ELECTROMAGNETIC MODEL OF TRANSFORMER

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I. PREFACE

At present time, we pay a great deal of consideration in the insulation design of transformer to the impulse voltage. In other words, the problem of how the transformer winding operates on the impulse voltage is the most essential one which has been studied by all transformer designers in the world.

In the method of developing analysis by calculation, we compose the differential equations for the ideal distributed circuit shown in Fig. 1, and solve it in the form of infinite series. But the circuit in Fig. 1 is only the idealized one to simplify the analysis of transformer winding, and the results obtained from this circuit are not sufficient to expect qualitative agreement with the practical transformer. At present state, especially, we can expect neither to determine accurately the inductance values corresponding to every harmonic which composes the internal oscillation, nor to expand the accurate analysis under taking into consideration the nonlineality of iron core.

In parallel with these analytical methods, experimental investigations by such as geometrical models and equivalent circuits have been studied, but these results have not been able to satisfy practically the purpose of transformer designers.

The electromagnetic model is one of the experimental methods and the shortcomings of the geometrical model and of the equivalent circuit are eliminated in this model. Namely, this is a kind of model transformer which is designed to possess the same internal oscillation characteristics as that of the original. Therefore the electromagnetic model has a merit of grasping the voltage distribution accurately within the original transformer and rationalizing the insulation design before the transformer is built. The response of the model and of the transformer between corresponding points are measured with the transient analyser and the results obtained are very encouraging.

Such electromagnetic model of transformer was developed under the same principle at Fuji Electric Mfg. Co. in Japan and General Electric Co. in the United States independently and nearly simultaneously in 1950 and by now we have built eight models already.

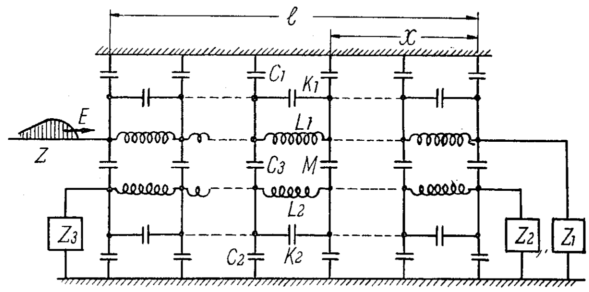


Fig. 1. Complete idealized circuit of a two-winding transformer to high frequency transients

II. THE ELECTROMAGNETIC MODEL

We transformer designers need to know the maximum voltages and the wave shapes between a great members of points within transformers of greatly diversified structures simply and accurately, for a wide range of applied waves, winding conditions and terminations to effect the most economical design. For these purposes the electromagnetic model was developed to furnish directly all answers required for transformer development.

1. Equivalent condition

In the electromagnetic model all quantites may be different from the corresponding quantities of the original transformer, except for the magnetic state of the core at corresponding times, in order to maintain the non-linear properties of the iron core.

This requires that

$$b_1(t_1)=b_0(t_0) \qquad (1)$$

$$h_1(t_1)=h_0(t_0) \qquad (2)$$

where

$b(t)$ = instantaneous value of flux density.

$h(t)$ = instantaneous value of field intensity.

and the quantities in the original will be designated by letters with 0, and the corresponding quantities in the model are refered to with the same letters, to which 1 are appended.

Namely, equation (1) and (2) show that the model has the same magnetic characteristics as the original. Further, expressing the ratio between corresponding core length of the model and of the original by k_e, the instantaneous value of induced voltage e is shown as follows,

$$e_1 = N_1 A_1 \frac{db_1}{dt_1} \qquad \cdots\cdots (3)$$

$$e_0 = N_0 A_0 \frac{db_0}{dt_0} \qquad \cdots\cdots (4)$$

where N denotes number of turns, t time, and A cross section of core. The meaning of appendage 1 and 0 are explained above.

Dividing equation (3) by equation (4) and let the voltage ratio between model and original be $k_e = \frac{e_1}{e_0}$,

$$k_e = \frac{e_1}{e_0} = N_1 A_1 \frac{db_1}{dt_1} \Big/ N_0 A_0 \frac{db_0}{dt_0} \qquad \cdots\cdots (5)$$

Further, we consider that the time ratio k_t is generally changeable for model and denote that

$$k_t = t_1/t_0 \qquad \cdots\cdots (6)$$

This shows physically that the phenomena which appears t_0 sec. later measured from the instant of wave applying to original corresponds to the phenomena of $k_t t_0$ sec. later for model.

