The result of all tests at the factorys shows excellent figures; the government witness tests are also completed with great success. The machine is now operating. Specially to be noted is the magnetic bearing which plays a great part to elevate the efficiency.

Since receiving order for such a record product, Our Company concentrated all the effort in the design and manufacture, based on experimental data as well as thorough investigation, on inexperienced matters; paying attention to even a piece of bolt, manufacture proceeded with all precautions. The company feel it a great pride to the completion of the machine with great success in operation both electrically and mechanically. The company is still seeking an opportunity to manufacture still higher class of machine based on the valuable experience thus gained.

EQUIVALENT CIRCUIT AND OSCILLATION OF POTENTIAL OF NEUTRAL POINT OF STAR-CONNECTED TRANSFORMER WINDING OF CYLINDRICAL-LAYER TYPE

By

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I. INTRODUCTION

Coils of the transformer winding of cylindrical-layer type[1] can be connected in two ways. Fig. 1a is the single coil connection, using the coils all wound in the same direction and Fig. 1b is the twin coil connection using the coils wound in different directions one by one in pairs. Further, when these windings are connected in star for 3-phase supply, the line terminal U may be located at the end of the outermost coil as shown in Fig. 1a and 1b or be located at the end of the innermost coil as shown in Fig. 1c. The former is called "normal arrangement" and the latter "inverted arrangement".

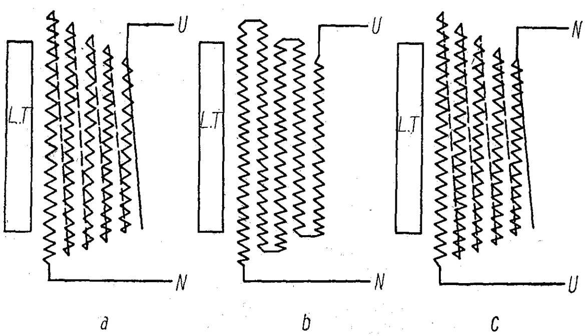

Fig. 1. Varieties of cylindrical-layer-windings

The cylindrical-layer winding is now widely adopted especially for extra high tension transformers with directly earthed neutral point not only in our Fuji Denki Co. (Refer to table 1) but also in E.E. Co. in Canada[2], G.E. Co. in U.S.A.[3] and

Table 1. Examples for Power Transformers with Cylindrical-Layer-Windings Manufactured by Fuji Denki (For BIL 750 kV or over)

Name of Customer	Capacity kVA	Voltage kV	No. of Pcs	Remarks
For Directly-Earthed Neutral System				
Dengen Kaihatsu K.K.	117,000	275/154/11	2	
〃	117,000	275/77/11	1	
Hokkaido Denryku K.K.	78,000	187/66/11	1	Mobile type
〃	78,000	187/66/11	1	〃 (under manufacturing)
Kansai Denryoku K.K.	45,000	275/132	1	
For Non-Directly Earthed Neutral System				
Tohoku Denryoku K.K.	55,750	154/66/11	1	Mobile type (under manufacturing)
Tokyo Denryoku K.K.	81,000	154/11	2	Mobile type
〃	*27,000	154/11	4	*3×1ϕ bank capacity
〃	*20,000	154/11	4	* 〃 〃
Hokuriku Denryoku K.K.	29.000	154/66/11	1	(under manufacturing)
Kansai Denryku K.K.	13,000	154/11	1	
Kyushu Denryoku K.K.	15,000	66/11	1	BIL 350 kV
Taiwan Power Co.	42,500	154/66/11	2	

Metropolitan-Vickers Co. in England as the most reliable and economical winding. Originally, however, it was proposed in Germany as an oscillation free winding for transformers for non-earthed neutral point transmission system. For example, Mr. J. Biermanns[4] of A.E.G. adopted the twin-coil connection in normal arrangement and Mr. R. Elsner[5] of S.S.W. proposed a perfectly oscillation-free transformer applying static shields on both inner and outer sides of the H.T. winding.

In 1950, we completed $3 \times 9{,}000$ kVA 1ϕ Oscillation-free type transformers[6] for 154 kV non-earthed neutral system according to Mr. R. Elsner's principle and in 1952, we completed a 45,000 kVA 3ϕ transformer[7], single-coil connection and normal arrangement, for 275 kV directly earthed neutral extra high tension system. The first $3 \times 9{,}000$ kVA ones proved to be rather expensive owing to their both sides H.T. shields and another improved ones[8] for 154 kV non-earthed neutral system were manufactured in 1952. These were $3 \times 6{,}660$ kVA with single-coil connection and inverted arrangement.

