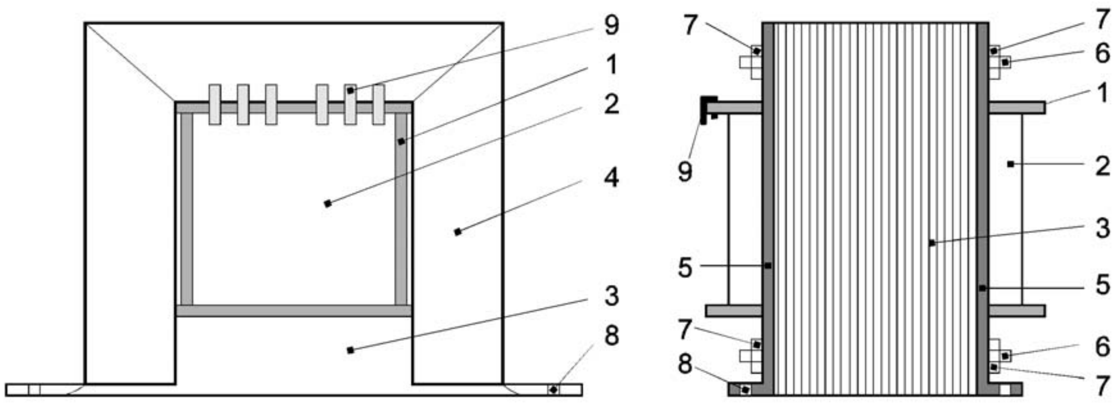
ANNEX A6*

DESIGN AND TECHNOLOGY OF THE MAINS SINGLE PHASE, LOW POWER TRANSFORMER

A6.1 Generalities

This presentation aims to help in knowing the constructive structure, the manufacturing technology, as well as the design methodology of the low power transformer (P <500W) used in the power supply circuit of electronic equipment.
The single-phase, low power mains transformer is a component present in many power circuit schemes of stationary electronic equipment. It is intended to change the voltage and current value from the level offered by the mains to primary circuit to the level or levels required in the secondary circuit or circuits. The transformer also offers galvanic isolation from the AC power supply of the chassis of the electronic device in which it is incorporated, and this way ensuring the electro-security of the operating personnel.

From a constructive point of view, a low-power mains transformer has the following important components, see Fig. A6.1:
• insulating case (bobbin, winding support, coil form, coil former, coil housing);
• windings
• ferromagnetic core made from silicon steel lamination sheets (E + I, U + I, I), or strips (columns, casing, toroidal)
• magnetic core fixture, clamping and mounting system of the chassis of the electronic device



(a) (b)

Fig. A6.1 *(a) Mains transformer assembled with sheath; (b) Mains transformer assembled with double-ended bolts; 1- case (bobbin), 2- windings, 3- magnetic core, 4- sheath for core fastening, 5- mounting brackets, 6-double-ended bolts, 7- nuts, 8- mounting holes, 9- terminal lugs.*

* This material is conceived to be used as a support for homeworks, and only refers to a certain constructive version, made under certain conditions, with certain electrotechnical materials. Some coefficients in the formulas used must be changed when relations for other materials and other design conditions are applied.

In present, the classic mains transformers are replaced in many applications with switched mode power supplies (SMPS), which operate at high frequencies (f> 20kHz) and also do include a ferrite core transformer. Due to higher efficiency, increased specific power, reduced weight, lower price, these sources are increasingly used. One of the advantages that the classic transformer still has is the simplicity and hence the high reliability. Another advantage is related to low electromagnetic emissions, which can be troublesome to some switching power sources. Among electronic equipment in which the ferromagnetic core mains transformer is still used, we mention: high performance audio amplifiers, some measuring equipments, microwave ovens, certain Weller soldering stations, certain mobile chargers, and others. Also, these transformers are used in circuits that have to operate at the mains frequency, for example, mains separators or uninteruptible power supplies (UPSs).

