MEASUREMENT OF LOAD LOSSES OF THREE-WINDING TRANSFORMERS

By

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I. INTRODUCTION

To determine load losses fit for specified load conditions in three-winding transformers, special method of measurement must be employed. For instance, when a certain load is connected the terminals of the secondary and tertiary windings respectively and voltage of rated frequency is impressed on the primary so that its rated current flows there, adjust these loads so that the secondary and tertiary currents become the rated values. Then reduct the secondary and tertiary outputs from the input, terming the balance the load losses of the transformer. Such a method may come in mind first, but it is generally difficult to obtain the load to suit the purpose. The one to be stated herein is not all new and studies have been made on the method mentioned in the JEC-120 (Standards of the Japanese Electrotechnical Committe — Standards for Stationary Induction Apparatus) to point out its defects and amend it.

The details are mentioned hereunder to wait for the comment of readers.

II. MEASUREMENT OF LOAD LOSSES OF THREE-WINDING TRANSFORMER

1. Investigation of the old method

The measurement of load losses of three winding transformers according to the JEC-120 is made in general as follows. Let *Vps*, *Vpt* and *Vst* be the load losses obtained respectively from short circuit tests between the primary and the secondary, between the primary and the tertiary and between the secondary and the tertiary. Then let A. B and C available from the following equation be the losses of the primary, the secondary and the tertiary windings. (To make the matter simple, convert them into the capacity of each winding and omit the temperature conversion.)

$$\left.\begin{aligned} \frac{V_{ps}+V_{pt}-V_{st}}{2} &\equiv A \\ \frac{V_{ps}+V_{st}-V_{pt}}{2} &\equiv B \\ \frac{V_{ps}+V_{st}-V_{ps}}{2} &\equiv C \end{aligned}\right\} \cdots\cdots\cdots\cdots\cdots\cdots\cdots(1)$$

This method is simple but further consideration reveals that A, B and C are not the load losses of the windings.

In concentric winding transformers, the distribution of leakage flux density during the short circuit test is, as a well known fact, shown in Fig. 1–3. (It is needless to mention that there is leakage magnetic flux in a radial direction due to the strengthening of the coil terminal and the provision of taps, but the design must be made to make this as small as possible. In reality, the leakage magnetic flux in the radial direction is omitted because of its small value.) When the load losses of the primary, secondary and tertiary windings due to the triangle magnetic flux distribution as shown in Figs. 1 and 3 are denoted V_p, V_s and V_t by taking the primary as a fundamental kVA, eddy cur-

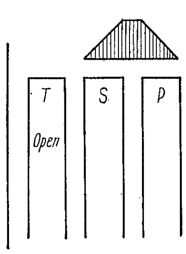

Fig. 1. Flux density distribution at T'ry open.

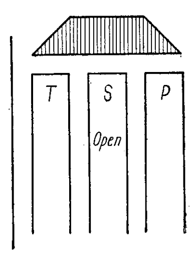

Fig. 2. Flux density distribution at S'ry open

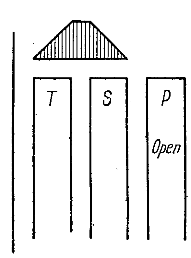

Fig. 3. Flux density distribution at P'ry open

rent loss σ in the secondary winding due to the magnetic flux distribution as in Fig. 2 is included in V_{pt} measured between the primary and tertiary in addition to V_p and V_t. Therefore Equation (1) is rearranged as follows.

$$\left.\begin{aligned}
&\frac{V_{ps}+V_{pt}-V_{st}}{2}\\
&=\frac{(V_p+V_s)+(V_p+\sigma+V_t)-(V_s+V_t)}{2}\\
&=V_p+\frac{\sigma}{2}\equiv A\\
&\frac{V_{ps}+V_{st}-V_{ps}}{2}\\
&=\frac{(V_p+V_s)+(V_s+V_t)-(V_p+\sigma+V_t)}{2}\\
&=V_s-\frac{\sigma}{2}\equiv B\\
&\frac{V_{pt}+V_{st}-V_{ps}}{2}\\
&=\frac{(V_p+\sigma+V_t)+(V_s+V_t)-(V_p+V_s)}{2}\\
&=V_t+\frac{\sigma}{2}\equiv C
\end{aligned}\right\}\quad(2)$$

As will be seen clearly in Equation (2), A, B and C are not the load losses of each coil. The load losses V_p, V_s and V_t are to be available from Equation (3).