Therefore, from equation (6)

$$dt_1 = k_t dt_0$$

$$\frac{1}{k_t} = \frac{dt_0}{dt_1} \qquad \cdots\cdots (7)$$

Substituting the following equations to equation (5)

$$A_1/A_0 = k_l^2 \qquad N_1/N_0 = k_N$$

$$\frac{db_1}{dt_1} \Big/ \frac{db_0}{dt_0} = [\text{since } b_1 = b_0] = \frac{dt_0}{dt_1} = \frac{1}{k_t}$$

we obtain :

$$k_e = \frac{e_1}{e_0} = k_N k_l^2 \frac{1}{k_t} \qquad \cdots\cdots (8)$$

Next we will consider about the current multiplying factor $k_i = i_1/i_0$. (In this case the current means the exciting current)

Denoting the magnetic path of core l_c, the relations between current and field intensity of model and original are :

$$4\pi N_1 i_1 = h_1 l_{c1} \qquad \cdots\cdots (9)$$

$$4\pi N_0 i_0 = h_0 l_{c1} \qquad \cdots\cdots (10)$$

Therefore $N_1 i_1 / N_0 i_0 = h_1 l_{c1} / h_0 l_{c0}$

$$i_1/i_0 = k_i = \frac{N_0}{N_1} \frac{h_1 l_{c1}}{h_0 l_{c1}} = [\text{since } h_1 = h_0] = \frac{k_l}{k_N} \qquad \cdots\cdots (11)$$

In other words, equation (8) and (11) must be resulted, to satisfy the relation that the model has the same magnetic characteristics as the original.

In the case of reduction the core of electromagnetic model, three scale factors such as length, width and height need not always have the same ratio, but the ratios of magnetic path and cross section may be chosen arbitrarily. In this case, the voltage scale k_e is

$$k_e = k_N k_A \frac{1}{k_t}$$

where $k_A = A_1/A_0$, namely the ratios of cross section of core.

Next, we will consider the relation needed for three electric constants such as L, C, R. Let k_Z be the impedance scale factor, from (8) and (11) apparently

$$k_Z = \frac{Z_1}{Z_0} = \frac{k_e}{k_i} = k_N^2 k_l \frac{1}{k_t} \qquad \cdots\cdots (12)$$

By approximately same procedure, we obtain the following equations for inductance scale factor k_L, capacitance scale factor k_C, and resistance scale factor k_R respectively :

$$k_L = \frac{L_1}{L_0} = k_N^2 k_l \qquad \cdots\cdots (13)$$

$$k_C = \frac{C_1}{C_0} = \frac{1}{k_N^2} \frac{1}{k_l} k_t^2 \qquad \cdots\cdots (14)$$

$$k_R = \frac{R_1}{R_0} = k_N^2 k_l \frac{1}{k_t} \qquad \cdots\cdots (15)$$

Generally, these three (or four) scale factors k_l, k_N, k_t (and k_A) may be chosen arbitrarily and independently, but once k_L and k_C are given, all these factors are established by proper dimensional analysis.

We will explain the typical examples of models in the following chapter.

2. Class of models

1) Case $k_L = 1$, $k_C = 1$

This is a case that L and C of the model are equal to the original. As $k_L = 1$ and $k_C = 1$

$$\begin{cases} k_N^2 k_l = 1 \\ \frac{1}{k_N^2} \frac{1}{k_l} k_t^2 = 1 \end{cases}$$

Consequently

$$k_N = \sqrt{\frac{1}{k_l}} \quad \text{and } k_t = 1$$

Substituting these equations to equations (8) and (11)

$$k_e = k_l^{\frac{3}{2}}, \quad \text{and} \quad k_i = k_l^{\frac{3}{2}}$$

If the length scale of core of model and original is chosen 1 : 10, namely $k_l = 1/10$,

$$k_N = \sqrt{10} = 3.16$$

$$k_e = \left(\frac{1}{10}\right)^{\frac{3}{2}} = 0.032$$

$$k_i = \left(\frac{1}{10}\right)^{\frac{3}{2}} = 0.032$$

As explained above, if L and C values of the model are determined same as that of the original respectively, the time scale factor k_t must be unity necessarily. Therefore the model built under these conditions can be examined with the same measuring equipment and be used with the same applied wave as original. Further the obtained oscillograms can be compared directly with each other and all the tedious labour of scaling and tracing oscillograms is thereby eliminated. Owing to these advantages, many electromagnetic models of transformers have been built with unity time scales and we call this model as THE FIRST CLASS OF MODEL in this article. G. E. in U. S. calls this type as the unity-time-scale model. And we, in Japan, have built already 8 models which belong to this class.

2) Case $k_L = k_C = n \quad (n > 1)$

In this case, both the inductance and the capacitance of the model must be n times as much as the original. Consequently, from equations (13) and (14)

$$k_L k_C = k_t^2 = n^2$$

$$\therefore \quad k_t = n$$

Therefore the time scale k_t comes to equal to the inductance or capacitance scale factor and we can use n times slowed wave to examine such models. If say $n=10$, (1×40) μs impulsive wave for original corresponds to (10×400) μs wave for model. This type is called by G.E. as the long-time-scale model and it is said that because of the large capacitance in the model, the possibility of errors by the effect of stray capacitance in measurement leads can be reduced or be kept to minimum. In this model, k_N, k_e and k_i become to respectively

$$k_N = \sqrt{\frac{n}{k_l}}$$

$$k_e = k_i = \sqrt{\frac{k_l^3}{n}}$$

In this article, we call this THE SECOND CLASS OF MODEL.

As explained in the foregoing, the frequency of applied test wave to the second class model, namely the long-time-scale model, can be reduced to $1/n$ times compared that of the original transformer, consequently the depth of penetration of magnetic flux into the core is greater than in the original. Therefore the core of the second class model can have a small cross section and would be required by geometrical similitude of k_l^2, but it is difficult to determine its limit qualitatively, so that we think that it is the good way to determine the dimensions of every part without considering these effect.

