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Author	後藤, 照彦(Goto, Teruhiko)
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A Measuring method of Dielectric Loss Angle of Electric Machines and Instruments During Actual Operation

(Received December 10, 1955)

Teruhiko Gotō*

Abstract

This report is aimed at studying the method to measure directly and continuosly the dielectric loss angle of the electrical insulations used in the electric machines and instruments during actual operation, that is to say, When the supply voltage is impressed actualy on the machines and instruments, especially when the load current is flowing trough them. [1]

The results indicate the possibility of the appearance of such a tan δ meter, which permits measurment without shutting down the mahcines and instruments or using auxil. high-voltage test equipment.

Introduction

Various studies have been devoted on a dielectric loss angle of the electrical insulations used in the electric machines and instruments during the past 20 years. Thus according to the situation, the methods of measuring tan δ of such insulations as that of the generator's coil or power cable appear to have been progressing too; for example, dynamo type tan δ meter or Schering Bridge with amplifier. Including the measuring insturments above mentioned, however, the other measuring methods such as the reactance variation method, resistance variation method, and high impedance bridge are all difficult or too incovenient to measure the tan δ of electric machines and instruments in the case of high supply voltage, because of the necessity of inserting the meter to high voltage side, especially when the load current is flowing through the machines and instruments, the meter will be structually unable to made them measurement. In order to solve these difficulties, there is an idea that the current is to be obtained indirectly from the current transformer the phase angle error of which is corrected by use of compensating winding or circuit. The current coil of the conventional tan δ meter has, however, high impedance, and so it is very undisirable to be connected with the secondary winding of the current transformer for the actual measurement. Here there are two

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* 後藤照彦 : Post-gracluate course student of Keio University

[1] M, Mori ; T, Gotô, The meeting of J, I, E, E 1952, Autum.

ways to be considered, first is using the matching transformer and the second is constructing a new type tan δ meter of very low impedance which can be connected with the current transfomer. In the first way we can not expect an ideal transformer which has no loss. Auther will take the second way though it has various problems to be solved.

The first is the problem of the design of the meter, the second is the correction of the phase angle error, the third is the current sensitivity of the meter and etc. Further, the differencial connection of the secondary windings of the two current transformers will make the measurment of the tan δ possible even when the load current is flowing the electric machines and instruments.

1. Dielectric loss factor meter with current transformer.

There are many kinds of electric machines and instruments. Here we shall present the power cable. Of course it may be the same with the other ones from the point of view of the tan δ measurement. To realize the idea about the measuring instrument of the electric loss factor of a power cable by the use of zero phase currnt transformer (Bushing type) which is usually used in actual field, for the first step, an attempt is made to reconstruct a meter which comparatively satisfies the necessary conditions. Let us reconstruct a mono-phase balance type power factor meter. The reconstructed meter can be coupled with current transformer though it is not satisfactory to be used as a fine tan δ meter. The current element of the meter is 0.03 ohm in impedance. As regards the two voltage elements, the series resistance inserted to the same-phase voltage element was made to be 1000 ohm in value and the capacitance inserted to the right-angle-phase voltage element was increased to $0.5\,\mu F$. As the result, the ratio of the ampere in each coil turned out to be about 15 at 50 cycle for conpensating the shortage of the sensitivity at the time when a power factor meter is used as a tan δ meter. The full scale is divided equally from 0 to 40 and is adjusted by a conventional tan δ meter. The test was to determine whether the method utilizing the current transformer to measure the dielectric loss angle is possible or not with the zero phase current transformer (Bushing type) tendered by the Engeneering Department of Tokyo Electric Power Co.. The charactristics of the current transformer is as follows.

type : F-64c
Zero phase primary current : 02A; secondary 0.002A
3400V400A, made by Shibaura in 1938.

Primary current	1A	2A	3A	4A	5A
Secondary current	25mA	50mA	95mA	95mA	115mA
Secondary open voltage	0.24V	0.6V	0.9V	1.4V	1.81V

remarks : mA meter burden.

In the case of measuring the dielectric loss factor of a power cable, it is an important problem whether the secondary winding is to be utilized as a voltage element or current element. To answer the problem, the relation between the primary current vector and secondary voltage vector may be considered, while the relation between primary current vector may be considered too.