In the followings, all references will be made to magnetic core on ferromagnetic material with E+I laminations

A6.2. The technology of realizing the single-phase, low power mains transformer

The realization of a single-phase, low-power transformer in serial production involves the following technological steps:

a) *laminations sheet manufacturing*, made on transformer ferromagnetic steel iron with higher silicon content (according to Standards), through punching press;

b) *thermal treatment of the laminations* (annealing at temperature of approx. 850°C, followed by slow cooling), to reduce the induced mechanical stresses and recovery of magnetic properties, affected by the mechanical punching;

c) *realization of bobbin (case)*, through injection molding of plastic material in a form or construction from specific elements, previously obtained through punching, from pressboard, laminated fiber sheet, (commercial names: pertinax, steclostratitex) etc.;

d) *spool of windings* , on a bobbin previously obtained, using spooling machines fully automatic or half automatic, using enameled copper wires produced according specific standards, we will use Romanian Standard (STAS 685-58);

<u>Note:</u>

The realization of windings (spooling) for mains transformers can be realized, depending on the technical and economical requirements in two ways:

- "without insulation between layers "
- " with insulation between layers "

The spooling process follows the following order of operations:
1) primary winding;
2) two insulating layers made on transformer insulation foil "trafo" (special wax impregnated paper or polyester, having the thickness of 30÷50μm);
3) first secondary winding, followed by one insulation layer, etc;
4) the whole winding coil is isolated at exterior.

In second case, a supplemental insulation layer is introduced after each layer of copper windings.

e) *Mounting of laminations in the case* – operation known briefly as "lamination of transformer".

Note:

In the case of a mains transformer where there is no a DC component, an alternate (interleaved) lamination is made, that is to say alternatively, on one side and on the other of the casing, first a type E lamination and then a type I one, and so on. The last 2-3 laminations pieces are forced to get in by a light copper or brass hammer, the transformer being placed on a steel plate. Non interleaved lamination is achieved by inserting into the housing on the same side all of the **E** laminations and on the other side all of **I** laminations. This way, an air-gap is obtained in the magnetic circuit. This variant is used in transformers (or coils) which are traversed by currents having a DC component, such as audio frequency transformers.

f) *Tightening of magnetic core package* with a sheath or with clips, double-ended bolts and nuts to prevent the vibration of the blades during transformer operation.

Note:

The sheath is made by punching of a steel sheet (TDA) with a thickness of 1÷1.25mm. The obtained sheath is after that galvanized with Zn for passivation. In some applications, the shielding of the transformer is also practiced by means of lateral caps made by deep drawing of a steel sheet or shielding is obtained by applying a short-circuited coil made of copper foil surrounding the winding and the magnetic core on the outside.

g) impregnation of the transformer by immersion in molten paraffin or polyurethane lacquer (e.g., 3503 Ez) which polymerizes by heating in the oven at a temperature of 80÷100°C for approx. 1 hour.

Note:

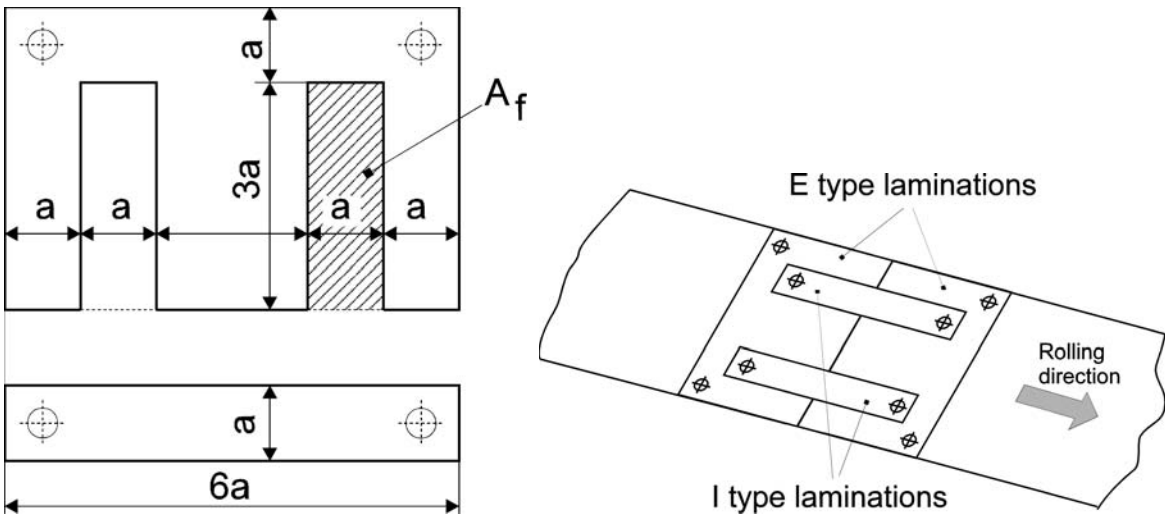
The impregnation of the mains transformers is carried out in an closed enclosure, in which the pressure was reduced to 10^{-1}÷10^{-2} torr (to eliminate the moisture from winding and from transformer insulation paper), after which it is introduced the impregnating bath.

