Correction of power transformer no-load losses, measured under nonsinusoidal voltage waveforms

D. Slomovitz

Indexing terms: Transformers

Abstract: A method to calculate the iron losses in power transformers with highly distorted supply voltages is introduced. The appearance of small loops inside the main hysteresis loop is analysed and a method is proposed that takes into account the relative height of the small loops, as well as the position of the small loops inside the main loop. The percentage of hysteresis and eddy current losses in the total no-load loss is evaluated. Results obtained by means of different methods of calculation are compared to the 50/50 criterion. This method is proposed for correcting the no-load losses measured in transformer tests when the applied voltage is highly distorted. An experiment corroborates the corrective method proposed.

List of principal symbols

P_{iron} = power loss in the iron core
P_e = eddy current loss in the iron core
P_h = hysteresis loss in the iron core
B_{max} = peak magnetic flux density
V_{flux} = test voltage measured with a peak flux-density response voltmeter
K_h = ratio: P_h/P_{iron}
K_e = ratio: P_e/P_{iron}
R_a = ratio: area of 1 small loop/area of main loop
R_h = ratio: height of 1 small loop/height of main loop
R_u = ratio: height of the centre of 1 small loop/peak of the main loop
E = percentage difference between the calculated and measured main loop histeresis energy, using the method proposed in the paper
E' = percentage difference between calculated and measured main loop histeresis energy, using the method proposed in Reference 5.
P_{es} = eddy current loss taking into account skin effect in the iron
P_{eo} = eddy current loss without taking skin effect into account

1 Introduction

Many papers [1–3] study the errors in the determination of iron losses in transformers (P_{iron}) when there is supply voltage distortion. All of their techniques are based on the determination of the magnetic flux by means of average voltmeters and correct eddy current losses P_e according to the readings of RMS voltmeters. The main limitation is that the distorted voltage cannot have more than two zero-crossings per period. Otherwise small loops would appear inside the main hysteresis loop enlarging the hysteresis loss P_h, and changing the apparent peak magnetic flux density B_{max}. Recently, Arsenau and Moore [4] have proposed a method of multiple zero-crossing voltage correction, based on the adjustment of the test voltage according to an actual peak flux-density voltmeter V_{flux} and correcting the P_h value according to the Lavers criterion [5]. To avoid errors arising from assuming that P_h and P_e are distributed approximately equally, it is assumed by many transformer standards for grain-oriented core-plate [6], they propose a method to calculate the proportion of hysteresis losses K_h and eddy current losses K_e.

$$P_{iron} = P_e + P_h \quad (1)$$

$$K_h = P_h/P_{iron}$$

$$K_e = P_e/P_{iron} \quad (2)$$

Using data obtained by testing the transformer with two different distorted waveforms, a 2 × 2 system of equations is generated, from which K_h and K_e can be determined.

However, we find that the errors that appear in applying this corrective method to our experimental data are very large. This reason leads us to propose a new and different corrective method.

Almost all of our analysis is based on highly distorted voltage waveforms that produce big loops inside the main hysteresis loop. We admit that at the present state of technological development it is very difficult to determine these from routine transformer tests, but we use them because experimental errors in these determinations are high; hence, one method to evaluate the quality of the proposed corrections involves using high distortions.

On the other hand, published information [8] shows that very highly distorted voltage waveform appears when high-power transformers are tested. We think that great effort should be made to obtain a voltage waveform as sinusoidal as possible; but a corrective method is necessary when the waveform cannot be improved.

2 Correction for hysteresis losses

A new method for evaluating P_h under highly distorted voltage waveforms is proposed. Data used in this analysis have been obtained from transformers with the following parameters: 8660/115 + 115 V, 5 kVA and 15 kVA, 50 Hz, single-phase, with a shell-type core made of 0.30 mm-thick grain-oriented silicon iron laminations of the Orsi 97 type (P_{iron} = 0.97 W at 1.5 T, B_{max} = 1.75 T).