It means that the phase angle between both vectors and the variation of the phase angle due to the change of the primay current are to be taken into consideration.

Speaking about the degree change of the phase angle, the smaller the better. Fig. 1_A and 1_B show the case of using single-phase power factor meter to measure the power factor of a resistance circuit. In Fig. 1_A the current coil of the meter is used as a voltage element and the voltage coil is used as a current coil. The phase angle between the primary current and the secondary voltage changes from 99. 8% to under 50% when the primary current varies from 1A to 5A.

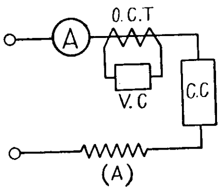

Fig. 1_A.

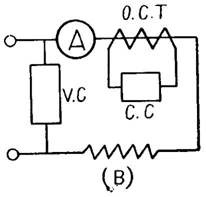

Fig 1_B.

primary current	1A	2A	3A
power factor (%)	99. 8	69. 8	under 50

remarks : high impedance burden

The change of the power factor is due to the increase of the exciting current of the current transformer. In the case of Fig. 1_B the secondary winding of the transformer is burdened with the current coil of the power factor meter (impedance 0. 14), and there is almost no change in the power factor as follows

primary current	1A	3A	5A
power factor (%)	99. 2	99. 2	99. 2

remarks : low impedance burden (0. 14)

This means that there is no visible change in the phase angle between primary current and secondary current, that is to say, the exciting current is very small.

The phase angle changes when a series resistance (1 ohm) is connected to the current coil circuit to check the consideration above mentioned.

primary current	1A	3A	5A
power factor	99. 2%	98. 6%	98. 5%

remarks : 1 ohm burden

Thus we find it desirable that the impedance of the current coil of the meter is to be under 0.1 ohm.

2. The compensation of the phase angle of the ring type current transformer.

Generally speaking the actual current transformers do not comform to ideal.

This is due to the fact that that the magnetizing and iron loss ampere-turns required to maintain the flux in the core to induce e. m. f. needed the sedondary current through total impedance of the secondary circuit subtract vectorially from the primary imput ampere turns. The flux length of the ring type current transformer used in this experiment is 424mm and its cross section is as shown diagramatically in Fig. 2 The exciting winding (secondary winding) has 37 turns, while third winding *A*. *B*. *C* and *D* have 10 turns each connected in parallel, and the forth (*E*) has 40 turns to compensate the phase angle error and to make up for the undesirable charactristics by feeding corrective ampere-turns. Fig. 3 shows diagramatically the principle of compensating the phase angle error between the primary current and the secondary current. In this case, the secondary winding (37 turns) is used for compensating winding. θ_1 represents the phase difference between primary current I_1' and secondary current I_2' which is leading to I_1'. The reason is, as we know, due to magnetizing and hysterisis loss. Now consider the third current I_2'' flowing through the compensating circuit. We find that $-nI_2$ is the primary conversion value of I_2 which is the resultant vector of I_2' and I_2'', and then I_1 in the primary resultant current. Comparing with the case without I_2'', θ changes to θ_1, while phase angle between I_2 and I_2' is φ, thus the actual primary current becomes in phase with I_2' when the relation $\theta=\varphi$ is adjusted. I_2' is used for current element of the new type tan δ meter, (reconstructed power factor meter with *C. T.*), and is 0.2A in magnitude at primary current of 3 ampere. I_2'' is the current flowing through the third winding which has in series a capacitance and a resistance for adjusting. The phase angles θ_1 and θ_2 generally decrease in the low current range of the current transformer accorcing to the increasing of the exciting current I_0, hysterisis angle r and primary I_1' while θ is itself very small

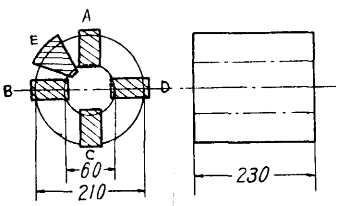

Fig. 2 dimemsions of ring type (Bushing type) cuurent transformer.

