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The Determination of Single-phase Transformer No-load Losses

Section 6: POWER ENGINEERING

Introduction

The information about transformer characteristics is necessary for designing, monitoring and operation. Transformer characteristics are vastly depended on reactive core losses (Q_0) and active core losses (P_0). These loses are connected with ferromagnetic material of a core, technology of transformer core production and also with transformer design. Core losses do not depend on the load current passing through a transformer but depend on transformer operating mode. Great number of factors influence P_0 and Q_0 such as input voltage magnitude, power frequency, voltage and current waveform distortion, power and peculiarities of a load. Therefore, P_0 and Q_0 can be culculated only for individual transformer operating mode. At the same time the information about cross-section area of transformer core, length of the middle field line and aperture occupation ratio is unknown.

There are many references, for instance [1,2], tell us about transformer no-load losses calculations.

Usually, electric quantities are replaced by magnetic quantities to calculate no-load losses. At the same time, immediate calculation of these losses by means of electric quantities is possible but this approach have been discussed murch less. We offer to calculate P_0 and Q_0 by means of current and voltage data arrays.

Measurement procedures and experimental data processing

It is supposed, that single-phase transformer has the third no-load winding W_0 apart from two operating windings W_1 and W_2 as it is shown in figure 1. The no-load winding

W_0 is used as measuring.

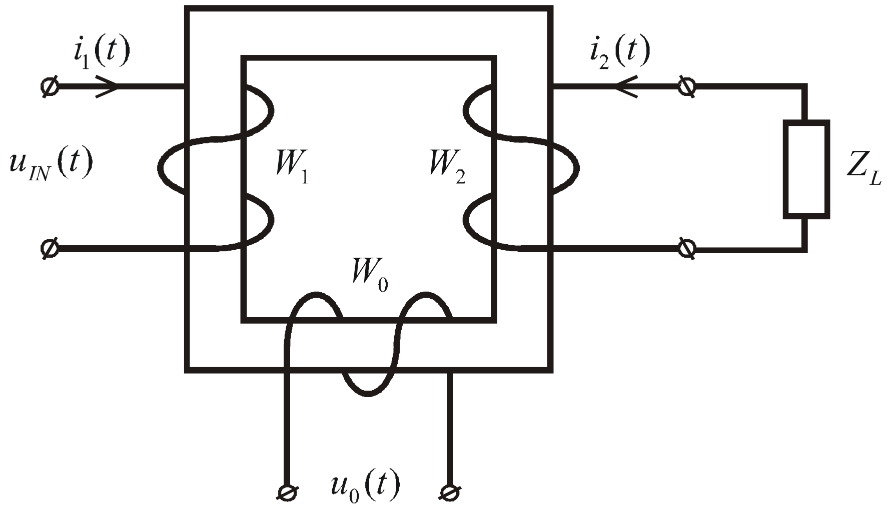

Figure 1 - Single-phase transformer with one inactive winding

Here:

$u_{IN}(t)$	is the input primary voltage.
$i_1(t)$	is the primary winding current.
$i_2(t)$	is the secondary winding current.
$u_0(t)$	is the voltage across no-load winding.
Z_L	is the load impedance.
W_1	is the number of turns in the primary transformer winding.
W_2	is the number of turns in the secondary transformer winding.
W_0	is the number of turns in the inactive transformer winding.

In this transformer operating mode currents $i_1(t)$ and $i_2(t)$ and voltage $u_0(t)$ are measured. All measurements are taken by means of equipment which allow to get instantaneous current and voltage data arrays (1), for example digital recorder of electric signals.

$$\left.\begin{array}{l} i_1(t_j)\,|_{j=1}^{N} = i_1(t_1), i_1(t_2), \ldots i_1(t_j), \ldots i_1(t_N); \\ i_2(t_j)\,|_{j=1}^{N} = i_2(t_1), i_2(t_2), \ldots i_2(t_j), \ldots i_2(t_N); \\ u_0(t_j)\,|_{j=1}^{N} = u_0(t_1), u_0(t_2), \ldots u_0(t_j), \ldots u_0(t_N). \end{array}\right\}, \qquad (1)$$

where:

$$t_j = t_{j-1} + \Delta t; \quad \Delta t = \frac{T}{N}; \qquad (2)$$

Δt	is a time sampling interval.
T	is a period of a signal.
N	is number of fragmentations during a period of a signal (T).

j is the fragment number, $j=\overline{1,N}$.