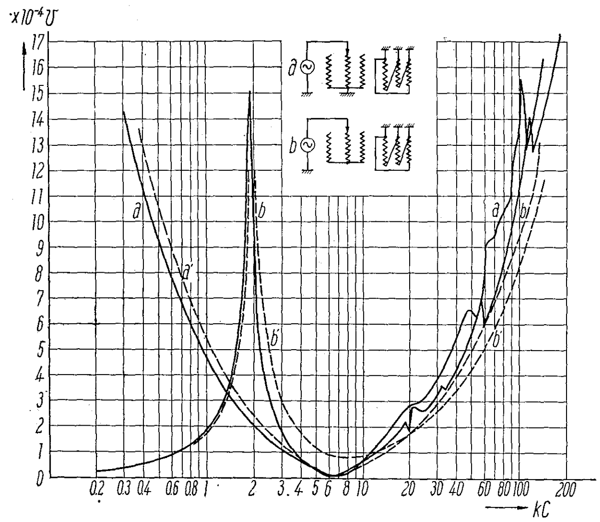

Fig. 2. Resonance characteristics of 45 MVA transformer

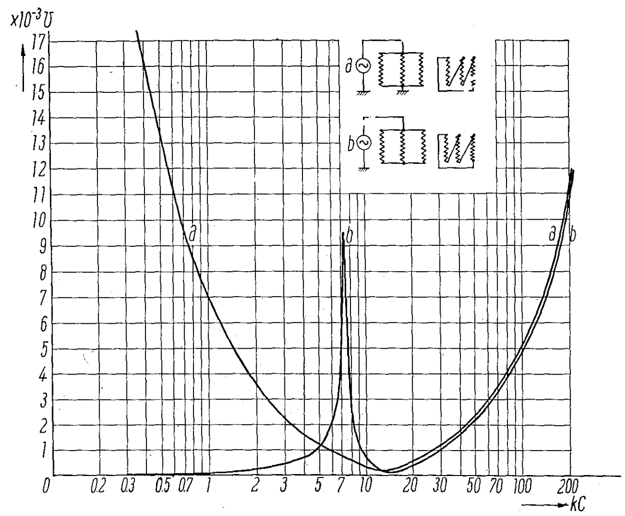

Fig. 3. Resonance characteristics of 81 MVA transformer

In case of single-coil connection, the voltage between the layer of adjacent coils remains equal to that of one single-coil throughout the layer while in case of twin-coil connection, it changes from 0 to 2 times of onecoil which makes this connection not suitable for high voltage transformers.

The coil at the neutral point of the normally arranged winding has a large static capacity between the L.T. winding, while the same coil of the inverted winding measures a small capacity between the transformer tank which results in a small rise of potential of neutral point in the case of non-earthed neutral system.

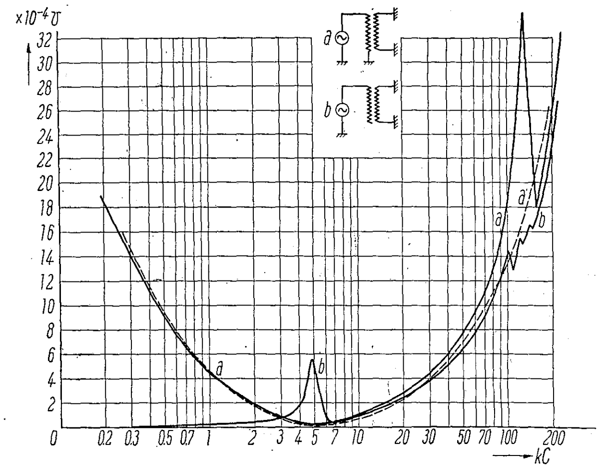

Fig. 4. Resonance characteristics of twin-connected (Fig. 1, b) transformer

II. RESONANCE FREQUENCY OF INTERNAL OSCILLATION

Fig. 2, Fig. 3, and Fig. 4 are the resonance curves of some transformers manufactured by us with cylindrical-layer-windings on both H.T. and L.T. sides. The curves were taken applying a high frequency oscillator at the H.T. terminal and earth. The ratings of the transformers are.

