frac{41880}{183,600}})$$

$$= 100(1 + \epsilon^{-0.358}) = 100 \times 1.698$$

$$= 169.8 \quad \text{KV.}$$

The maximum voltage between layers of the first coil due to transient overvoltage will be

$$1936 \times 1.698 = 3287.3 \quad \text{volts.}$$

From Fig. 4.4, the dielectric strength of 3 layers of pressphane insulations of 0.13 mm. thick is about 4000 volts before vaccum. This shows that the insulation is enough to withstand the transient overvoltage.

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