h) *technical quality control* in which the electrical parameters are checked (secondary voltage or voltages, winding resistance, transformation ratio, insulation resistance between windings, respectively between the primary and the magnetic core). The mechanical parameters are also checked.

A6.3. Design of a single phase, low power mains transformer

A6.3.1. Introductory Notions

In order to easily understand the design flow of a mains transformer, some introductory notions referenced in some calculus will be presented.
Laminations type – Usual there are used standardized laminations of type E+I "economical", or “scrapless” E+I laminations, see Fig. A6.2, called this way, because starting from one silicon steel stripe there are concomitant obtained through punching two **E** and two **I** laminations pieces, without losing any material from the steel metal stripe, as seen in Fig. A6.2.b. Dimensions of the laminations are given by the letter E, followed by a[mm], which is the base dimension (parameter) of the E lamination. There exists following standardized economical laminations: E5; E6.4; E8; E10; E12.5; E14; E16; E18; E20; E25; E32. Main geometrical parameters of the standardized E+I economical lamination are shown in Figure A6.2.a.



(a) (b)

Fig. A6.2 *(a) Dimensions of standardized economical lamination sheets;* A_f *– window area; (b) punching of „scrapless" lamination sheets.*

The thickness of the laminated sheets is also standardized to values of g_1=0.35mm and respectively, g_2=0.5mm.

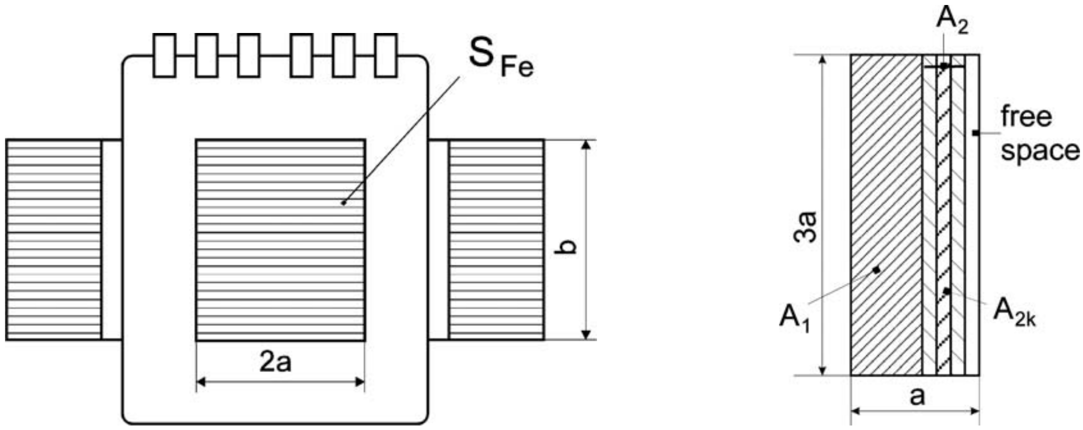
Window area of the E laminated sheet $A_F[cm^2]$ – represents the surface destined to windings and is represented with hatch in Figure A6.2.a. The value of this is:

$$A_F[cm^2]=0.03\cdot a^2[mm]$$

Iron cross-section $S_{Fe}[cm^2]$ – represents the cross section area of the magnetic core inside the winding case, Figure A6.3.a. It's value is:

$$S_{Fe}[cm^2]=0.02\times a[mm]\times b[mm],$$

where b[mm] – represents the thickness of the laminated sheets package



S_{Fe} – iron core cross section $\qquad\qquad$ $A_t=A_1+A_2$; $\gamma=A_t/A_f$

(a) $\qquad\qquad$ (b)