For Fig. 2
- 3ϕ 45 MVA, 275/11 kV.
- H.T. side. 6 layers, single-coil connection.
- L.T. side. cylindrical-block winding.

For Fig. 3
- 3ϕ 81 MVA 154/11 kV
- H.T. side. 7 layers, single-coil connection.
- L.T. side. cylindrical-block winding.

For Fig. 4
- 1ϕ 10 kVA 3.3/0.2 kV.
- (magnetic model corresponding to 1ϕ ca 30 MVA, 3ϕ ca 45 MVA)
- H.T. side. 6 layers, twin-coil connection.
- L.T. side. cylindrical-block winding.

Fig. 5 is a resonance curve for a transformer

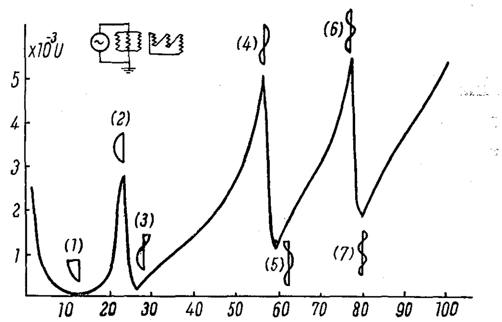

Fig. 5. Resonance characteristics of core type transformer with disc coil

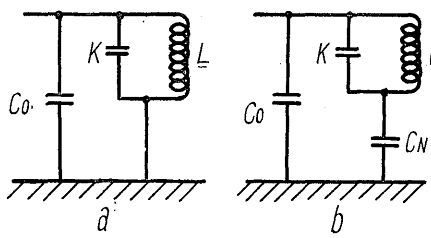

Fig. 6. Equivalent circuit for resonance characteristics

with ordinary disc coil windings,[9] the existence of harmonics on the curve is the characteristics of the internal oscillation.

On the basis of the above resonance curves, we can denote the equivalent circuit of internal oscillation for cylindrical-layer-winding with simplified

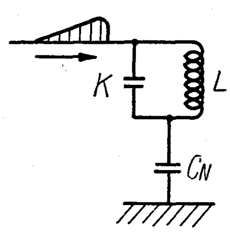

Fig. 7. Equivalent circuit for internal oscillations

diagram as shown in Fig. 6. C_0 is the capacity between line terminal shield or first layer coil and earth. K is the series capacity between line terminal and neutral point. C_N is the capacity between neutral Coil or neutral shield and earth. L is the leakage inductance for delta-connected $L.T.$ winding. Values for all these constants can be measured or calculated and measurement and calculation coincide practically.

In Fig. 6 a and b, the admittance of the circuit is:

$$\frac{1}{wL}-wK-wC_0=\frac{1}{wL}-w(K+C_0) \quad \ldots\ldots(1)$$

and

$$\frac{-\left(\frac{1}{wL}-wK\right)wC_N}{\frac{1}{wL}-wK+wC_N}-wC_0$$

$$=\frac{(1-w^2LK)wC_N}{w^2L(K+C_N)-1}-wC_0 \quad \ldots\ldots(2)$$

The equation (1) will be zero when $w^2L\ (K+C_0)=1$, that is, the circuit will come in the state of parallel resonance when

$$f_p=\frac{1}{2\pi\sqrt{L\ (K+C_0)}} \quad \ldots\ldots\ldots\ldots\ldots(3)$$

Equation (2) will be ∞ when $w^2L(K+C_N)=1$, that is, series resonance occurs when

$$f_s=\frac{1}{2\pi\sqrt{L(K+C_N)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

In the case of normally arranged winding, C_N corresponds to the capacity between innermost coil to $L.T.$ winding and C_0 is the same between outermost coil and transformer tank. The former is practically far more larger than the latter and as the result, it is quite natural that $f_p > f_s$ as shown in Fig. 2, 3 and 4.

The calculated values for K, C_0, C_N and L and these of f_p and f_s from equations (3) and (4) are:

For Fig. 2

$K=1{,}460$ pF	$L=0.3$ H
$C_0=1{,}000$ pF	$f_p=6.3$ kc
$C_N=7{,}000$ pF $\times 3$	$f_s=1.95$ kc

For Fig. 3

$K=2{,}000$ pF $\times 3$	$L=0.09$ H $\times 1/3$
$C_0=2{,}540$ pF	$f_p=10$ kc
$C_N=6{,}370$ pF $\times 1/3$	$f_s=5.8$ kc

For Fig. 4

$K=1{,}460$ pF	$L=0.36$ H
$C_0=730$ pF	$f_p=5.6$ kc
$C_N=2{,}800$ pF	$f_s=4.1$ kc

Further calculations were made and we found the calculated resonance curves as the dotted lines in Fig. 2 and 4.