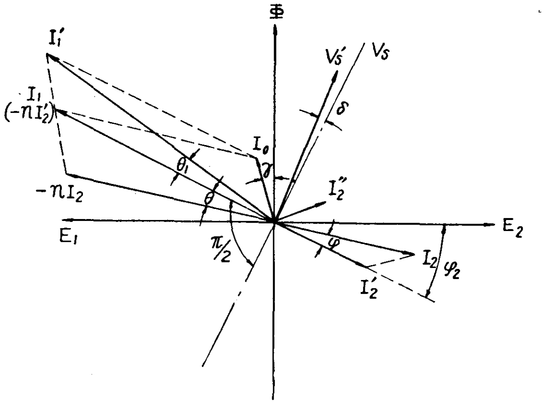

Fig. 3 vector diagram of compensating phase error.

angle and so the magnitude and angle of I_2'' is small too. (Fig. 4) Fig. 5 represents the diagram of correcting the power factor meter utilizing current fransformer by a conventional tan δ meter which has high impedance current coil. VC_1 and CC_1 each indicates the voltage coil and current coil of the tan δ meter, while VC_2 and CC_2 each indicates the same coil of the new type dielectric loss factor meter with current transformer. In Fig. 5, CC_1 and CC_2 are first connected to each other in a series circuit to be adjusted (the position is shown by dotted line). The adjustment of δ angle is easily possible by controling the variable l_1 and R_o to obtain the given tan δ value. In Fig. 3 let I_1 be a current flowing through the circuit constructed with series capacitance, resistance and the test piece, while V_s' is an impressing voltage to the test piece. Then the angle between vector V_s' and V_s that is at right angle to I_1 is the angle δ of tan δ. The setting of V_s' to V_s is possible by controling l_1 in Fig. 5 Thus the correcting curve from tan $\delta=0$ to 30% is obtained as shown in Fig. 6 curve a represents a corrective curve at constant primary current of 3 amperes. Curve b shows the same corective curve in the case of using current transformer, when the adjustment of phase error is tried by means of third winding on the current transformer. The secondary current is about 200mA. Generally speaking, curve a and b should theoriticaly coinside to each other. The difference in Fig. 6 is due to the fact that the reconstructed new type tan δ meter had the poor torque for the mechanism, thus causing errors owing to the friction loss and etc.. This is, however, not obstacle to actual measurment. Fig. 7 represents the relation between primary current and adjusting resistance in the case that each primary current is kept in phase with

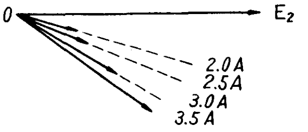

Fig. 4 chang of I''_2

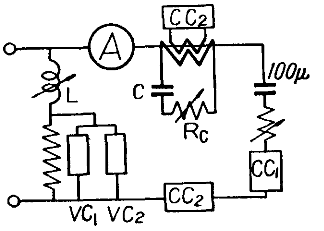

Fig. 5 calibration of new type tan δ meter (reconstructed power factor meter coupled with C. T.)