III. CONSIDERATION FROM THE VIEW OF INTERNAL OSCILLATION THEORY

1. Consideration from the point of standing wave theory

1) In the case when infinite rectangular wave is applied:

When an infinite rectangular wave E_I is applied at the terminal of the winding shown in Fig. 2, the voltage to ground in the arbitrary point is shown as the following equation:

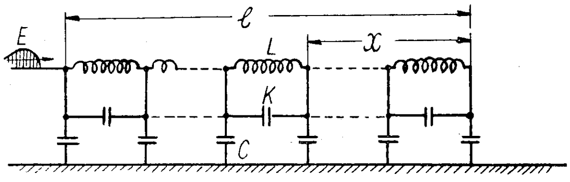


Fig. 2. Simplified equivalent circuit (secondary winding is ignored)

for grounded neutral:

$$e = E\frac{x}{l} + E\sum_{1}^{\infty} A_s \sin\frac{s\pi x}{l} \cos \omega_s t \quad \ldots\ldots (16)$$

where

$$A_s = \frac{2\alpha^2 l^2 \cos s\pi}{s\pi(\alpha^2 l^2 + s^2\pi^2)}$$

$$\omega_s = \frac{\dfrac{s^2\pi^2}{l^2}}{\sqrt{LK\left(\alpha^2 + \dfrac{s^2\pi^2}{l}\right)}}$$

l = length of winding

x = point along the winding, measured from the neutral end

$s = 1, 2, 3 \ldots\ldots$

$$\alpha = \sqrt{\frac{C}{K}}$$

C = shunt capacitance to ground per unit length of winding

K = series capacitance per unit length of winding

L = inductance per unit length of winding, including the partial interlinkages

for isolated neutral:

$$e = E + E\sum_{1}^{\infty} B_s \cos\frac{s\pi x}{2l} \cos \Omega_s t \quad \ldots\ldots\ldots\ldots (17)$$

$$B_s = \frac{-16\alpha^2 l^2 \sin\dfrac{s\pi}{2}}{s\pi(s^2\pi^2 + 4\alpha^2 l^2)}$$

$$\Omega_s = \frac{\dfrac{s^2\pi^2}{4l^2}}{\sqrt{LK\left(\alpha^2 + \dfrac{s^2\pi^2}{4l^2}\right)}}$$

Since these oscillation characteristics shown by above equations must be similar for model and original, A_s, B_s, ω_s, Ω_s will be needed to equal to each other, consequently C/K and LK must be same to each other.

In the case of first class,

$$k_C = 1 \qquad k_L k_C = 1$$

therefore the above two conditions are apparently satisfied. On the contrary, for the second class model, it is

$$k_L k_C = n^2$$

therefore we cannot expect that the characteristics of model and original become similar except the case of $n=1$. This owes to the fact that the test wave is same for two cases in spite of the frequency applied to second class must be n times longer than the original.

2) In the case of $E(\varepsilon^{-at}-\varepsilon^{-bt})$ wave is applied: for grounded neutral:

$$e=E(\varepsilon^{-at}-\varepsilon^{-bt})\frac{x}{l}+E\sum_{1}^{\infty}A_s\sin\frac{s\pi x}{l}\left[\frac{a^2\varepsilon^{-at}}{a^2+\omega_s^2}-\frac{b^2\varepsilon^{-bt}}{b^2+\omega_s^2}+\frac{\omega_s}{\sqrt{a^2+\omega_s^2}}\cos\left(\omega_s t+\tan^{-1}\frac{a}{\omega_s}\right)-\frac{\omega_s}{\sqrt{b^2+\omega_s^2}}\cos\left(\omega_s t+\tan^{-1}\frac{b}{\omega_s}\right)\right] \quad \text{......... (18)}$$

Here we will prove that the model of second class corresponds to the original under the condition of

$$a\to\frac{a}{n},\qquad b\to\frac{b}{n}.$$

Since A_s can be same for model and original if $\alpha=\sqrt{\frac{C}{K}}$ is equal, we consider next the term within [ ] in (18).

Rewriting,

$$\frac{a^2,\ b^2}{a^2,\ b^2+\omega_s^2}=\frac{1}{1+\left(\frac{\omega_s}{a,\ b}\right)^2}$$

$$\frac{\omega_s}{\sqrt{a^2,\ b^2+\omega_s^2}}=\frac{1}{\sqrt{1+\left(\frac{a,\ b}{\omega_s}\right)^2}}$$

Refering to $\omega_{s1}=\frac{1}{n}\omega_{s0}$, these two terms will be equal for model and original if a and b for model are $1/n$ times as much as for the original. Consequently, the constant terms in equation (18) are same to model and original, while the terms which are muliplied by t such as at, bt and $\omega_s t$ etc. become $1/n$ times in model as much as in original.

Namely, at, bt and $\omega_s t$ become

$$a_1t_1=\frac{a_0}{n}t_1,\quad b_1t_1=\frac{b_0}{n}t_1,\quad \omega_{s1}t_1=\frac{\omega_{s0}}{n}t_1.$$

Putting $t_1=nt_0$, $a_1t_1=\frac{a_0}{n}nt_0=a_0t_0$ etc.