$$\left.\begin{aligned}
V_p&=A-\frac{\sigma}{2}\\
V_s&=B+\frac{\sigma}{2}\\
V_t&=C-\frac{\sigma}{2}
\end{aligned}\right\}\quad\cdots\cdots\cdots\cdots\cdots\cdots(3)$$

For the reader's information, it is to be pointed out that an example of calculation in the JEC-120 involves an inconsistency of the load loss of the secondary winding being smaller than the resistance loss. That is, the impedance wattage of the secondary 20 MVA at 75°C is 0.144 %, whereas the resistance loss is 0.169 %, the former being thus smaller. This is caused by the fact that the load loss of the secondary is considered to be smaller by $\frac{\sigma}{2}$ according to the foregoing Equation (2) and those of the primary and tertiary larger by $\frac{\sigma}{2}$.

2. Amendment of Old Measurement

As the load loss of each winding is to be available from Equation (3) as stated in the above, it is satisfactory if $\frac{\sigma}{2}$ is obtained. This $\frac{\sigma}{2}$ is to be obtained with ease as follows.

Let eddy current loss of the secondary winding due to the triangle magnetic flux density as shown in Figs. 1 and 3 be denoted by σ_2, and due to the equal magnetic flux density as shown in Fig. 2 by σ. Then in general

$$\sigma \fallingdotseq 3\sigma_2 \cdots\cdots\cdots\cdots\cdots\cdots(4)$$

is available. (Refer to the appendix.)

When secondary loss taking the primary as foundamental kVA is denoted by W_2

$$V_s=W_2+\sigma_2 \cdots\cdots\cdots\cdots\cdots\cdots(5)$$

From Equation (3)~(5)

$$B+\frac{\sigma}{2}=W_2+\frac{\sigma}{3}$$

$$\therefore\quad \frac{\sigma}{6}=(W_2-B) \quad\cdots\cdots\cdots\cdots(6)$$

Thus σ is available from Equation (6). This is substituted in Equation (3),

$$\left.\begin{aligned}
V_p&=A-3(W_2-B)\\
V_s&=B+3(W_2-B)\\
V_t&=C-3(W_3-B)
\end{aligned}\right\}\cdots\cdots\cdots\cdots(7)$$

Then the load loss of each coil is obtained.

3. Examples of Calculation

According the foregoing method, the previous example, the load loss of (20/22/10 MVA), is calculated for trial.

Percent impedance wattages of 20,000 kVA at 9°C are given that $V_{ps}=0.428$ %, $V_{pt}=0.708$ % and $V_{st}=0.480$%.

From these

$$A=\frac{0.428+0.708-0.480}{2}=0.328\%$$

$$B=\frac{0.428-0.480-0.780}{2}=0.100\%$$

$$C=\frac{0.708+0.480-0.428}{2}=0.380\%$$

On the other hand, resistance losses in 20,000 kVA calculated from the resistance at 9°C are; the primary is 0.134%, the secondary 0.133% and the tertiary 0.264%.

From Equation (6)

$$\frac{\sigma}{2}=3\times(0.133-0.100)=0.099\%$$

From Equation (3)

$$V_p=0.328-0.099=0.229\%$$
$$V_s=0.100+0.099=0.199\%$$
$$V_t=0.380-0.099=0.281\%$$

If these impedance wattages are converted at the case of 75°C, from $\frac{234.5+75}{234.5+9}=1.27$

The primary impedance wattage
$=0.134\times1.27+(0.229-0.134)/1.27$
$=0.170+0.075=0.245\%$

The secondary impedance wattage
$=0.133\times1.27+(0.199-0.133)/1.27$
$=0.169+0.052=0.221\%$

The tertiary impedance wattage

$$=0.264\times1.27+(0.281-0.264)/1.27$$
$$=0.335+0.014=0.349\ \%$$

If these values are converted into the capacities of winding, that of the primary is 0.245%, the secondary 0.243 % and the tertiary 0.174%.

Hence, the load losses at 75°C are given as follows.

The primary	For Reference Resistance loss	According to the JEC method
$20{,}000\times0.245\times\frac{1}{100}=49$ kW	34 kW	64,6 kW
The Secondary		
$22{,}000\times0.243\times\frac{1}{100}=53.5$ kW	40.8 kW	34.5 kW
The tertiary		
$10{,}000\times0.174\times\frac{1}{100}=17.4$ kW	16.8 kW	21.3 kW

As will be found, the calculation according to this method involves no inconsistency that the load loss of the secondary winding becomes smaller than resistance loss.