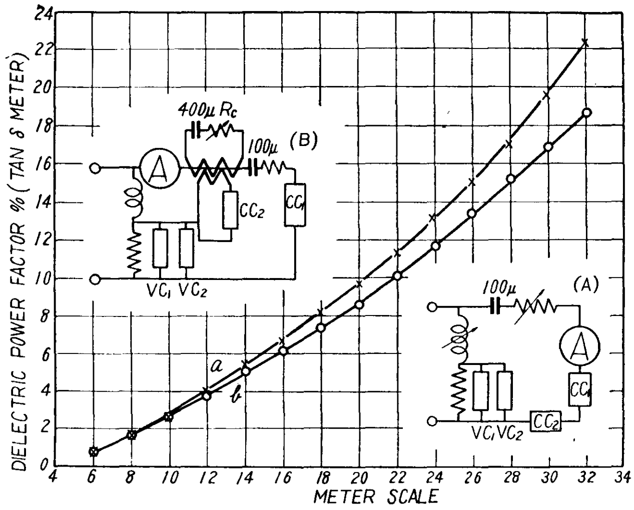

Fig. 6 calibration curve of new type tan δ meter utilizing current transformer

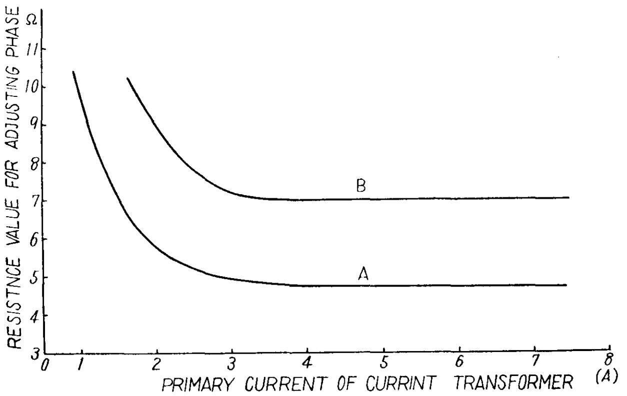

Fig. 7 reration betwen resistance of adjuster and primary current of current transformer

the secondary current by controling the variable resistance R_c which is in series with the capacitance in the third winding circuit. Curve B indicates the case when the charactristics of the same current transformer are in good condition, excited by the direct current flowing through the forth winding.

3. On the several errors of the Bushing-type current transformer.

Now we may look for several points in relation to designing a transformer for the purpose of tan δ measuring. We shall look for them from the point of view of errors.

We know the following approximate general expression

$$B = K \times \text{(ampere-turns per cm)}^n \tag{1}$$

The ampere-turns per cm include both the pure magnetizing and iron-loss components. n is the constant number related to the material of core.

If a number of magnetizing ampere-truns T through core is given

$$\text{ampere-turns per cm at radius } r = \frac{T}{2\pi r}$$

The flux density B at radius r. From (1)

$$Br = K\left(\frac{T}{2\pi r}\right)^n \tag{2}$$

When the size of the core is decided

$$Br \propto r^{-n} \tag{3}$$

n is the constant number decided by the kinds of the material of the core.

We know n is 5/3 for Stalloy and 5/4 for Mumetal.[2]

Next We may consider a transformer which has the fixed inside and outside diameters, while the length L is variable. If the total flux is given, the flux density is inversely proportional to the axial length

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(2 A. Hobson Instrnment transformers J. I. E. E. 1944.

$$B \infty \frac{1}{L} \qquad \text{Here from (1)}$$

$$\text{Ampere-turns per cm} \infty B^{\frac{1}{n}}$$

or $$\text{Ampere-turns per cm} \infty L^{-\frac{1}{n}}$$

As the core diameters are fixed, the length of the magnetic path is also fixed

$$\text{Total magnetizing ampere-turns} \infty L^{-\frac{1}{n}} \quad \cdots\cdots (4)$$

The total number of magnetizing ampere-turns represents the overall error of the transformer (vector sum of the ratio and phase angle errors). This gives the relation between transformer error and axial length of core when the core diameter remains constant. Next, the relation between the error and outside diameter of the core may be discussed as follows.

symbols ; L : core length (effective value)
T : total magnetizing turns
R_i : inside radius
R_o : outside radius

The flux density at radius r cm is obtained from (1)

$$Br = K\left(\frac{T}{2\pi r}\right)^n$$

The total flux ϕ in the core is $\varphi = L\int_{R_i}^{R_o} Brdr = \frac{LKT^n}{2^n \pi^n}\int_{R_i}^{R_o} r^{-n}dr$

For a core with given axial length, inside radius and material

$$\Phi = T^n\left(\frac{k^{n-1}-1}{k^{n-1}}\right) \qquad \left[k = \frac{R_o}{R_i}\right] \quad \cdots\cdots (5)$$

This turns to

$$T \infty \Phi^{\frac{1}{n}}\left(\frac{k^{n-1}}{k^{n-1}-1}\right)^{\frac{1}{n}}$$

When the total flux is fixed

$$T \infty \frac{k^{(n-1)/n}}{(k^{n-1}-1)^{\frac{1}{n}}} \quad \cdots\cdots (6)$$

T shows the transformer error in regard to the ratio k.