Paper 6332C (P7), first received 8th December 1987 and in revised form 4th May 1988

The author is with the Usinas y Transmisiones Electricas Laboratorio, PO Box 19934, Montevideo, Uruguay

Although very small transformers were used for this analysis, the results are valid for larger ones because the behaviour of the cores is similar.

As a power source, a programmable waveform generator has been used. Its block diagram is shown in Fig. 1.

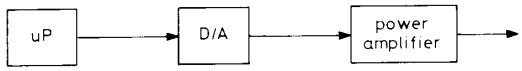

Fig. 1 *Programmable waveform generator*

The microprocessor holds the discretised waveform in its memory. The program reads the values periodically and the output is processed by means of a digital-analogue convertor. A power amplifier drives the transformer under test on its low-voltage side. With this source, any voltage waveform is easily produced.

The results have been obtained integrating the voltage on the high-voltage side and drawing the hysteresis curve with an *x-y* analogue plotter. The frequency used was 0.1 Hz.

Different waveforms have been used so that different small loops appeared in different positions. The saturation level of the main loop has been changed during the tests, as well as the relative height and position of the small loops.

We will compute the ratio of small loop area to main loop area, because this value coincides with the value of the ratio of energies. This is because the loops are plotted in the B/H plane and therefore the energy of each kind of loop is proportional to the dissipated energy in each case. We will define the area ratio R_a

$$R_a = \frac{\text{area of one small loop}}{\text{area of main loop}} \tag{3}$$

height ratio R_h:

$$R_h = \frac{\text{height peak to peak of one small loop}}{\text{height peak to peak of main loop}} \tag{4}$$

and as relative position of the small loop R_u, expressed in absolute value:

$$R_u = \frac{\text{height of centre of small loop}}{\text{height of peak of main loop}} \tag{5}$$

In Fig. 2 definitions are explained in detail. As all the hysteresis cycles studied have two small loops, approximately symmetrical, average values of both were used to determine the previously defined magnitudes. In the following, the influence on R_a of the already defined relations, as well as of the saturation level, will be discussed so as to find a method that allows the energy related solely to the main hysteresis loop to be calculated from tests in which small loops were present in the main hysteresis loop.

2.1 Influence of saturation level

This analysis has been performed by changing the peak of the magnetic flux density between 1.0 and 1.6 T while keeping R_h and R_u approximately constant. Two different kinds of cycle have been used, with small loops near the centre on one hand and near the extremes on the other, as shown in Fig. 3. The waveforms used are listed in Table 1.

The relation between R_a and B_{max} is shown in Fig. 4. The points measured for cycles with $R_h = 0.4$, $R_u = 0$ are marked by circles, and the ones with $R_h = 0.3$, $R_u = 0.7$ by triangles. For each of the two kinds of cycle analysed, R_a remains practically constant. The standard deviation of R_a is smaller than 6%, whereas B_{max} varies between 1.0