Therefore $\varepsilon^{-a_0t_0}=\varepsilon^{-a_1t_1}$ etc. are resulted. In other words, the wave phenomena appear t_0 sec. later for model is reproduced t_1 sec. later for original.

Generally speaking, as the same conclusion as explained above can be obtained also both in cases of isolated neutral and the case of the wave of arbitrary shape which has a finite front and finite tail length, the second class of model may be equivalent to the original for all practical applied waves.

2. On the velocity of propagation

Rearranging the above equation (16)

$$e=E\frac{x}{l}+E\sum_{1}^{\infty}\frac{A_s}{2}\left[\sin\left(\frac{s\pi x}{l}+\omega_s t\right)+\sin\left(\frac{s\pi x}{l}-w_s t\right)\right]$$

the propagation velocity of the sth harmonics can be written as follows:

$$v_s=\frac{l\omega_s}{s\pi} \quad \text{.................................. (19)}$$

For the first class of model $\omega_{s1}=\omega_{s0}$, consequently the ratio of the propagation velocity along the winding of model and original is

$$\frac{v_{s1}}{v_{s0}}=\frac{l_1}{l_0}$$

Namely the velocity of propagation within model and original is not equal, but it is in proportion to its winding length.

This means that the wave will transmit along the same % of coil in the given time both for model and original.

On the contrary, for the second class the foregoing equivalency is not resulted. As explained above we must consider the performance to the applied wave $E(\varepsilon^{-at}-\varepsilon^{-bt})$.

Rearranging the equation (18)

$$\begin{aligned}e=&E(\varepsilon^{-at}-\varepsilon^{-bt})\frac{x}{l}\\&+E\sum_{1}^{\infty}A_s\sin\frac{s\pi x}{l}\left[\frac{a^2\varepsilon^{-at}}{a^2+\omega_s^2}-\frac{b^2\varepsilon^{-bt}}{b^2+\omega_s^2}\right]\\&+E\sum_{1}^{\infty}\frac{\omega_s}{\sqrt{a^2+\ _s^2}}\frac{A_s}{2}\left[\sin\left(\frac{s\pi x}{l}+\omega_s t+\tan^{-1}\frac{a}{\omega_s}\right)+\sin\left(\frac{s\pi x}{l}-\omega_s t-\tan^{-1}\frac{a}{\omega_s}\right)\right]\\&-E\sum_{1}^{\infty}\frac{\omega_s}{\sqrt{b^2+\omega_s^2}}\frac{A_s}{2}\left[\sin\left(\frac{s\pi x}{l}+\omega_s t+\tan^{-1}\frac{b}{\omega_s}\right)+\sin\left(\frac{s\pi x}{l}-\omega_s t-\tan^{-1}\frac{b}{\omega_s}\right)\right]\end{aligned}$$

$$\text{.. (20)}$$

Therefore the propagation velocity is

$$v_s=\frac{l\omega_s}{s\pi}$$

therefore

$$\frac{v_{s1}}{v_{s0}}=\frac{1}{n}\frac{l_1}{l_0} \quad \text{.............................. (21)}$$

Consequently if we assume that

$$\frac{t_1}{t_0}=n \quad \text{...................................... (22)}$$

correspond to $a_1=\frac{a_0}{n}$, $b_1=\frac{b_0}{n}$, then from (21) and (22)

$$\frac{v_{s1}t_1}{v_{s0}t_0}=\frac{l_1}{l_0}$$

This equation means that % winding traveled in t_1 sec. for model and in t_0 sec. for original is equal to each other. In other words, in case of the first class, the propagation velocity along the winding within the same time is proportional to each other, but in case of the second class, t_1 sec. for model corresponds to t_0 sec. for original and the time axis of model is elongated n times as long as that of the original. This is the meaning of equivalency of model for the velocity of wave propagation.

IV. THE EXAMPLES OF ELECTRO-MAGNETIC MODEL

1. General

Electromagnetic models according to the foregoing theory were developed by Fuji Electric Mfg. Co. in Japan and General Electric Co. in the United States independently and approximately at the same time. Since 1950, electromagnetic models have been manufactured by Fuji Electric Mfg. Co., as shown in Table 1, and they performed a great achievement in investigation of original insulation designs. All these models shown in Table 1 belong to the first class namely L, C correspond with originals, respectively.

2. Problems on design

Various points to be attended to on design for the first class are as follows:

1) For non-linear inductance, the iron core is to be reduced geometrically.

2) Number of turnes is to be reduced by the same ratio k_n in high tension and low tension winding respectively, (in general, number of turns of model is more than that of the original), but even in this case, number of layers, number of coils of model are to be taken equally to the original. That is, number of turns per layer (in cylindrical coil) or number of turns per coil (in disk coil) should be increased in accordance with k_n.

3) Constants to be equalized for model and original are as follows:

Static capacitance:

Shunt capacitance to ground (to core, to yoke, to tank and to the other coil etc.)

Reactance:

Leakage reactance between coils (in Ω). (In case of adjusting the static capacitance, it is necessary to equalize the capacitance to the corresponding element of coil. For instance, when original 1 turn corresponds to model 3 turns, series capacitance between turns must be put equally to original 1 turn and model 3 turns).