Due to the relations form (1) to (6) we can calculate the charactristics or performance curve of a given transformer, and further may design transformer with low error to be connected to the reconstructed new type dielectric loss angle meter previously mentioned.

The value of the phase adjusting resistance changes according to the primary current as shown in Fig. 7 And so, it is necessary to graduate the value of the phase adjusting resistance. On the one hand, it is necessary also to know the value of primary current before the actual measrement of the tan δ.

The primary current is measured easily by a current transformer, and the current transformer just used in this method is applied to the purpose. The problem of error appears at about 2 or 3 amperes at which the value of the phase adjusting resistance changes considerably. When tan δ =10% is measured at primary current of 2.5 amperes, that is to say, the supplemantal resistance is set to 2.5A,if the primary current changes to 2A or 3A for some reasons, the error appears as shown in Table 1. The degree change of the current −20% or +15% means at once the same change of the impressing voltage. As the result+8% or −4% error appears. Such voltage changing degree, however, may be considered the maximum limit possible in actual cases.

primary current	2.0A	2.5A	3.0A
variation of primary current	-20%	0	+20%
tan δ on scals	10.8%	10%	9.6%
error	+8%	0	-4 %

Table 1

primary current	2A	2.5A	3.0A	3.5A	3.9A
variation of primary current	-21%	-17 %	0	+17 %	+30%
tan δ on scale (%)	10.2	10.2	10	9.6	9.5

Table 2

The method of setting the fourth winding on the current transformer is used to correct the error. A test case with a direct current exciting the current transformer and the magnetizing ampere-turn of 0.25A—40 *T* causes the result as shown in Table 2.

4. The inductive impediment due to the external electric current.

Generally speaking the magnetic flux density of the current transformer is very low and as the result the charactristics of the current transformer may be disturbed by the residual magnetic flux or other external flux. The following experiment was tried on the effects of the residual magnetic flux. The tan δ measurment was made at primary current of 3A after the over current of 50A or 200A was forced during 1 second through the primary conductor (1 turn) of the current transformer.

The result is shown in Table 3 in which the alternating current of 200 amperes makes a few effects on the actual tan δ value, from 6% to 7% (table 3.). Next, the effect of the inductive disturbance due to the alternating current through a conductor parallel to the primary winding (1 turn) at the distance of 18cm from the center axis of the current transformer is examined. As shown in Table 4, a considerable effect appears proving it is necessary to apply sufficients shielding.

current and time	befote	after	variation
50A, one second	5%	5 %	0
200A, one second (the first time)	5%	5.3 %	6%
200A, one second (the second time)	5%	5.35%	7%

Table 3 disturbance by residual magnetism

inpediment current	0A	2.4A	3.4A	4.5A	6.6A	9.0A
tan δ	4.7%	4.9%	5.1%	5.3%	5.8%	6.4%

Table 4 Inductive disturbance by external current

As the result the appearance of a new type tan δ meter for the power cable or generator winding is possible if the design is suitable. And such new type meter will be used in actual field if attention is paied to the following points : suitable magnetic flux density, negligible effect of the residual magnetic flux and complete shielding to protect the inductive disturb are due to other electric currents near by.

5. The measurement of the dielectric loss factor of the live power cable.

Now we shall consider the possibility of the measurement of the tan δ of a power cable through which the load current is flowing actually. The differential connection of the second windings of the two current transformers which have the same charactristics may give answer to the problem.