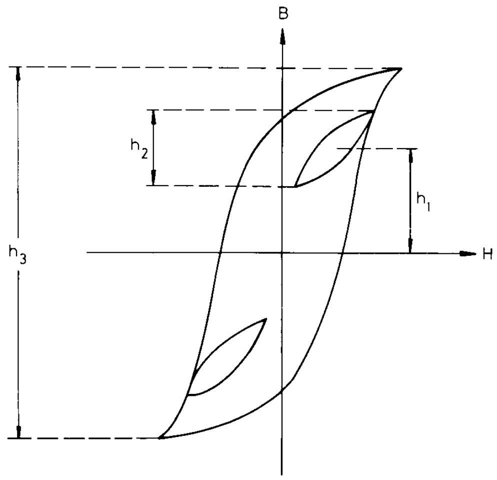

Fig. 2 *Definitions of the height ratio, R_h, and relative position, R_u*

$R_h = h_2/h_3$

$R_u = \frac{h_1}{(h_3/2)}$

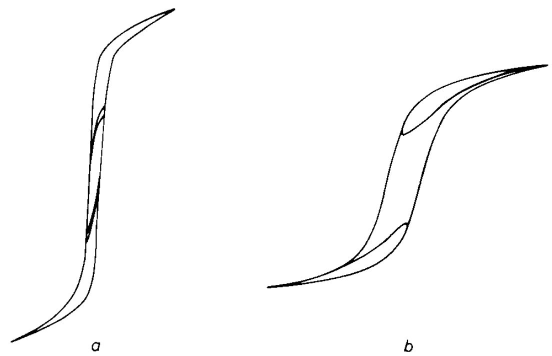

Fig. 3 *Types of cycle used in incidence-of-saturation-level study*

a $R_h = 0.4$; $R_u = 0$

b $R_h = 0.3$; $R_u = 0.7$

Table 1

Curve	B_{max} T	R_a	R_h	R_u	E %	E' %
1	1.38	0.11	0.24	0.523	−1.4	−7.0
2	1.15	0.12	0.22	0.615	+0.6	−3.6
3	0.95	0.10	0.22	0.624	−2.9	−6.7
4	1.67	0.11	0.22	0.583	−0.3	−5.1
5	1.02	0.177	0.287	0.705	−1.2	−1.4
6	1.12	0.171	0.274	0.696	−0.2	−1.0
7	1.23	0.189	0.296	0.689	−0.2	−0.5
8	1.20	0.211	0.300	0.685	+2.6	+2.3
9	0.98	0.208	0.399	0	+5.0	−6.7
10	1.17	0.183	0.402	0	+0.9	−10
11	1.33	0.208	0.407	0.030	+3.3	−7.4
12	1.45	0.193	0.411	0.039	+0.5	−9.7
13	1.54	0.171	0.412	0.063	−3.3	−13
14	1.54	0.222	0.30	0.673	+4.5	+3.9
15	1.64	0.189	0.28	0.653	+2.8	+1.0
16	1.54	0.116	0.22	0.629	−0.4	−4.2
17	1.62	0.172	0.41	0.083	−3.3	−12
18	1.62	0.043	0.11	0.698	−1.3	−5.0
19	1.60	0.065	0.23	0.116	−0.9	−13
20	1.34	0.081	0.14	0.871	−1.6	−1.7
21	1.60	0.063	0.12	0.785	−0.4	−2.6

and 1.6 T. It should be noted that this is a second-order error and thus can be ignored. Therefore, we suggest not including any correction depending on the degree of saturation of the iron. In any case, such values would be very difficult to measure in routine transformer tests.

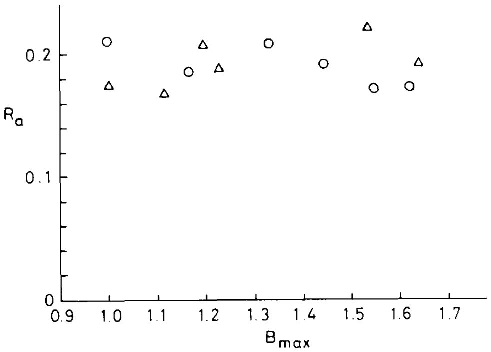

Fig. 4 *Measured values of R_a as a function of B_{max}*
○ $R_h = 0.4$; $R_u = 0$
△ $R_h = 0.3$; $R_u = 0.7$

2.2 Incidence of height ratio and relative position

Given a certain hysteresis curve, with a determined height ratio and area ratio, we will define the coefficient m as

$$m = \ln(R_a)/\ln(R_h) \qquad (6)$$

in other words

$$R_a = R_h^m \qquad (7)$$

Keeping R_u constant and changing R_a and R_h, the value of m remains practically constant. On the other hand, the value of m is sensitive to changes in the ratio R_u. The idea is to evaluate R_a in terms of R_h and R_u, because these parameters are easy to measure, by means of an oscillogram of the integral of the voltage, in routine transformer tests.