Further we start to operate with current $i_2'(t_j)$ and voltage $u_0'(t_j)$, reduced to the primary winding circuit.

Reduced transformer magnetizing current is obtained by formula (3)

$$i_0(t_j)|_{j=1}^{N}=\left[i_1(t_j)-i_2'(t_j)\right]_{j=1}^{N}. \quad (3)$$

There are two models of active core losses calculations.

The first model has been given in [3]:

$$P_0^I=\frac{1}{N}\sum_{j=1}^{N}\left[i_0(t_j)\cdot u_0'(t_j)\right]. \quad (4)$$

The second model has been based on well-known fact, that core losses are proportionate to the hysteresis loop area F_{HL}. Generally, if a magnetizing current $i_0(t)$ is proportionate to a magnetic-field strength in a core and also an integral of a reduced voltage in a no-load winding $\int u_0'(t)dt$ is proportionate to an elecromagnetic induction, the function $\int u_0'dt=f\left(i_0\right)$ is the scaled hysteresis loop. The division of the scaled hysteresis loop area by the period of signal equals to core losses (5)

$$P_0^{II}=\frac{F_{ПГ}}{T}. \quad (5)$$

The electromagnetic induction in the iron core is calculated by numerical integration of the voltage array $u_0'(t_j)|_{j=1}^{N}$. Firstly, the intermediate data array $|m(t_j)|$ of integral numerical values must be found. Constant component of this array differs from nought but value of this array at the moment t_1 is assumed to be equal to nought:

$$|m(t_1)|=0.$$

The other values are calculated by means of trapezium rule, which is described in [4]

$$m(t_j)=m(t_{j-1})+\Delta t\cdot\frac{u_0'(t_j)+u_0'(t_{j-1})}{2}.$$

This array has some random constant component, therefore the array $\int u_0'(t)dt$ is found by subtracting constant component M from array $|m(t_j)|$:

$$\int u_0'(t_j)dt=m(t_j)-M,$$

where $M=\frac{1}{N}\sum_{j=1}^{N}m(t_j)$.

The dependency of the voltage $u'_0(t)$ and integral of the voltage $\int u'_0(t)dt$ upon time are presented in figure 2.