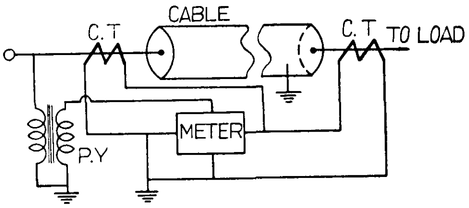

Fig. 8 diagram of measurement of tan δ in actual case

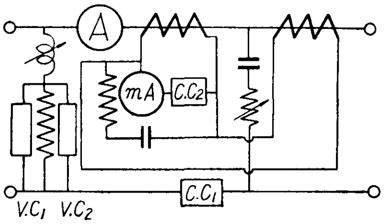

Fig. 9 calibration diagram of new type tan δ meter

The diagram is shown in Fig. 8 The two current transformers used in our laboratory are the wound type ones with the same charactristics 15VA, 100A, 3KV. The experiment was done as shown in Fig. 9, which shows the method of adjusting the new type tan δ meter (reconstructed power factor meter) with a conventional tan δ meter after the primary current of the current transformer is set to be in phase with the secondary current. The principle was already mentioned in § 2. In this case, however, the secondary windings are regarded as the burden to each other besides the current coil of the new type reconstructed tan δ meter. One current transformer is excited by the other one, and the vector diagram is as shown in Fig. 10 I_2 represents the current in the burden, the current coil of the meter. I_{02} is the secondary burden current in the other current transformer. Thus the primary conversion value $-nI_2$ of the resultant I_2' is composed of the exciting current vector I_{01} to produce the resultant vector I_1' . φ_{12}' is the phase angle between I_1' and I_2 , which is exceeding to φ_{12} the phase angle between I_1'. Vector I_{02} causes φ_{12}' to increase compared with φ_{12}. Now, secondary phase correcting current I_{2c}'' is to get the secondary resultant vector I_2''. I_1'' is the resultant vector of I_{01} and $-nI_2''$ which is the primary conversion value of I_2''. We find it is necessary that I_1'' is in phase with I_2. After such adjustment the new type reconstructed $\tan\delta$ meter is corrected with the usual $\tan\delta$ meter as shown in Fig. 9. Fig. 11 represents the result. The difference of both curve is due to the same reason as that in Fig. 6.

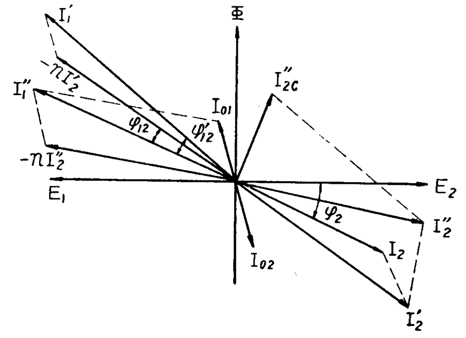

Fig. 10 adjustment of phase angle between primary current and secondary one

Auther questioned that both the current transformers have the same charactristics, but are they quite the same to each other? The actual unbalanced current is detected when the two secondary windings are differencialy connected and the load current is flowing. It is found that even the primary current of 100A induces only 5mA or less in the secondary differencial circuit and scarcely affects the actual measurement.

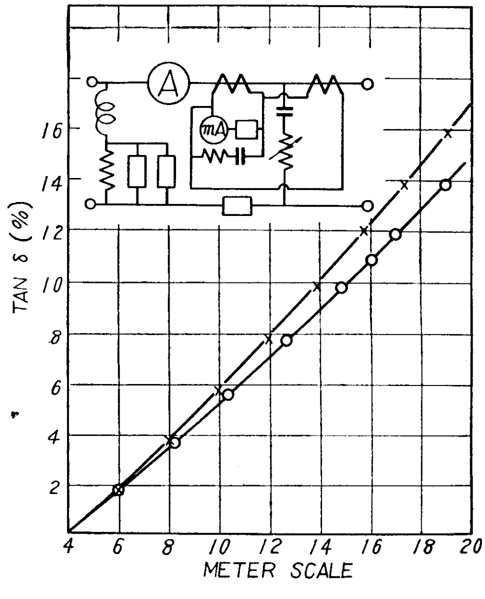

Fig. 11 calibration curve of new type $\tan\delta$ meter (primary current : 5A)

6. The practical application

The result of the investigation in the labolatory were applied in the actual field, Oshima Substation and Konuma Sbustation of Tokyo Electric power Co.. The main parts used in Oshima Substation were as follow.

Test power cable : Sunamachi No. 1 line
20KV, 100mm belt cable
C. T Wound type, 40VA, 15A/5A, 50

C. T	ring type 1A/0.02A secondary 49 turns
P. T	2000V/11000V/110V 50∞ KB/2 type

First, the preparatory test was held on the new type reconstructed tan δ meter using wound type current transformer. The current sensitivity was min. 50mA.