4) As number of turns of model are generally more and the mean length is shorter and its copper size is smaller than the original, capacitance between turns is apt to be smaller, the use of conductor with high dielectric constant and thin insulation thickness, such as P.V.F. wire, should be considered.

5) The static capacitance and reactance can be calculated by following simple formulas with adequate accuracy:

shunt capacitance of coil to ground:

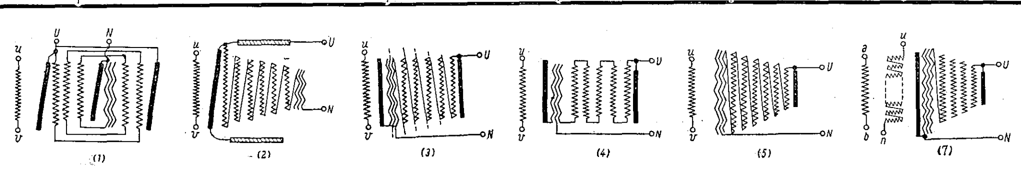
$$C = \frac{\varepsilon h}{4.6 \log_{10} \dfrac{\phi_2}{\phi_1}} \frac{10}{9} pF$$

(This formula is also applicable to the capacitance between layers of cylindrical coil)

Table 1. Examples of electromagnetic model

No.	Year	Specification of original	Connection	Model kVA	Model weight (kg)	Model height (m/m)
1	Nov. 1950	1 ϕ 154 kV 9,000 kVA	(1)	Approx. 10	250 (1.3%)	740
2	July 1952	1 ϕ 154 kV 6,700 kVA	(2)	Approx. 10	200 (1.8%)	740
3	Feb. 1953	3 ϕ 275 kV 45,000 kVA	(3)	10	200 (0.8%)	740
4	Nov. 1953	(for investigation)	(4)	10	200	740
5	Aug. 1954	3 ϕ 154 kV 81,000 kVA	(5)	100	360 (0.6%)	750
6	Aug. 1954	(for investigation)	neglect	100	360	750
7	Feb. 1955	3 ϕ 275/147/10.5 kV 90/99/45 MVA	(7)	90/99/45	1,400 (1.1%)	990
8	Feb. 1955	3 ϕ 275/77/10.5 kV 90/99/45 MVA	(8)	90/99/45	1,000 (1.4%)	990

Connection



series capacitance along the coil:

$$C_s = \frac{\varepsilon l_m b}{4\pi d} \cdot \frac{10}{9} pF$$

(This formula is also applicable to the capacitance between coils and between turns.)

where:

ϕ_1, ϕ_2; inner and outer diameter respectively
h: height of coil
ε: dielectric constant
d: gap length (between coils or between turns)
b: width of a coil or a turn
l_m: average length
(all dimensions are in centimeter)

leakage reactance between coils:

$$X = 8\pi^2 f N^2 l_m \frac{\delta + \frac{a_1 + a_2}{3}}{h} 10^{-9}\Omega$$

where:

δ: gap length between high and low tension coil
a_1, a_2: width of high and low tension coil respectively
(all dimensions are in centimeter)

For example, in case of the iron core dimension of first class model is $1/n$ times as much as of original,

$$N_1 = \sqrt{n}\, N_0 \qquad l_1 = \frac{l_0}{n} \qquad h_1 = \frac{h_0}{n}$$

$$\delta_1 + \frac{a_{11} + a_{21}}{3} = \frac{1}{n}\left(\delta_0 + \frac{a_{10} + a_{20}}{3}\right)$$

consequently $X_1 = X_0$

3. Comparison of characteristics

Fig. 3 shows the new transient analyser set and the model for 90/99/45 MVA three windings transformer shown in No. 7 in Table 1. And Fig. 5 shows the comparison of the wave forms between model and original for 154 kV, 81,000 kVA cylindrical coil transformer (No. 5 in Table 1).

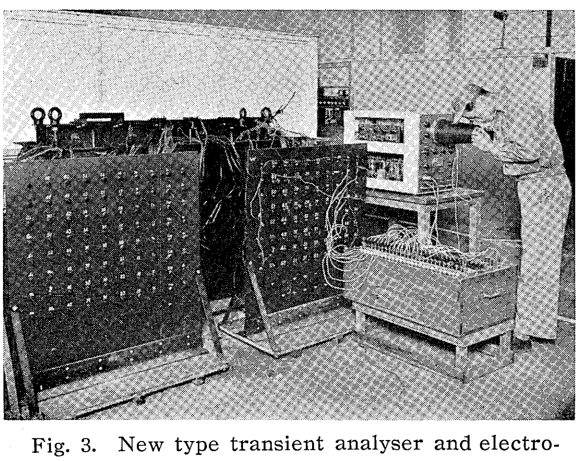
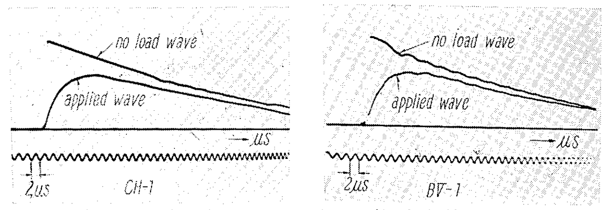
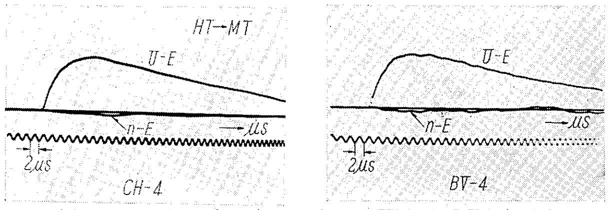