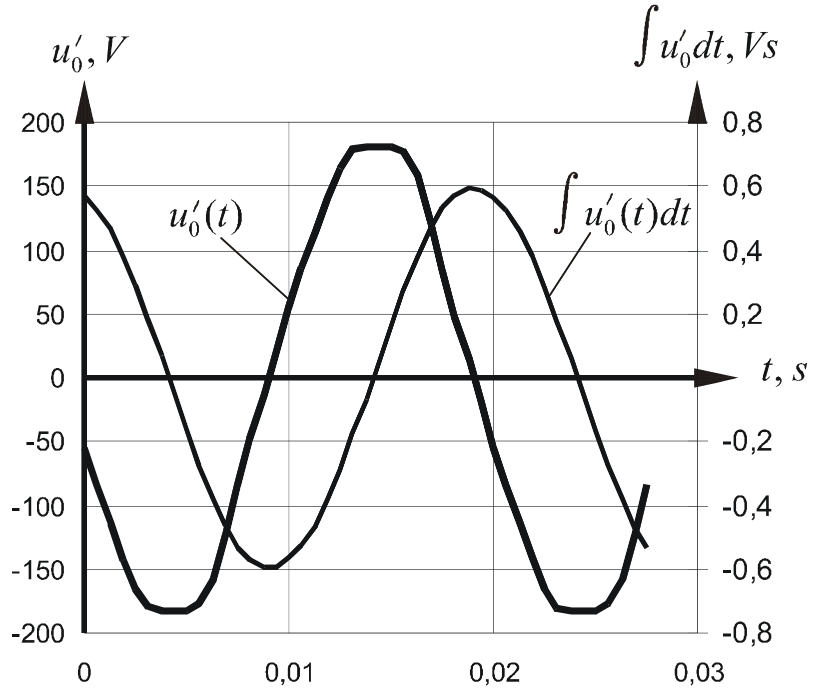

Figure 2 - The dependences $u'_0(t)$ and $\int u'_0(t)dt$

The area F_{HL} is calculated as the polygon area

$$F_{HL} = 0,5\sum_{j=1}^{N}[i_0(t_j) - i_0(t_{j+1})]\cdot[\int u'_0(t_j)dt + \int u'_0(t_{j+1})dt]. \quad (6)$$

The calculation of reactive core losses Q_0 has been based on procedure from [3]. It looks as formula (7):

$$Q_0 = \frac{1}{2\pi}F_{VCC}, \quad (7)$$

where:

$$F_{VCC} = \frac{1}{2}\sum_{j=1}^{N}[i_0(t_{j+1}) - i_0(t_j)]\cdot[u'_0(t_{j+1}) + u'_0(t_j)] \quad (8)$$

is the area of volt-ampere characteristic. The relation between Q_0 and F_{VCC} has been presented in [5].

Experimental results

Foregoing prosedures are checked in a number of transformers with shell core, output power $P_{OUT} \leq 1\,kW$ and number of winding turns are $W_1 = 380$, $W_2 = 62$ and $W_3 = 12$. Current and voltage data arrays are obtained by means of electric recorder "Black Box". Six no-load tests and six load tests are carried out under different values of the primary winding voltage U_{IN} between 89V and 258V.

Characteristics $\int u_0'(t)dt = f(i_0)$ for three no-load tests under different values of the primary winding voltage U_{IN} (89V, 133V and 258V) are presented in figure 3.

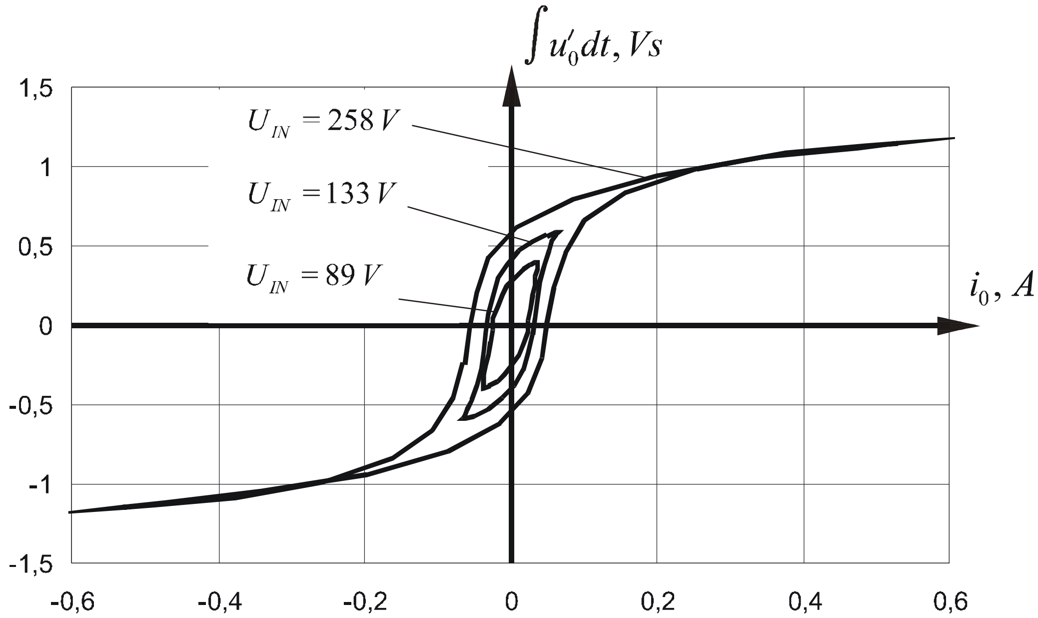

Figure 3 - Characteristics $\int u_0'(t)dt = f(i_0)$ for no-load tests

Three load tests under different values of primary winding voltage U_{IN} (87V, 130V and 250V) are presented in figure 4.