In order to evaluate the relationship between m and R_u, experimental data shown on Table 1 have been used. A straight line that best fits the points plotted on a graph of m against R_u (Fig. 5), according to a least-squares analysis, is proposed. The equation for the straight line is

$$m = a - b \cdot R_u \qquad (8)$$

Coefficients a and b for our data are $a = 1.9$ and $b = 0.78$. Fig. 5 shows the resulting straight line.

Based on this relationship, and assuming that m depends only on R_u, it is possible to calculate R_a from the values R_h and R_u using eqns. 8 and 7. Given a hysteresis cycle of the kind analysed, it can be verified that

$$\text{main loop area} = \frac{\text{total area}}{1 + 2R_a}$$

We can obtain the total area by direct measurement, and as far as the value of R_a is concerned, we can calculate it from the values of R_h and R_u. With the purpose of evaluating the error of this method in calculating the main loop areas, we will compare this value to the one actually measured, using an equation derived from the accurate definition of main loop area in terms of R_a:

$$\text{measured main loop area} = \frac{\text{total area}}{1 + 2\,(\text{measured } R_a)}$$

We will define the area error E as

$$E = \left(\frac{\text{calculated main loop area}}{\text{measured main loop area}} - 1\right) \times 100$$

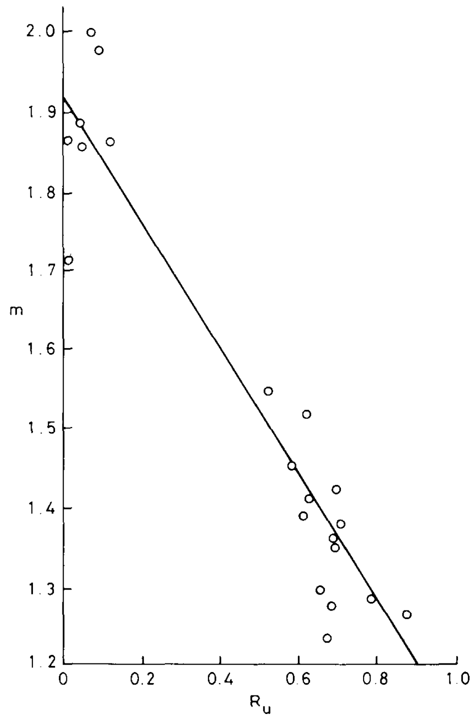

Fig. 5 *Dependence between m and R_u*
$m = 1.9 - 0.78\ R_u$

so that

$$E = \left(\frac{1 + 2 \cdot (\text{measured } R_a)}{1 + 2 \cdot (\text{calculated } R_a)} - 1\right) \times 100 \qquad (9)$$

Hence, the value of E is the percentage error in calculating the energy related to a sinusoidal regime, from hysteresis cycles produced by a highly distorted voltage, using the method of calculation proposed. The value of E has been computed for all of the cycles of Table 1, and it appears on the sixth column of the same table. The standard deviation for all the cases analysed is 2.3%. This value is slightly below the estimated errors of the data collected, so that from this point of view the method of calculation proposed is correct. It should be remembered that the waveforms used were strongly distorted and the area of the small loops represent between 20% and 40% of the area of the main one. The method proposed allows us to calculate, based on test data, the area ratio R_{a_i} for each small loop i. Finally, this permits the calculation of hysteresis losses under sinusoidal voltages P_{hsin}, from the losses under distorted voltages P_{hdis}, and vice versa, as

$$P_{hsin} = P_{hdis} \Big/ \left(1 + \sum_{1}^{N} R_{a_i}\right) \qquad (10)$$

where N = total number of small loops.