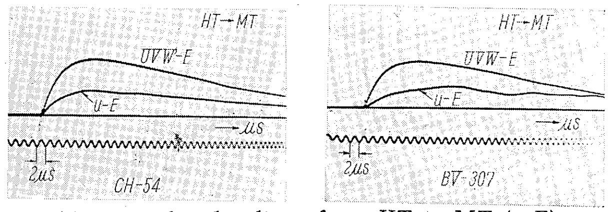
Fig. 3. New type transient analyser and electromagnetic model of 275/147/10.5 kV, 90/99/45 MVA transformer



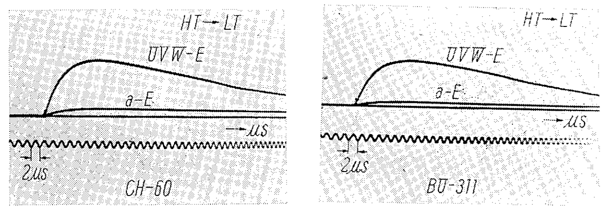
(1) No load wave and applied full wave



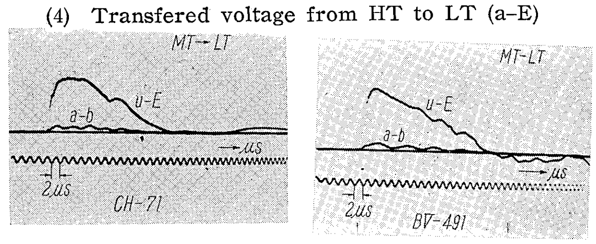
(2) Transfered voltage from HT to MT (n–E)



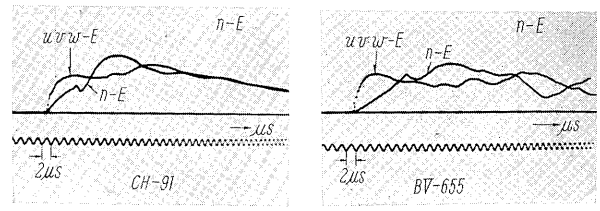
(3) Transfered voltage from HT to MT (u–E)



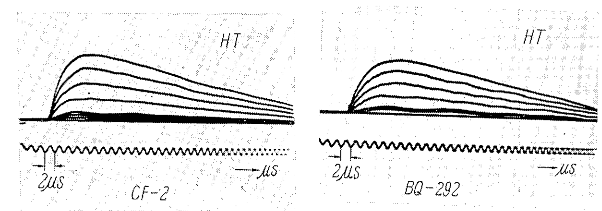
(4) Transfered voltage from HT to LT (a–E)



(5) Transfered voltage from MT to LT (a–b)

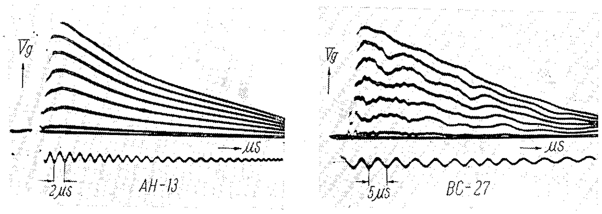


(6) MT neutral voltage (n–E)



(7) Voltage distribution within HT winding

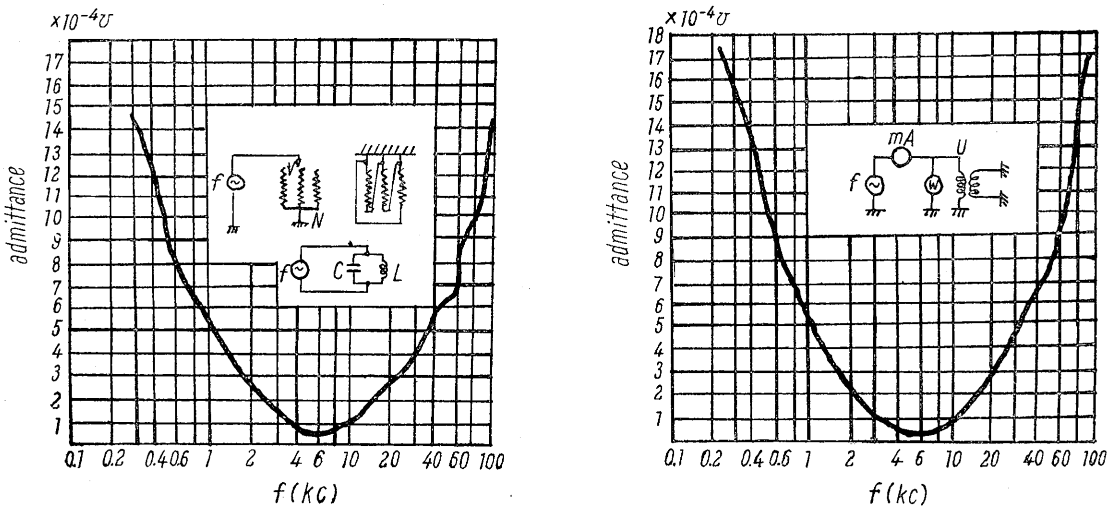
Fig. 4. Voltage oscillograms of 3ϕ 275/147/10.5 kV 90/99/45 MVA transformer and its electromagnetic model,
Left hand: model, Right hand: transformer