III. OSCILLATION OF POTENTIAL OF NON-EARTHED NEUTRAL POINT

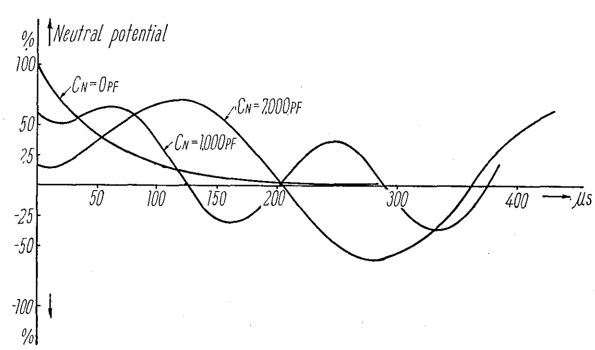

Fig. 8. Oscillation of neutral point for wave tail of 40 μs

By using above equivalent circuit, we are now able to examine the oscillation of potential of non-earthed neutral point when a transformer is attacked by a surge voltage. For this purpose, we may take Fig. 7 omitting C_0 which acts only to lengthen the incoming wave front, that is, we specify the wave shape direct at the terminal of K and L.

The potential of neutral point for a rectangular wave with endless wave tail will be

$$e_N = E\left(1 - \frac{C_N}{K+C_N}\cos\beta t\right) \cdots\cdots\cdots\cdots\cdots (5)$$

where E = magnitude of incoming wave

β = angular velocity of oscillation

when total number of coils in series is N, the potential of n-th coil from the terminal will be

$$e_n = E\left(1 - \frac{n}{N}\,\frac{C_N}{K+C_N}\cos\beta t\right) \cdots\cdots\cdots (6)$$

The length of wave tail, however, has a great influence on the potential of neutral point. If we denote the incoming wave by $E\varepsilon^{-at}$ and change the value of a, we may clearly observe its effects.

In Fig. 6, the value of current

$$i = \frac{PC(P^2LK+1)}{p^2(KL+C_NL)+1}E\varepsilon^{-at} \cdots\cdots\cdots\cdots (7)$$

and the potential of neutral point

$$e_N = \frac{1}{C_N}\int idt = \frac{i}{pC}$$

$$= \frac{p^2LK+1}{p^2(KL+C_NL)+1}E\varepsilon^{-at} \cdots\cdots\cdots\cdots (8)$$

Solving the equation, we get

$$e_N = \frac{\beta(1-\alpha^2)}{\sqrt{\alpha^2+\beta^2}}E\sin(\beta t-\theta)$$

$$+\frac{a^2\alpha^2+\beta^2}{a^2+\beta^2}E\varepsilon^{-at} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (9)$$

But here

$$\alpha^2 = \frac{K}{K+C_N} \qquad \beta^2 = \frac{1}{L(K+C_N)}$$

and $\tan^{-1}\beta/a = \theta$ ………………… (10)

β is the angular velocity of oscillation and its frequency and period of oscillation are

$$f = \frac{1}{2\pi\sqrt{L(K+C_N)}} \text{ and } T = 2\pi\sqrt{L(K+C_N)}$$

respectively.

The first term of equation (9) is a sinusoidal function which becomes maximum at $\beta t - \theta = \frac{\pi}{2}$. The second term is a exponential function just same as the incoming wave.

When $t=0$

$$e_N = \frac{\beta^2(1-\alpha^2)}{\sqrt{\alpha^2+\beta^2}}E\sin\theta + \frac{a^2\alpha^2+\beta^2}{a^2+\beta^2}E = \alpha^2 E$$

$$= \frac{K}{K+C_N}E \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (11)$$

This is the initial neutral point potential.

When $C_N=0$, then $\alpha=1$ and

$$e_N = E\varepsilon^{-at}$$

This corresponds to the perfect oscillation-free type proposed by Mr. R. Elsner. When $C_N=\infty$, then $\alpha=\beta=0$ and $e_N=0$ which means directly earthed neutral point.