3 Comparison to other proposed corrective methods

In Reference 5 an approximate method for correction of the hysteresis losses is proposed, according to eqn. 10, but in this case R_a is calculated according to the equation

$$R_a = kR_h \quad (11)$$

That paper proposes a value of k between 0.6 and 0.7.

Using this equation, and taking $k = 0.65$, we have calculated the error value E', according to eqn. 9, which are listed on the seventh column of Table 1. The standard deviation for all the E' values is 6.9%, which is three times the one obtained for the E values using our method.

Instead of taking the value proposed for k mentioned in the paper, it is possible to calculate it by a least-squares method, to fit it as closely as possible to the points taken as data. The result for our data is $k = 0.52$.

With this value, the standard deviation is 5.1%, exceeding the value obtained using our method by more than a factor of two.

Nakata *et al.*, [7] introduced another paper on this subject, but they do not conclude with a practical corrective method for use with transformer tests.

4 Correction for eddy-current loss

The P_e values vary quadratically in relation to the RMS voltage:

$$P_e = k' V_{RMS}^2 \quad (12)$$

The correction of P_e must therefore be done according to the following equation:

$$K_r = (V_{RMS}/V_{flux})^2 \quad (13)$$

adjusting the value of V_{flux} to the nominal test value. With the core plate data supplied by the manufacturer for the transformers used (thickness = 0.30 mm, resistivity = 48 $\mu\Omega$ cm, relative permeability = 3000) the influence of frequency on skin depth has been studied. We define the ratio between eddy current losses without taking into account the mentioned effect (P_{eo}) and the losses taking this effect into account (P_{es}), as

$$K_s = P_{es}/P_{eo} \quad (14)$$

Table 2 shows the calculated values of skin depths d and

Table 2

Frequency Hz	d mm	K_s
50	0.5	1.00
150	0.28	1.00
300	0.20	1.00
500	0.15	0.98
2000	0.075	0.75

the values of K_s: for harmonic frequencies of up to ten times the fundamental, the correction would be under 2%. Considering that even the highly distorted waveforms used in this work have low amplitudes at high frequencies, we do not consider it necessary to make any correction for this effect.

5 Evaluation of the proposed corrections at power frequencies

For these tests we used the programmable waveform power source described above, but adjusted at a frequency close to 50 Hz (44.5 Hz). The output voltage stability was higher than 0.2% for short time intervals, the set of instruments used consisted of a 0.2 class moving-iron voltmeter for the RMS readings, and a $6\frac{1}{2}$ digit average voltmeter with an error lower than 0.1%. For the measurement of V_{flux} an electronic device consisting of an integrator followed by a peak-detector has been developed, showing errors less than 0.3%.

The power has been measured with a Zera digital wattmeter, with errors lower than 0.1%. Seven different voltage waveforms have been studied, changing the relative height and the position of the small loops, as well as the saturation level. In Fig. 6, the shape of the integral of

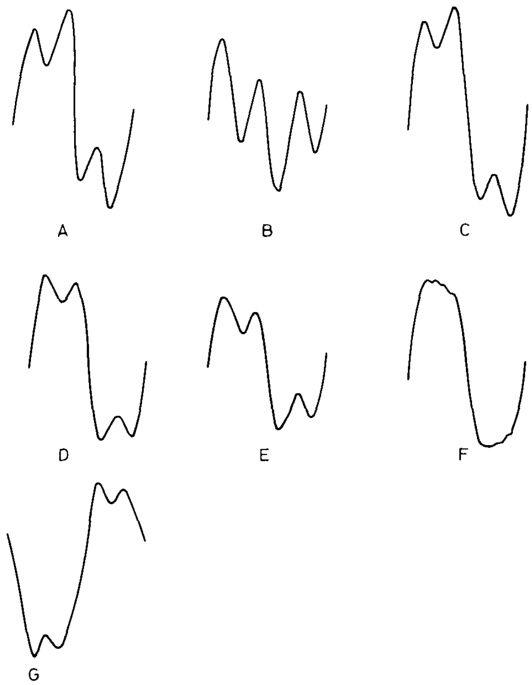

Fig. 6 *Integral-voltage waveforms used to evaluate the proposed correction at power frequencies*