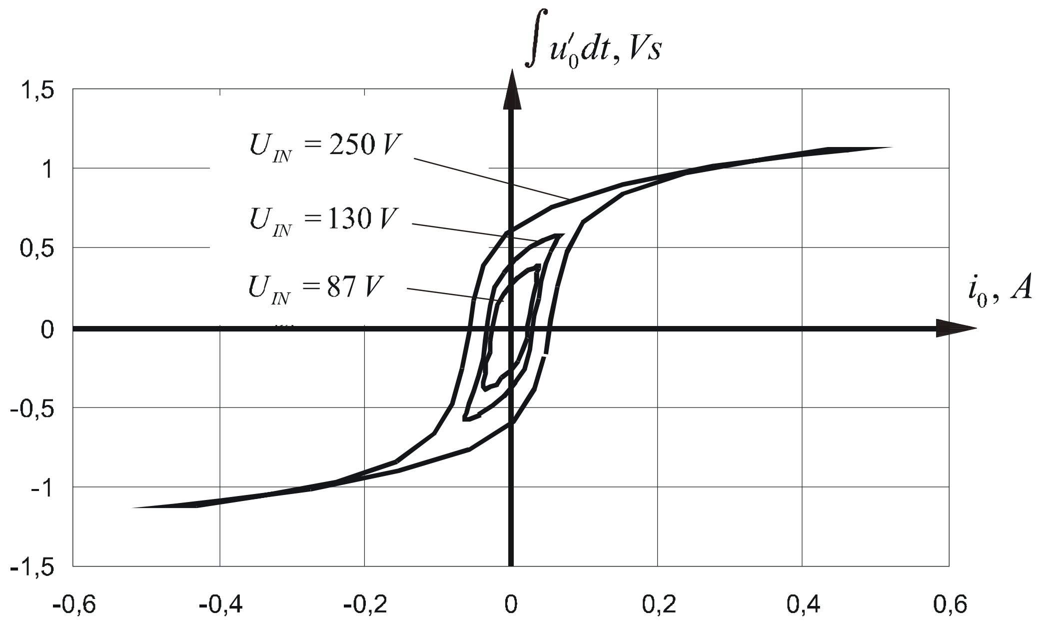

Figure 4 - Characteristics $\int u_0'(t)dt = f(i_0)$ for load tests

Volt-ampere characteristics $u_0'(i_0)$ for transformer tests are indicated in figures 5 and 6.