(A) Model (B) Transformer

Fig. 5. Voltage oscillogram of 3ϕ 154/12.6 kV 81,000 kVA transformer and its electromagnetic model

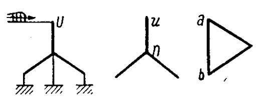
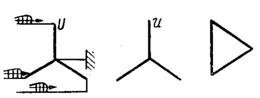
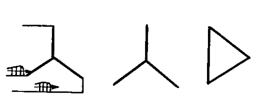
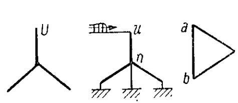
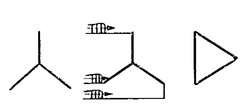
As seen in these oscillograms, internal voltage distribution between two are closely resembled except that the steepness of wave front in model is less sharp. Further, in the original many fine oscillations are superposed in the wave front part which are not in model. These are because the model is designed to equalize to L, C of original in oil impregnated state, and the model is measured after oil-impregnated state, on the contrary the original is tested at pre-impregnated state, and this causes the



Transformer Model

Fig. 6. Resonance characteristics of 275/13.2 kV, 45,000 kVA transformer and its electromagnetic model

Table 2. Voltage amplitude (%) of 90/99/45 MVA 275/147/10.5 kV transformer and its electromagnetic model (measured with the transient analyser)

Voltage applied to	Connection		Voltage regulation	u–E	n–E	a–E	a–b	
High tension winding		original	60[1]	65	9[2]	6	13	
		model	64	60	9	5	12	
		original	170	23	18	0	0	
		model	160	20	18	0	0	n–E
		original	70	45[3]	38	10[4]	0	65
		model	62	42	39	12	0	70
Middle tension winding		original	41	80	11	9	11[5]	
		model	—	75	13	10	11	n–E
		original	80	80	79	30	0	125[6]
		model	79	75	75	35	0	122

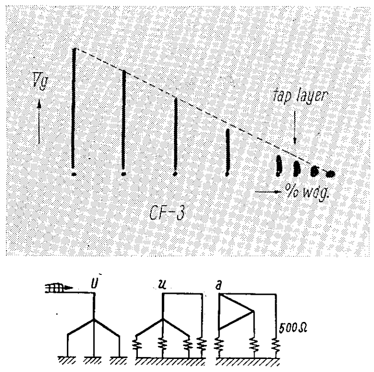
Note: (1)∼(6): these are shown by oscillograms (1)∼(6) respectively in Fig. 5.

difference in their static capacity.

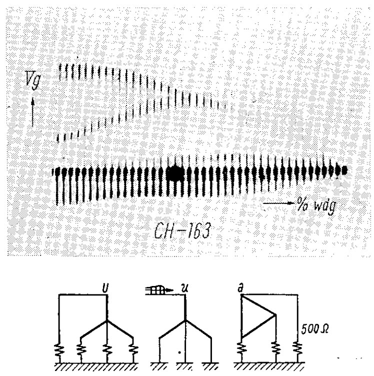
In Table 2 the comparative table of actually measured crest values between model and the original are shown and Fig. 4 shows these typical oscillograms. Both resemble closely each other and the accuracy of the electromagnetic model is entirely adequate for design purposes. Moreover, Fig. 6 is comparative chart of resonance characteristics for 275 kV 45,000 kVA transformer and its original. (No. 3 in Table 1).

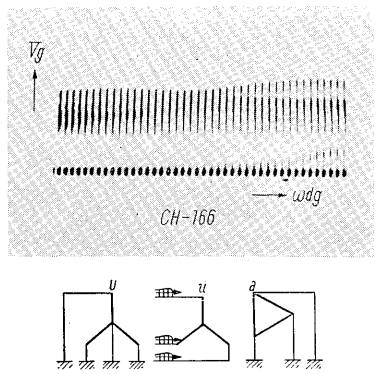
4. Examples of new oscillograms

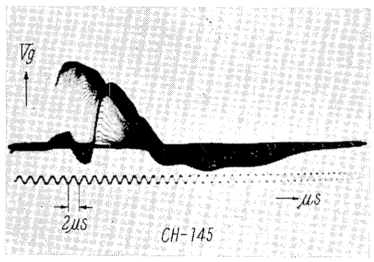
It is frequently impossible for the original to extract the sufficient numbers of measuring leads, consequently the internal voltage distribution after the