Furthermore, the comparison made on several actual examples between the load losses based on the above method and those on the old method (according to the JEC) are given in the following table.

Capacity M.VA			Load Losses (kW) by Foregoing method			Resistance Losses (kW)			Load Losses (kW) by old method (JEC–120)		
P'ry	S'ry	T'ry	P'ry	S'ry	T'ry	P'ry	S'ry	T'ry	P'ry	S'ry	T'ry
60	66	30	135.1	105.2	31.9	103	95.5	28	147	90.8	34.9
50	40	10	120	66.3	9.8	77.3	49.6	9.3	159	41.4	11.3
30	33	15	84.2	75.2	16.9	73.0	63.4	15.8	102.5	56	21.4
30	33	15	107.6	86.6	19.6	89.6	82.0	17.6	113.3	79.7	21.0
13.33	18	13.33	62.9	58.1	33.3	50.5	53.5	30.8	66.8	50.9	37.2
20	20	10	72	51.0	20.5	61.2	46.2	18.2	79.2	43.9	22.3
20	22	10	61.1	48.3	11.1	42.8	43.3	9.9	67.3	40.8	12.7

4. Load Losses in Actual Operating Conditions

As mentioned above, if the load losses seperated for each windings according to the JEC method are given amendments as A, B and C, the inconsistency of the secondary load loss being smaller than the resistance loss is annuled. But the load losses of all the windings obtained by such amendment are not to be regarded as these of actual operation. For instance, in three-winding transformers of which the secondary and tertiary take loads of the same phase, there is a relation that (primary input)=(secondary output)+(testiary output) and the leakage-magnetic-flux distribution of all windings in operation clearly becomes as shown in Fig. 5.

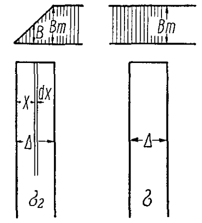

Fig. 4. Eddy current loss in conductors due to leakage flux.

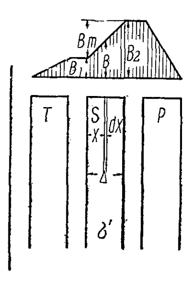

Fig. 5. Flux density distribution at 3 winding operation

In **2**, it was considered that the load loss V_s of the secondary included eddy current loss σ_2 due to the triangle magnetic flux distribution as shown in Fig. 1 or Fig. 3. But in this case it must include eddy current loss σ' produced by the trapezoid magnetic flux distribution as illustrated in Fig. 4.

Let the ratio of capacity of windings be

Primary : Secondary : Tertiary $=1:m:n$

and the losses of the windings be V_1, V_2 and V_3. Then V_2 only differs from the case of **2**, that is

$$V_2=m^2W_2+\sigma' \quad\cdots\cdots(8)$$

Further, between σ' and σ_2 is the relation shown in Equation (9) (The proof for Equation (9) is given in the appendix.)

$$\sigma'\fallingdotseq(m^2+3n^2+3mn)\sigma_2 \quad\cdots\cdots(9)$$

From Equations (4), (6), (8) and (9)

$$V_2=m^2\left(B+\frac{\sigma}{6}\right)+\frac{\alpha}{3}(m^2+3n^2+3mn)$$
$$=m^2B+(3m^2+6n^2+mn)(W_2-B)\quad\cdots(10)$$

Since the primary and secondary are regarded as in the same way as Equation (7), (Equation (7) is based on taking the primary kVA as fundamental.), from Equations (7) and (10)

$$\left.\begin{aligned}V_1&=V_p=A-3(W_2-B)\\V_2&=m^2\left\{B+3\left(1+2\frac{n^2}{m^2}+2\frac{n}{m}\right)(W_2-B)\right\}\\V_3&=n^2V_t=n^2\left\{C-3\,(W_2-B)\right\}\end{aligned}\right\}\cdots(11)$$

III. CONCLUSION

As for the measurement of load losses of three-winding transformers, there is a special notice in the preface to the JEC-120, 1952 or its predecessor JEC-36, Feb. 1934 that "The method to be described below differs somewhat from the actual conditions, but as no other proper method is available, this method is recommonded as a matter of convenience. It will be understood from this that the method is the result of thorough discussions.