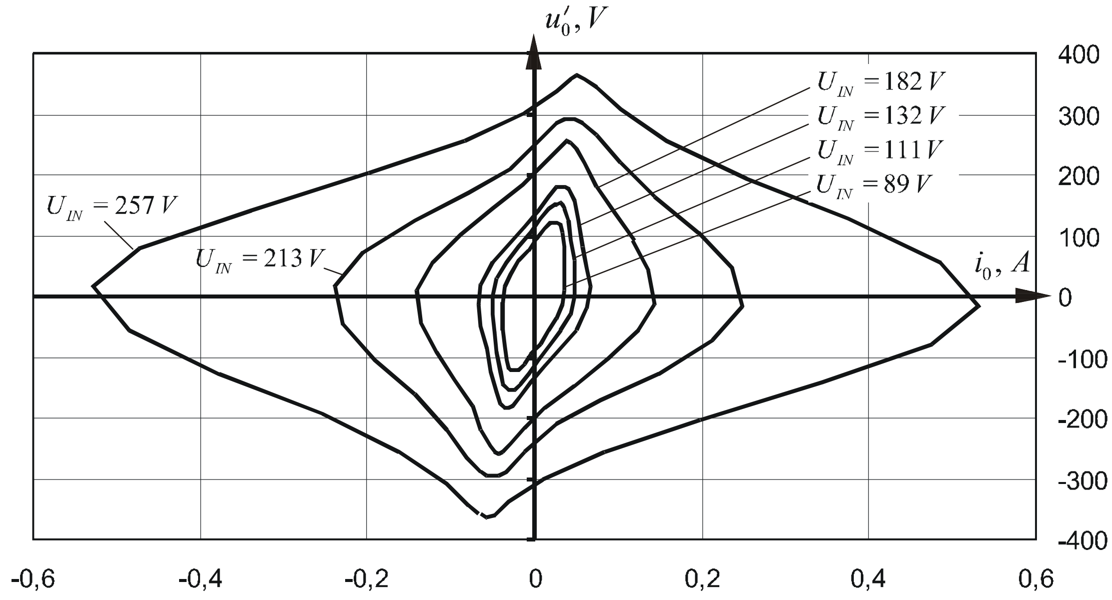

Figure 5 - Volt-ampere characteristics $u_0'(i_0)$ for no-load tests

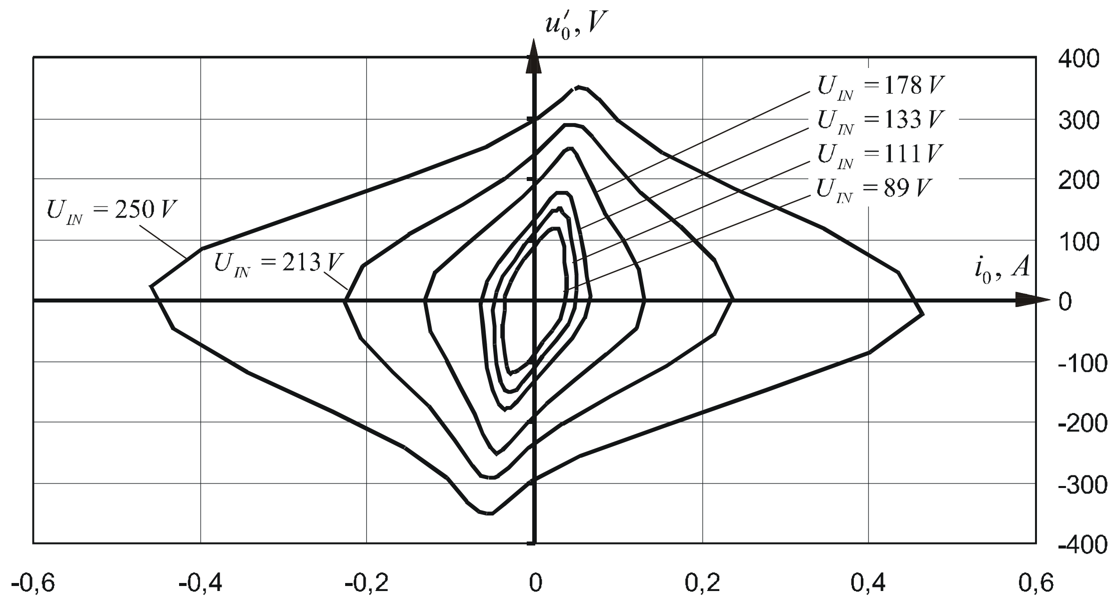

Figure 6 - Volt-ampere characteristics $u_0'(i_0)$ for load tests

Experimental results for no-load and load tests are presented in tables 1 and 2. The ratio $\frac{P_0^{II}}{P_0^{I}}$ shows good coincidence between results of active core loss calculations by means of different methods.

Table 1 - Results of active and reactive core losses calculations for no-load tests

Number of no-load test	1	2	3	4	5	6
U_{IN}, V	89,6	112,1	133,2	183,2	215	257,9
P_0^I, W	1,498	2,209	2,997	5,124	6,831	8,123
F_{HL}, VAs	0,0297	0,0438	0,0594	0,1017	0,1357	0,1614
P_0^{II}, W	1,484	2,189	2,97	5,083	6,785	8,072
$\frac{P_0^{II}}{P_0^I}$	0,991	0,991	0,991	0,992	0,993	0,994
F_{VCC}, VA	12,059	19,35	29,715	81,69	158,4	389,2
Q_0, VAr	1,919	3,0798	4,729	13,0	25,2	61,9