When C_N is small as in the case of inverted arrangement, the amplitude of oscillation, the first time of equation (9), will be small, which is also clear in equation (5). The absolute value of neutral potential, however, being the sum of the first and second terms of (9), will also be small when C_N is large enough. This is due to that when C_N is large, the period of oscillation becomes long and at the instant when the first term reaches its maximum, the second term is already small enough.

Let us take the K and L of 45 MVA transformer in Fig. 2, that is $K=1{,}460$ pF, $L=0.3$ H and make some comparisons. Fig. 8 shows the effect of value

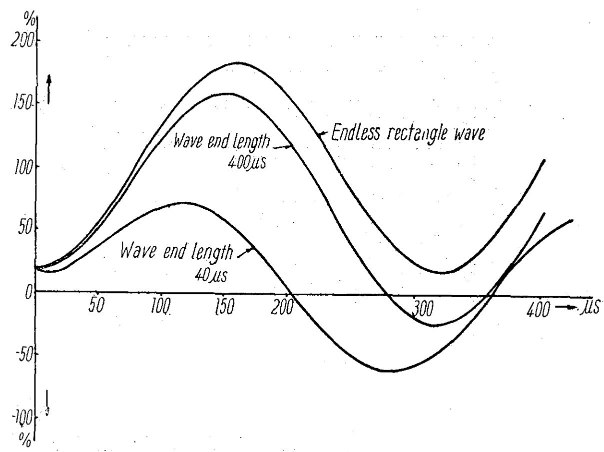

Fig. 9. Oscillation of neutral point for C_N=7,000 pF

of e_N for incoming wave with our Japanese standard wave tail length 40 μs. Here, $E\varepsilon^{-at}=0.5$ for $t=40\times10^{-6}$, that is, $a=0.0175\times10^{-6}$. $C_N=7{,}000$ pF corresponds to normal arrangement and gives $T=318$ μs. $C_N=1{,}000$ pF is for inverted arrangement and $T=173$ μs. The normal arrangement gives a little larger potential than the inverted arrangement.

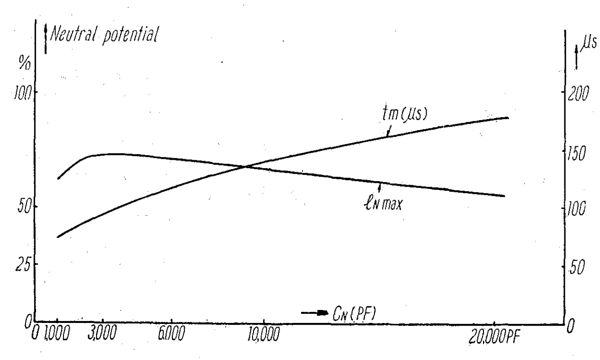

Fig. 10. Oscillation of neutral point for wave tail of 40μ

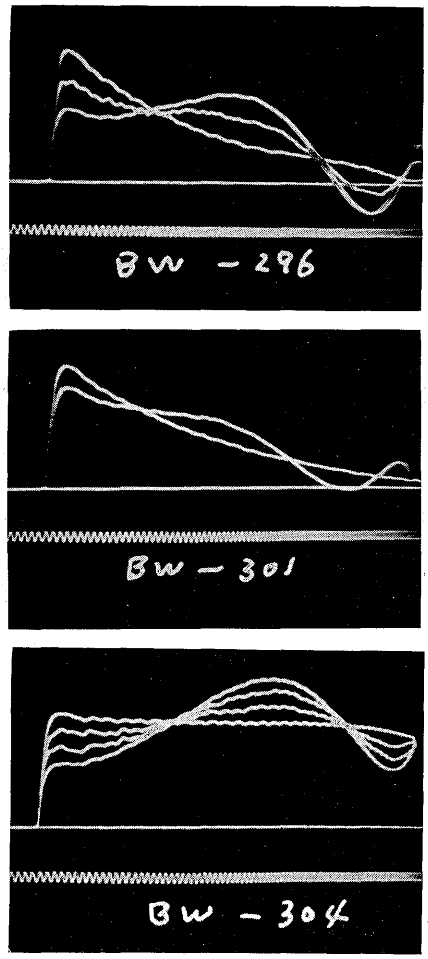

Fig. 11. Neutral point oscillations of 90/99/45 MVA transformer

Fig. 9 demonstrates the effect of wave tail length for a given $C_N=7{,}000$ pF and $T=318\ \mu$s. Wave tail lengths of 40 μs, 400 μs and infinitive correspond to $a=0.0175\times10^{-6}$, $a=0.00175\times10^{-6}$ and $a\doteq0$. The longer the wave tail length is, the larger the rise of potential.