The method given by the writer does not necessarily coincide with the actual conditions. It is, however, considered this new method goes toward the actual conditions somewhat by solving the problem of inconsistency that the secondary load loss becomes smaller than the resistance loss in case the JEC method is adopted. Particularly when the secondary and the tertiary are in the same phase as in Equation (11), the result are thought to be almost equal to the actual conditions. When leading load is born by the tertiary, the state of magnetic flux distribution changes with time in the actual case, which must be taken into consideration, necessitating further studies.

Even in the case of the JEC method, there is seldom a case when the secondary load loss becomes smaller than the resistance loss. This is caused by either the effect of magnetic flux in the radial direction or that of eddy current loss being relatively large. It is unquestionable that Equation (6) is not realized in this case.

The foregoing is writer's opinion on the measurement of three-winding transformers and he will be very glad if any comments and advices are given by the readers on this matter.

APPENDIX

Proof for Equations (4) and (9)

Assume that trapezoid magnetic fluxes B, B_2 pass through a rectangular conductor a b as shown in Fig. 1′, where the magnetic flux is sinusoidal and B_1 and B_2 are the maximum values. Let eddy current density at the position X be i_1 and ρ be specific resistance of copper.

$$\frac{\partial i_1}{\partial x}dx\rho=-\frac{\partial B}{\partial t}dx$$
$$=-\omega\left(B_1+\frac{B_2-B_1}{a}x\right)\cos\omega t$$

From this

$$i_1\rho=c_1-\omega\left(B_1x+\frac{B_2-B_1}{2a}x^2\right)\cos\omega t\quad\cdots(1)'$$

If c_1 is obtained from a condition

$$\int_0^a i_1dx=0$$

and an effective value j_1 is substituted to i_1, Equation (1)′ becomes

$$j_1=\frac{\omega}{\sqrt{2}\,\rho}\left(\frac{B_2-2B_1}{6}a-B_1x-\frac{B_2-B_1}{2a}x^2\right)\cdots(2)'$$

If eddy current loss of a conductor $a\times b\times 1$ according to j_1 is denoted by w

$$w=b\rho\int_0^a j_1^2dx$$

There Equation (2)′ is substituted in it and reduced to

$$w=\frac{\omega^2ba^3}{360\rho}(4B^2+7B_1B_2+4B_1^2)\cdots\cdots\cdots(3)'$$

When the conductor in Fig. 1′ is a winding of n_0 layer as shown in Fig. 2′ and the flux density at both ends is B_{1m} and B_{2m}, the following equation is formed as to the nth layer.

$$\left.\begin{aligned}B_1&=B_{1m}+\frac{B_{2m}-B_{1m}}{n_0}(n-1)\\B_2&=B_{1m}+\frac{B_{2m}-B_{1m}}{n_0}n\end{aligned}\right\}\cdots\cdots\cdots(4)'$$

Let w_n be the eddy current loss of this conductor.

Equation (4)′ is substituted to Equation (3)′ and reduced to

$$w_n=\frac{\omega^2ba^3}{360\rho}\left(15B_{1m}^2+15B_{1m}\frac{B_{2m}-B_{1m}}{n_0}(2n-1)+\frac{(B_{2m}-B_{1m})^2}{n_0^2}(15n^2-15n+4)\right)\cdots\cdots(5)'$$

Let total eddy current losses with respect to m_0 and n_0 be W.

Since $W=m_0\sum_{n=1}^{n=n_0}w_n$

Equation (5)′ is substituted in it and reduced to

$$W=\frac{\omega^2ba^3m_0}{360\rho}\frac{1}{n_0}\left(B_{1m}^2(5n_0^2-1)+B_{2m}^2(5n_0^2-1)+B_{1m}B_{2m}(5n_0^2+2)\right)\cdots\cdots\cdots(6)'$$

In Item 4 of the body of this article, σ' in Fig. 4 just corresponds to Equation (6)′.

In this case, if ampere-turns of the secondary winding and tertiary winding are denoted by AT_2 and AT_3,

$$B_{1m}=kAT_3,\quad B_{2m}=k(AT_2+AT_3)$$

Then there are substituted in Equation (6)′

$$\sigma'=W=\frac{\omega^2ba^3m_0}{360\rho}k^2\left((AT_2)^2\frac{5n_0^2-1}{n_0}+(AT_3)^215n_0+(AT_2)(AT_3)15n_0\right)\cdots\cdots\cdots\cdots(7)'$$