Table 2. Results of active and reactive core losses calculations for load tests

Number of load test	1	2	3	4	5	6
U_{IN}, V	87,2	109,2	130,4	178,6	212,7	250,4
P_0^I, W	1,47	2,196	2,983	5,395	7,218	8,61
F_{HL}, VAs	0,0291	0,0435	0,0591	0,1069	0,1432	0,1711
P_0^{II}, W	1,455	2,176	2,957	5,345	7,161	8,555
$\frac{P_0^{II}}{P_0^I}$	0,99	0,991	0,991	0,991	0,992	0,994
F_{VCC}, VA	11,65	18,88	29,0	73,04	147,93	331,08
Q_0, VAr	1,85	3,0	4,616	11,62	23,54	52,69

Differences between results of P_0 and Q_0 calculations for load and no-load tests are shown in figure 7.

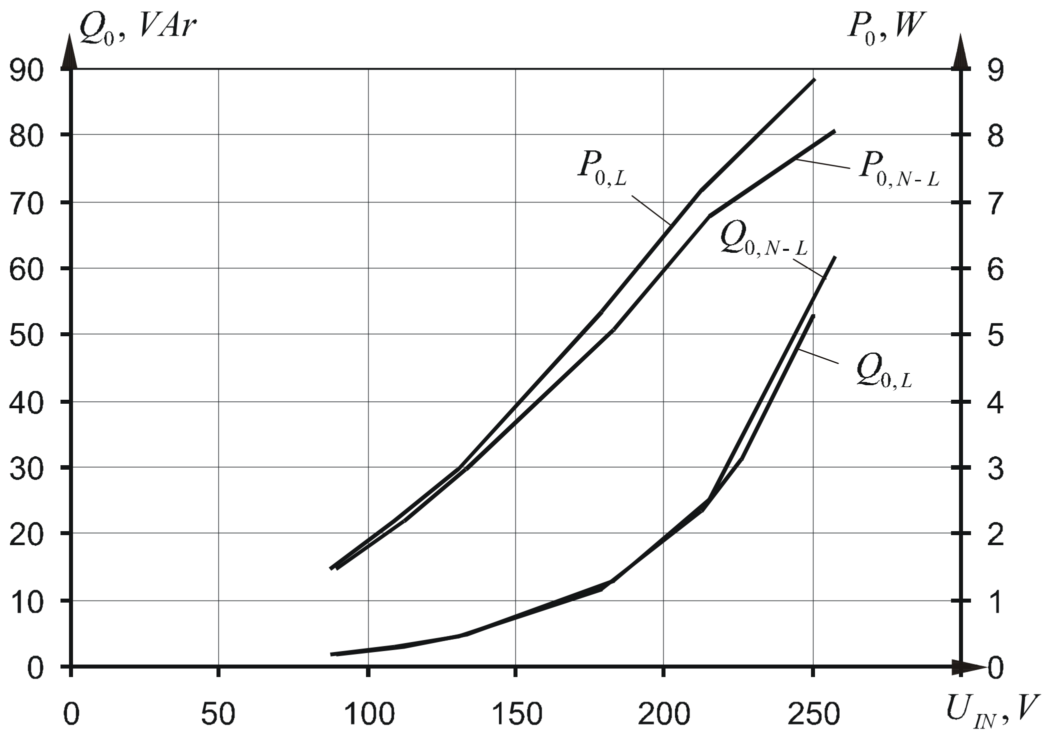

Figure 7 - Dependences P_0 and Q_0 upon input voltage U_{IN}

Conclusion

1. The method of transformer reactive core losses Q_0 and active core losses P_0 calculations by means of current and voltage data arrays is presented in this article.
2. The scaled hysteresis loop conception for the electrical quantities $\int u_0'(t)dt = f\left(i_0\right)$ is introduced. This loop define a real operating mode of transformer. Corresponding characteristics are obtained for several transformer operating modes.
3. New method of transformer active core losses P_0 calculation by means of scaled hysteresis loop area is offered. Comparison between new method results and results obtained using [3] shows the efficiency of this method.
4. Comparison of the dependences P_0 and Q_0 upon input voltage U_{IN} between the load and no-load tests shows that though in some cases values P_0 and Q_0 is founded by means of transformer no-load test, but in general case it is necessary to take a measurements in transformer operating mode.

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