each voltage wave is shown. The evaluation was made on a 5 kVA transformer with the voltage waveform corresponding to curves *a* to *e*. Data from other papers were also used, relating to a 233 MVA single-phase transformer and a 50 kVA single-phase transformer. The oscillogram *f* corresponds to the integral of a wave shown in Reference 8 for a level of 115%, whose voltage wave, in spite of having ten zero-crossings per period, has very small areas related to the zero crossings, so the integral oscillogram does not show measurable small loops. Curve *g* corresponds to the voltage waves introduced in Reference 4 for $V_{flux} = 115\%$, and data related to it (in Table 3) has been taken from the mentioned paper. Table 3 details the readings of measurements performed, the corrections calculated according to the condensed method given in eqn. 15 and the percentage differences in total power losses compared to a sinusoidal source voltage. The sinusoidal voltages show small differences between V_{RMS} and $V_{average}$ owing to the existence of a small harmonic distortion. Because of this they have also been corrected, in this case using the IEC criterion.

It has been assumed that P_e and P_h are distributed equally. Obviously, with distorted voltages, other distributions would provoke changes in the results. It is because of this that taking $K_h = 0.56$ and $K_e = 0.44$, the percentage differences shown in Table 3, would be under the 2% instead of the 5.7% that appears in the waveform *b*. Anyway, taking into account the high values to be corrected (140% in this case), even the value 5.7% turns out to be small, and the correction proposed of great exactitude.

Table 3

Waveform	V_{avg} V	V_{rms} V	V_{flux} V	Measured power W	m	R_h	Corrected power W	P_{iron} difference to sinusoidal voltage %
A	206.7	226.4	148.9	24.63	1.46	0.181	14.17	−2.0
B	271.7	276.0	148.9	32.84	1.85	0.410	13.63	−5.7
C	188.0	213.6	148.9	22.65	1.28	0.128	14.15	−2.1
C	200.9	227.8	161.5	26.36	1.28	0.128	16.82	−2.2
C	226.8	273.0	182.4	36.35	1.28	0.128	21.48	−4.4
D	184.0	215.6	148.9	23.00	1.26	0.119	14.23	−1.6
D	200.9	234.4	166.4	27.72	1.26	0.119	17.76	−2.8
D	216.6	270.2	181.5	35.90	1.26	0.119	21.41	−3.7
E	267.8	298.0	199.1	44.92	1.39	0.164	26.41	−5.4
F	148.4	187.8	148.9	18.41	—	0	14.21	−1.7
G	292.3	347.3	274.8	548.1	1.27	0.079	409.5	+0.4
G	305.4	335.2	275.1	530.0	1.27	0.079	413.4	+1.1
sin	148.9	149.9	148.9	14.56	—	0	14.46	—
sin	160.5	161.8	160.4	17.12	—	0	16.97	—
sin	180.5	183.6	180.4	22.36	—	0	21.97	—
sin	198.5	205.6	198.7	28.80	—	0	27.82	—

We do not consider it convenient to determine experimentally, in each case, the values of K_h and K_e, as proposed in a previous paper [4], since this would demand the use of different distorted voltage waveforms, which is highly cumbersome for transformer routine tests. On the other hand, it must be taken into account that the use of two different waveforms to generate a 2×2 system of equations, should be followed by a study on error propagation to make sure that the uncertainties of the values measured do not significantly affect the results K_h and K_e. Using our data, and data shown in other papers, we have calculated: the K_h and K_e coefficients, their sensitivity to variation related to directly measured values, and the power P_{iron} using this method. A summary of the results for our transformer appears in Table 4, for different voltage waveforms. All have $V_{flux} = 148.9$ V. Therefore, building the system of equations with the voltage waveforms *a* and *b* the value K_h is 0.93, whereas with the waveforms *c* and *d*, K_h would be 0.15.