Fig. 10 gives the maximum e_N for our standard tail length 40 μs and for various C_N ranging from 1,000 to 20,000 pF. The rise is maximum at $C_N=3{,}000$ pF.

Fig. 11, 12, and 13 illustrate some oscillographic records of internal potential distribution of cylindrical-layer windings the uppermost curve is the potential of terminal, the lowermost is that of the neutral. The timing scale is 200 kc/s. that is, 1 c/s equals to 5 μs.

The oscillograms Fig. 11 a, b and c are for 275 kV 90/99/45 MVA transformer.

For a and c, $C_N=9{,}000$ pF (normal arrangement) and wave tail 40 μs. For b, $C_N=1{,}800$ pF (inverted arrangement) and wave tail practically endless.

Fig 12 a, b and c are for 275 kV 45 MVA transformer. Here C_N normal is 7,000 pF and C_N inverted is 1,000 pF, b corresponds to inverted arrangement. In case c, the *L.T.* side is left open and as its results and because of large L (exciting impedance) and long T, no significant rise of neutral potential is observed.

Fig. 12 is for the 10 kVA magnetic model of twin-coil connection corresponding to Fig. 4. In a, c and e the *L.T.* side is short circuited and in b, d and f the same is left open.

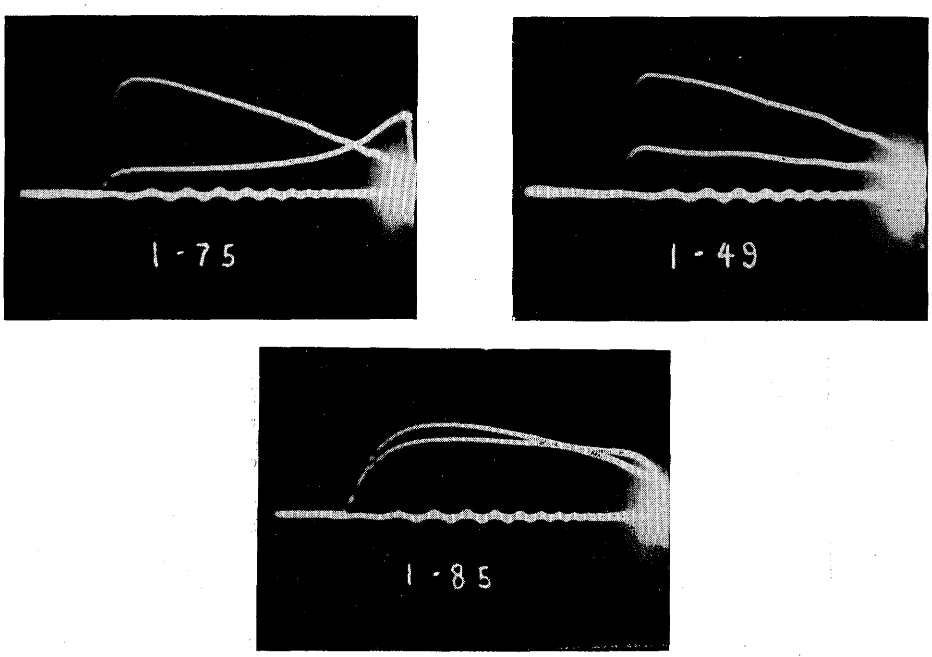

Fig. 12. Neutral point oscillations of 45 MVA transformer

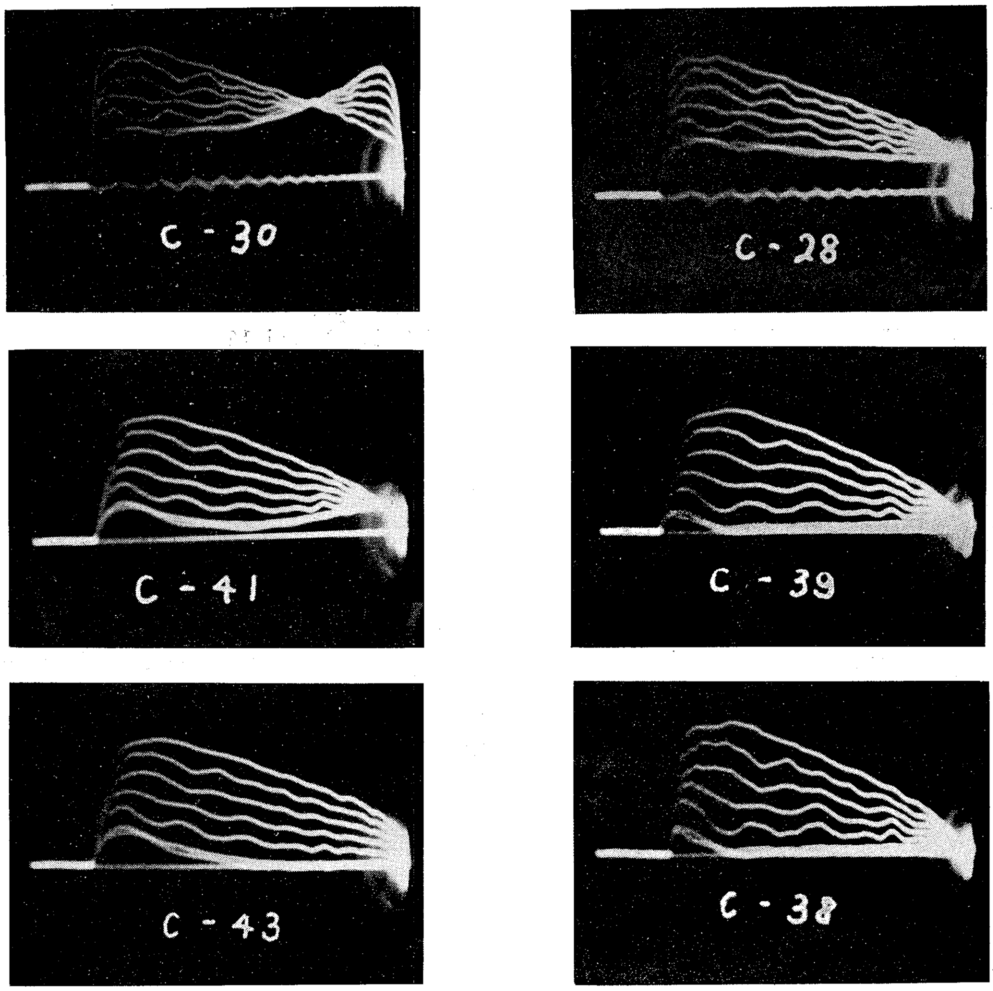

Fig. 13. Oscillations of twin-connected (Fig. 1, b) transformer

In a and b the neutral point is open, while in c and d earthed with 2,500 Ω and in e and f earthed with 500 Ω.

By observing the oscillograms, the effect of *L.T.* side winding and neutral earthing resister will be clear.

IV. COMPARISON WITH "SURGE PROOF" TRANSFORMER

The "Surge Proof" Transformer developed by W.H. Co. in U.S.A. and here in Japan manufactured by Mitsubishi Electrical Co. also consists of small number of series connected coils similar to our cylindrical-layer-winding, but when its H.T. and L.T. windings are arranged in sandwich construction, the oscillation phenomena will be somewhat different.

For example, Fig. 14 is a resonance characteristic for a 50 MVA surge-proof transformer.[10] The curve is similar to that of a ordinally disc coil transformer in Fig. 5. This is due to the distributed capacity of winding against earth.