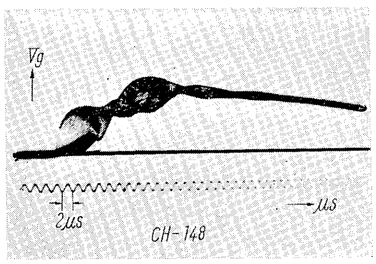
(a) High voltage winding





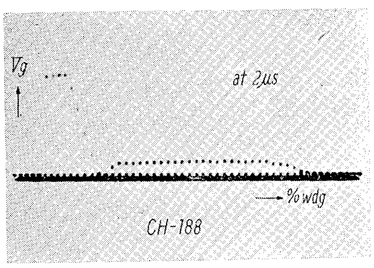


(b) Middle voltage winding

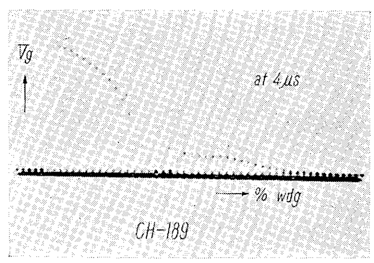


(c) Middle voltage winding

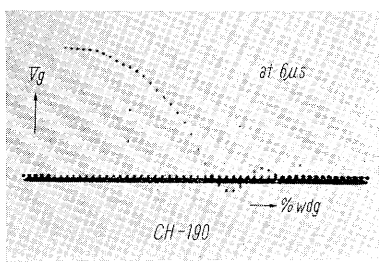
Fig. 7. Full-wave maximum voltage to ground in impulsed windings of 275/147/10.5 kV, 90/99/45 MVA transformer model



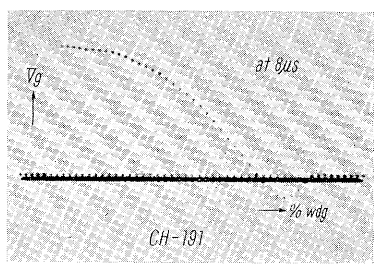
(a) At 2 μS



(b) At 4 μS



(c) At 6 μS



(d) At 8 μS

Fig. 8. Simultaneous voltage distribution to ground in impulsed middle-voltage winding of 275/147/10.5 kV, 90/99/45 MVA transformer

completion of original can never be known. On this point too, the electromagnetic has an advantage. Fig. 7 and 8 show the oscillograms of envelop voltage and instantaneous voltage distribution of model after completion measured by new type transient analyser. It can be said that the consideration for voltage oscillation has been much more clarified by these measurements.

V. UTILIZATION OF THE ELECTROMAGNETIC MODEL

One of the important application of the foregoing electromagnetic model is failure detection. With artificial failure in the model, it may be possible to correlate changes in the model applied wave and neutral current with changes which have denoted failure of the transformer.

Another important application is the determination of the constants of the impulse generator which will produce the specified test waves, and of the terminations of the non-impulsed windings, whose voltage should not exceed certain limits.

Moreover, it is needless to say that models may also be very useful to determine in special cases which winding structure is best suited to meet the given specifications.

However, its utilization is not limited to the impulse wave only. Since its constants of internal electric and magnetic characteristics including nonlineality of iron core are equalized to the original, the model should show the similar characteristics to the original in regard to the general performance of transformer as an element in the system.

For example, the utilization of the model combined with the artificial line covered such wide application area as generating conditions of abnormal voltage due to the ground fault in power system, the effect of iron core saturation characteristics to the stability in power system, exciting rush current of transformer, performance of transformer upon interruption of circuit, the effect of capacitors, circuit breaker recovery voltages, etc.

That is, it can be expected that the further development of electromagnetic model has great possibilities.

VI. SUMMARY AND CONCLUSION

1) The electromagnetic model is a transformer which its internal characteristics including non-lineality of iron core are designed to be equivalent or similar to the original, and by its development the complex internal oscillation within transformer can be modeled easily, accurately and according to various conditions.

2) The iron core of electromagnetic model should be reduced with a geometrical scale factor to the original, and length scale, time scale and coil number scale can properly be gained according to the individual purposes. The relation between them and electric constants is shown in formulas from (8) to (15).

3) Whether taking L and C equivalent or n times to the original, two types of electromagnetic models are considered and we call them the first class and second class of model respectively. (These correspond to the unity-time-scale model and long-time-scale model by G.E. respectively.)

4) The electromagnetic model has been developed from the same principle simultaneously and individually in 1950 by Fuji Electric Mfg. Co. in Japan and General Electric Co. in the United States, and a great achievement in grasping the condition of internal voltage oscillations in transformer could be performed. Eight electromagnetic models of first class were manufactured by Fuji Electric Mfg. Co., while General Electric manufactured sixteen models of first and second class. The accuracy of these electromagnetic model is entirely adequate for design purposes. One or two examples of these test results obtained by our laboratory are shown in Table 2 and Fig. 4～8.

5) In addition to the failure detection and determination of constants of impulse generator, the electromagnetic model is also used to study transformers as component of a power system, since they reproduce both the internal and external performance of the original.

6) The development of the electromagnetic model and its application are by no means completed. Further improvement on electromagnetic model and its full practical utilization in investigation for both in and out of transformer are greatly expected.