Table 4

Waveforms used		K_h	P_{iron} differences to sinusoidal voltage %
A	*B*	0.93	+17
B	*D*	1.2	+44
C	*D*	0.15	−20
F	*C*	1.6	+90
A	*D*	36	−105

If the waves *f* and *c* were used, K_h would have a value higher than 1; the same applies with the waves *a* and *d*. In this last case, the total power calculated would be negative. Even with the data shown in the referred paper, corresponding to the waveform *g* of Table 3, a variation of V_{flux} of +0.5% for the first wave (from 274.8 V to 276.2 V), would make K_h vary from 0.42 to 0.34, which shows the very high sensitivity of this method.

On the other hand, by using our method of correction for wave *g*, percentage differences in P_{iron} of 0.42% and 1.1% lower than those shown in the referred paper (−2%), are obtained. Although it is not possible to reduce the errors of measurement much further (not only because of the instruments used, but also the variation of the source voltage) the calculation of K_n and K_e by that method would allow excessive errors, negating its usefulness.

6 Conclusion

A simple method for calculating the iron losses in transformers when the applied voltage is highly distorted has been introduced. This method was applied to the correction of transformer no-load loss measurements. A correction of hysteresis losses has been proposed that takes into account the relative height of the small loops as well as their position inside the main loop. This information must be derived from a voltage-integral oscillogram. The method of correction consists of adjusting the test voltage, to obtain a peak magnetic flux density equal to the nominal one and using the equation

$$P_{corr} = \frac{P_{measured}}{(1 + \sum_1^N R_{hi}^m)0.5 + (V_{RMS}/V_{flux})^2\ 0.5} \tag{15}$$

where $m = 1.9 - 0.78\ R_u$ and
N = total number of small loops
The coefficients 1.9 and 0.78 were proposed from our data; more experimental work is necessary to confirm these values. Furthermore, this study was performed on single-phase transformers so these conclusions are limited to them. Further research is needed to include three-phase transformers.

This equation coincides with the one proposed by the present standards if there are no small loops, because in this case $R_h = 0$ and V_{flux} coincides with $V_{average}$.

The inconvenience of calculating the distribution coefficients of the hysteresis losses and the eddy current losses has been analysed, concluding that it is convenient to use equal distribution for oriented-grain irons.

From the evaluation conducted with our data, and data introduced in other papers, good agreement between the actual values and those obtained by the use of these corrections is evident.

7 Acknowledgment

The author wishes to thank Mr. Jorge Fernandez of the laboratory staff for his assistance with much of the experimental work.

8 References

1 CAMILLI, G.: 'A flux voltmeter for magnetic test', *AIEE Trans.*, 1926, **45**, pp. 721–728
2 SPECHT, T.R., RADEMACHER, L.B., and MOORE, H.R.: 'Measurement of iron and copper losses in transformers', *AIEE Trans.*, 1958, **77**, pp. 470–476
3 NILSSON, E.: 'Simplified transformer test with average-value method', *Elteknik*, 1968, **11**, pp. 132–135

4 ARSENEAU, R., and MOORE, W.J.M.: 'A method for estimating the sinusoidal iron losses of a transformer from measurements made with distorted voltage waveforms', *IEEE Trans.*, 1984, **PAS-103**
5 LAVERS, J.D., BIRINGER, P.P., and HOLLITSCHHER, H.: 'A simple method of estimating the minor loop hysteresis loss in thin laminations', *IEEE Trans.*, 1978, **MAG-14**, pp. 368–388
6 I.E.C. STANDARD 76-1, 'Power transformers', Part 1, 1976
7 NAKATA, T., ISHIHARA, Y., and NAKANO, M.: 'Iron losses of silicon steel core produced by distorted flux', Electr. Eng. Jpn, 1970, **90**, pp. 10–20
8 MALEWSKI, R., ARSENEAU, R.A., and MOORE, W.J.M.: 'A comparison of instrumentation for measuring the losses of large power transformers', *IEEE Trans.*, 1983, **PAS-102**, pp. 1570–1573