Fig. A6.3 *(a) Transversal cross section through a mains transformer;*
(b) Windings arrangement in the window area.

Filling factor of window γ - defined as the ratio between the total area occupied by windings in the window, $A_t[cm^2]$ and the window total area, $A_F[cm^2]$, according to:

$$\gamma = \frac{A_t\left[cm^2\right]}{A_F\left[cm^2\right]} = \frac{A_1\left[cm^2\right] + A_2\left[cm^2\right]}{0{,}03 \cdot a^2\left[mm\right]},$$

where: $A_1[cm^2]$ – represents the area occupied by the primary winding;

$A_2[cm^2]$ - represents the area occupied by the secondary winding or windings; (A_{2k} – area occupied by secondary winding *k*);

$A_t[cm^2] = A_1[cm^2] + A_2[cm^2]$ – total area occupied by windings.

Note:

In order that a mains transformer to be easily produced in series production, the optimum value for the filling factor is γ_o=0.7, but generally a value of filling factor $\gamma\in[0{,}64\div0{,}76]$ is accepted. A greater filling factor leads to difficulties in the lamination phase regarding the insertion of lamination into the bobbin. A lower filling factor is uneconomical, with the transformer being oversized.

A6.3.2. Initial design data

The design of a low power mains transformer is based on the following known data (initial design data):

- $U_1[V]$ - the rms (effective) value of the primary voltage, usually representing the voltage of the single-phase AC (110V, 220V);
- f [Hz] - the frequency of the single phase, alternating current;
- k - the number of secondary windings;
- $U_{2k}[V]$ - the effective voltage with load in the secondary winding k;
- $I_{2k}[A]$ - the effective current in the load, in the secondary winding k;

- B_M[T] - maximum allowable magnetic field (induction) in the magnetic core;
- The implemented winding process ("with or without insulation between layers") required by the electrical and climatic conditions in which the respective transformer will be used. Figure A6.4 shows the electrical diagram of a mains transformer with the parameters specified above.

The design of the mains transformer consists in calculating the data necessary for its realization in practice, namely:
n_1 - the number of turns in the primary winding;
n_{2k} - the number of turns in the secondary winding k;
d_1 [mm] - the diameter of the winding conductor in the primary winding;
d_{2k} [mm] - the diameter of the winding conductor in the k secondary winding;
a[mm]- type of standardized sheets that are used so that, $\gamma_{Standard} \in [0,64 \div 0,76]$;
b [cm] - the thickness of the bundled lamination sheets;
N - the number of required lamination sheets

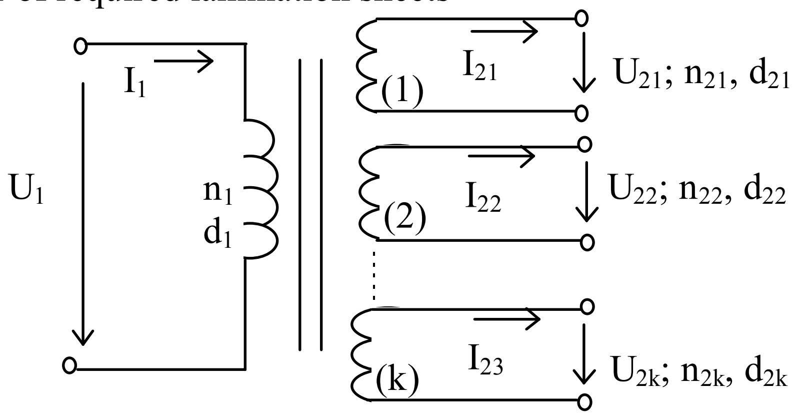


Fig. A6.4 *Electric schematic of a mains transformer.*

A6.3.3. The methodology of designing the single phase, low power mains transformer