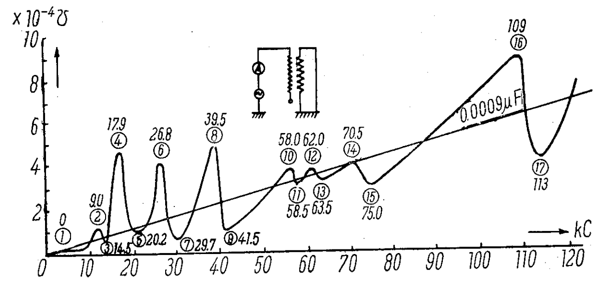

Fig. 14. Resonance characteristics of "Surge proof" transformer

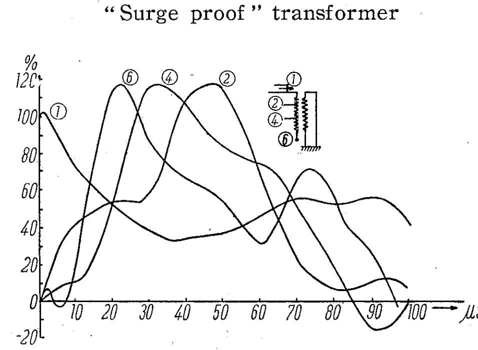

Fig. 15. Internal oscillations of "Surge proof" transformer

Fig. 15 and 16 demonstrate its internal oscillation and neutral potential. The oscillations are quite irregular and the rises of neutral potential are between 120% and 140% even if the wave tail lengths are rather short (20 μs to 40 μs)

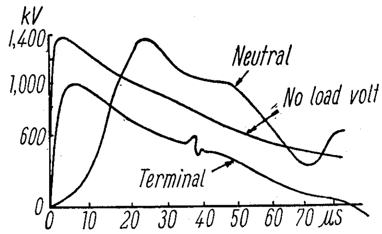

Fig. 16. Neutral oscillations of "Surge proof" transformer

V. CONCLUSIONS

For the cylindrical-layer-winding :—

1) The equivalent circuit for internal oscillation can be given by a simple circuit shown in Fig. 5. or Fig. 6.
2) The potential of non-earthed neutral point is to be calculated by equation (9).
3) The amplitude of oscillation will be small if C_N is small.
4) For incoming wave of short tail length, with increased value of C_N, the rise of neutral point potential will be decreased.
5) For $L=0.3$ H $K=1{,}460$ pF and standard wave tail length of 40μs., the rise of neutral point potential will be maximum at when $C_N=3{,}000$ pF.
6) The Oscillation of "surge proof" winding with its sandwich-like coil arrangement is quite different from those of the cylindrical layer winding.

References

1) Power Transformers with cylindrical layer-windings H. Yamamoto. Journal of E. E. of Japan. Sept. and Oct. 1955.
2) High voltage power transformer design. M.B. Mallet Trans. of A.I.E.E. vol. 62/66, 1943/47. p. 526–531/1086–1092.
3) Here's Concentric Layer G. E. Co. E. E. Mar. 1952 p. 25A–28A.
4) Forschritte im Transformatorenbau. J. Biermanns. E.T.Z. 58 Jahrg (1937) Heft 24/25 s. 660–662/687–689.
5) Zur Theorie des schwingungsfreien Drehstrom-Transformators E. Elsner Wiss V. S.W. 1938 Jan. S. 1–23.
6) Perfectly shielded oscillation-free transformer Yamamoto, Anahara. Papers for E.E. of Japan. Nov. 1952 No. 4–33.
7) Power transformers with cylindrical-layer winding. Yamamoto, Anahara Papers for E.E. of Japan. Oct, 1953 No. 4–23.
8) A new power transformer with cylindrical-layer winding H. Yamamoto. Ohm Jan. 19. p. 47–50.
9) The internal potential oscillation of power transformer. Miyamoto. Toshiba Review. Aug. 1939.
10) Impulse Test of 50 MVA Transformer Ono, Kimura. Journal of E. E. of Japan Apr. 1941.

50 c/s MAIN MOTORS FOR A. C. LOCOMOTIVES

By

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I. INTRODUCTION

In view of the brilliant success in 50∿ a.c. electrification of railways in Europe, the Japan National Railways after preparation for a few years, materialized it in 1954 with the trial run of two units of 50∿ a.c. locomotives on the Sendai-Yamagata Line. One of them was of the mercury rectifier type, and the other was of the commutator motor type. Our company co-operated in the a.c. electrification project of the National Railways by designing and manufacturing the main electric motors for the commutator motor type locomotive.

The single phase series commutator motor used as the main motor of the a.c. locomotive was the first product manufactured in Japan. Furthermore, as the main electric motor is of cardinal importance for commutator motor type locomotives, the National Railways ordered two units each from three manufactures namely Fuji, Hitachi, and Toyo to test and compare their performance. Upon receiving the order, our company made a painstaking effort in designing and manufacturing, and completed them in August, 1955 with far better successful results of the factory tests than those expected.

The first test runs were completed successfully in the fall of the same year. The following brief report is then made for the reference to those who may find it interesting.