The adjusting method is as has been previously mentioned. In this case, it is important to check the actual charging current. Table 5 represents the correction table of the new type reconstructed tan δ meter at primary current of 1.7A. The survey diagram is shown in Fig. 12. To our regret, we did not measure tan.δ of the cable through which the load current was flowing, for it would have had little value with no chance to compare with the other methods that were unable to measure the tan δ when the current was flowing.

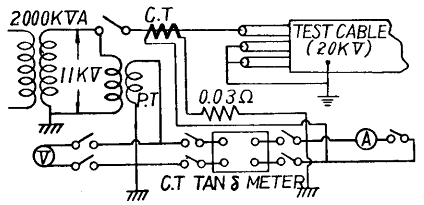

Fig. 12 actual survey diagram by new tyye tan δ meter utilizing wound type current transformer

Anyhow, the tan δ of the actual test cable was measured without the load current just after the cable was warmed up to 40C° by the heating due to the copper loss supply. The result is represented in Table 6. We know that the tan δ value decreased with the cooling of the cable. These tan δ values were found to be between the values measured by Schering bridge method and tan δ meter method at the same time. We tried

scale	4	5.8	7.1	8.3	9.3	11.2	12.6	15.0
tan δ value	0	0.5	1.0	1.5	2	3	4	5

Table 5 Meter correction (at 1.7A)

time	interval	voltage	charging current	tan δ	freqency
1st		11.2KV	1.72A	1.1 %	48 cycles
2nd	11 minutes	11.0KV	1.72A	0.96%	48 〃
3rd	6 minutes	11.0KV	1.72A	0.82%	48 〃
4th	22 minutes	11.0KV	1.68A	0.74%	48 〃
5th	38 minutes	11.6KV	1.86A	0.66%	48 〃
6th	33 minutes	10.4KV	1.68A	0.78%	48 〃
7th	9 minutes	10.4KV	1.68A	0,78%	48 〃
8th	73 minutes	11.0KV	1.72A	0.78%	47.5 〃
9th	37 minutes	11.0KV	1.72A	0.74%	48 〃

Table 6 tan δ measurement by new type tan δ meter utilizing wound type current transformer (sunamachi No. 1 Line, black phase)

a survey of the tan δ of an actual cable by the new type reconstructed tan δ meter utilizing a ring type current transformer at Konuma Substation of Tokyo Electric Co. The test cable is Konuma 22KV No. 4 line which runs from Konuma to Higashi-oku a distance of about 2.3km. The connection diagram is shown in Fgi. 13 The main parts used in the survey were the following.

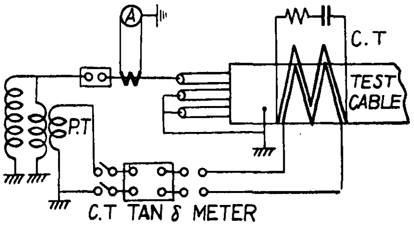

Fig. 13 actual survey diagram by new tan δ meter utilizing ring type C. T.

P. T. a special type voltage-current-transformer 100VA
primary voltage 22000V secondary voltage 110V
Z. C. T. diameter 100mm, ratio 100 : 1, insulating voltage 25KV

The new type tanδ meter utilizing ring-type current transformer was adjusted at primary current of 3.5A that is the same as the actual charging current at the supressing voltage 14KV. The result is shown in Table 7. These values were a little larger than the values obtained by Schering Bridge though the difference is rather small. This problem, however, will be solved by finer construction.

phase	voltage	tan δ
lst phase	14KV	1.2 %
2nd phase	14KV	1.35%
3rd phase	14KV	1.54%

Table 7 tan δ measurement at Konuma (No. 4 Line)

If the meter was designed to work at 25mA, we should have the same result as that of wound type current transformar.

Conclusion

Judging from the results of the study in the laboratory and the surveys in the actual field, it has been determined that a tan δ meter can be constructed to measure the tan δ of a power cable or windings in an electric machine when the supply voltage is supressing or the load current is flowing. We are to study the design of such a meter with higher current sensitivity and its application to the generator's windings and etc.,

Acknowledgement

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