In Item 2 of the body, σ_2 in Fig. 1 or Fig. 3 is equal to the value available from Equation (6)′ by taking

$$B_{1m}=0\ \text{and}\ B_{2m}=\frac{1}{k}\left(\frac{AT_2}{m}\right)$$

Therefore $\sigma_2=\dfrac{\omega^2ba^3m_0}{360\rho}k^2\left(\dfrac{AT_2}{m}\right)^2\dfrac{5n_0^2-1}{n_0}$ (8)′

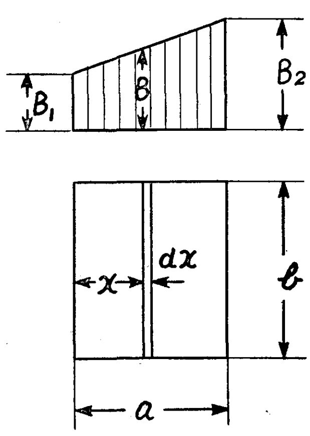

Fig. 5′ Eddy current loss in conductor due to leakage flux.

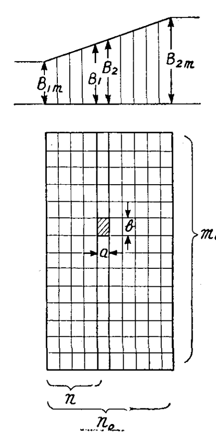

Fig. 6′ Flux density distribution at 2ry winding

Comparing Equation (7)′ and Equation (8)′,

$$\sigma' \doteqdot (m^2+3n^2+3mn)\sigma_2 \cdots\cdots\cdots\cdots (9)'$$

It coincides with Equation (9) in the body of this article. m and n are the capacity ratio of the secondary and tertiary windings when the capacity of the primary is assumed to be 1.

Next, σ in Fig. 2 of Item 4 in the body of the article is equal to that available from Equation (3)′ by assuming $B_1=B_2=k\left(\frac{AT_2}{m}\right)$ for one conductor.

Therefore, for total of the secondary winding

$$\sigma=\frac{w^2ba^3m_0}{360\rho}k^2\,15\left(\frac{AT_2}{m}\right)^2 \cdots\cdots\cdots (10)'$$

Comparing Equation (8)′ with Equation (10)′

$$\sigma \doteqdot 3\,\tau_2 \cdots\cdots\cdots\cdots (11)'$$

This Equation (11)′ coincides with Equation (4) in the body of this article.

AMPLITRANS TYPE AUTOMATIC VOLTAGE AND POWER-FACTOR REGULATING DEVICE

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I. INTRODUCTION

Usually the synchronous machine of large capacity is provided with main and sub-exciters and is controlled for its excitation by the automatic voltage regulator or automatic power factor regulator, the over-load limiting device, and automatic voltage balancing device for synchronizing operation. Consequently, the controlling system of the excitation becomes considerably complex to set side by side the above-mentioned devices which are independent apparatus each having unique principle of operation. Also, these devices are in many cases of very sensitive regulating relay systems having contacts or moving parts of very delicate constructions which operate off and on very frequently. They require fine adjustments and difficult maintenances, which are apt to be the causes of the failures. Automatic regulators using electronic tubes are also static type devices and good performances can be obtained by manufacturing. However, as a economically practical device, it is inferior in the point of reliability owing to its limited output and possibility of degrading the life and performance.

Rotary amplifiers are sometime used, but magnetic amplifiers are perfectly static type. Therefore, it is mechanically substantial and has semi-permanent life without any troubles for maintenance. Not only linear characteristics but also any non-linear characteristics can be easily obtained from it and also very superior characteristics can be obtained by selecting the superior materials. Consequently, it is best fitted for these devices at the present stage. Fuji Denki is manufacturing the iron core material of highest characteristics which can be obtained in our country, and by using this material we are getting various kinds of magnetic amplifiers inclusive of D.C. amplification of such small energy as EMF of thermo-couple. We call this magnetic amplifier as " Amplitrans ", which is adopted as our standard for the various automatic controlling devices. The present device, which is described here, is the collective automatic regulating device which can control automatically and smoothly the series of excitation control such as AVR (Automatic Voltage Regulation), APFR (Automatic Power Factor Regulation), kVA limiting, and automatic voltage balancing at the time of synchronizing, and yet it is a perfect static type device, of which each part consisting of " Amplitrans ". Further, magnetic amplifiers having the considerable large capacity can be manufactured economically, and this device dispenses with the sub-exciter because its out-put enough to excite the main-exciter directly. Therefore, it can be said to serves as a sub-exciter. This device has already many actural results of operation with very excellent performances.