Abstracts of papers published in other Parts of the *IEE PROCEEDINGS*

The following papers of interest to readers of *IEE Proceedings Part C, Generation, Transmission & Distribution* have appeared in other Parts of the *IEE Proceedings:*

Method of detecting and modelling presence of shorted turns in DC field winding of cylindrical rotor synchronous machines using two airgap search coils
R.L. STOLL and A. HENNACHE

IEE Proc. B, 1988, **135**, (6), pp. 281–294

A method is described for detecting the loss of one or more turns in a concentric coil of the rotor field winding of a synchronous machine using two search coils in the airgap. This back-to-back method yields an EMF proportional to the rate of change of the 'missing' flux linking the search coils, and is sufficiently sensitive for the coils to be positioned close to the stator surface. A two-dimensional linear analysis of the airgap field is used to model the method with good accuracy, and includes an estimate of the resulting unbalanced magnetic pull. A simple one-dimensional analysis predicts the EMF harmonics that are introduced by static or dynamic rotor eccentricity. Results from a small four-pole experimental machine are presented, including the effect of a known amount of static eccentricity. Calculations for a larger two-pole machine are also included, and a possibly useful method of fault location detection using the ratio of the magnitudes of only two harmonics taken from the search coil output is discussed.

Coupling of discharge currents between conductors of electrical machines owing to laminated steel core
P.J. TAVNER and R.J. JACKSON

IEE Proc. B, 1988, **135**, (6), pp. 295–307

Over the past few years, a number of techniques have evolved for detecting discharges in the insulation systems of electrical machines by measuring the discharge currents flowing at the machine terminals. The propagation of these currents through the winding, from the discharge site to the terminals, is influenced by the capacitive and inductive coupling between the conductors of the winding. The paper is concerned solely with the inductive component of that coupling, through the laminated steel stator core of the machine. It describes how this coupling makes a significant contribution to the equivalent circuit for the propagation of discharge currents containing frequencies from 20 kHz to 20 MHz.

Physical significance of sub-subtransient quantities in dynamic behaviour of synchronous machines
I.M. CANAY

IEE Proc. B, **135**, (6), pp. 334–340

The recent accurate modelling of alternating-current machines sometimes requires, in addition to the known transient and subtransient quantities, the use of sub-subtransient quantities. The sub-subtransient time constants are very small; they can, however, have a great influence on the machine performance. The physical meaning of these new sub-subtransient quantities for the stability and switch-on process of the synchronous machine is explained and illustrated with examples. It is shown that by introducing the sub-subtransient values, the effect of the solid turborotor and the behaviour of the salient-pole machine with solid poles can be treated with sufficient accuracy.

Robust self-tuning regulator for a synchronous generator
Q.H. WU and PROF. B.W. HOGG

IEE Proc. D, **135**, (6), pp. 463–473

The paper is concerned with an application of a self-tuning control strategy to a synchronous generator system. In the stochastic control strategy, an auxiliary predictor is introduced and the variance between the actual output of the system and the desired track of the output is directly predicted, to restrain excessive control signals and to improve the control performance of the system. The paper also proposes a new supervision scheme for the robust self-tuning regulator, which includes modification of the covariance matrix in the estimation algorithm, moving boundaries imposed on parameter values, and turning on or off the control algorithm to protect estimated parameters from bursting, and to enhance parameter tracking during the dynamic and transient conditions encountered over the full range of operating conditions. Results obtained using a detailed nonlinear simulation of a turbogenerator illustrate the effectiveness of the control strategy and the supervision scheme.