The design of a mains transformer comprises the following calculation steps:
a) evaluate the total absorbed power from the secondary, P_2 [W], as follows:

$$P_2[W] = \sum_k P_{2k} = \sum_k U_{2k} I_{2k}$$

b) calculate the power absorbed in primary, P_1 [W], for an estimated transformer efficiency (yield) η=0,85;

$$P_1[W] = \frac{P_2[W]}{\eta} = \frac{P_2[W]}{0,85} = 1,176 \cdot P_2[W]$$

Note:

In a real mains transformer there are losses through magnetization (hysteresis) and by eddy currents (Foucault) in the magnetic core, as well as Joule effect losses in the copper conductors of the windings. These losses lead to the heating of the core and of the winding conductor during the operation of the transformer. For a mains transformer rated at $P_1 \approx 100$W realized with Romanian **E** + **I** laminations, the losses through magnetization can be estimated at approx. 8%, eddy current losses at approx. 2% and Joule effect losses at approx. 5%, so a total estimated loss of approx. 15%, which justifies the above yield.

c) calculate the iron cross section, $S_{Fe}[cm^2]$ of magnetic core, using:

$$S_{Fe}\left[cm^2\right] = 1{,}2 \cdot \sqrt{P_1[W]}$$

<u>Note:</u>

The connection between the cross section and the power is explained by the fact that, due to the shape of the magnetic circuit, the space available for windings is limited. When power increases, the area occupied by windings increases, and the window area is proportional to S_{Fe}. Also, with increased power the losses also increase, which requires the increase of S_{Fe}., in order to enlarge the cooling surface (the contact surface of the core with the air, represented by the lateral surface of the windings). Experimentally, we reached the optimum value of the proportionality ratio between section and power, ie 1.2.

d) compute the number of turns per volt n_0, with the relation:

$$n_0 = \frac{45 \div 48}{S_{Fe}}$$

derived from electromagnetic induction law, for f=50Hz and B_M=1,2T.

<u>Note:</u>

The above relationship was derived as follows:

The U voltage, induced in a spiral coil with **n** turns according to the law of electromagnetic induction, has the expression:

$$U_{\max} = -n\frac{d\Phi_{\max}}{dt}, \text{ but } \Phi_{\max} = B_{\max} \cdot S_{Fe}, \text{ and } U_{\max} = \sqrt{2}U_{ef}$$

In a permanent harmonic (sinusoidal) regime, the derivation of a physical quantity is equivalent to its multiplication with $\omega=2\pi f$, so that is obtained:

$\sqrt{2} \cdot U_{ef} = 2\pi \cdot f \cdot n \cdot B_{\max} \cdot S_{Fe}$, where from $n_0 = \frac{n}{U_{ef}}$ has the expression:

$$n_0 = \frac{\sqrt{2}}{2\pi \cdot f \cdot B_{\max} \cdot S_{Fe}} = \frac{1}{4{,}44 \cdot f \cdot B_{\max} \cdot S_{Fe}}$$

For f=50Hz, B_{max}=B_M=1,2T and S_{Fe} expressed in cm^2, the above relation becomes:

$$n_0\left[sp/V\right] = \frac{10^4}{4{,}44 \cdot 50 \cdot 1{,}2 \cdot S_{Fe}\left[cm^2\right]} = \frac{38}{S_{Fe}\left[cm^2\right]}$$

The theoretical figure from above, 38 will be increased at increases 45÷48 since the magnetic core must not reach saturation when the mains voltage will be at limit 242V (220V + 10%) or in case that in some of the secondary windings will be crossed by a DC component, which will cause additional core magnetization. This last situation can occur in rectifying circuits. It is recommended to use the value 48 because it corresponds to an optimal thermal regime (approx. 60 °C) of the transformer, verified experimentally, leading to a good match of the measured values with the calculated ones, avoiding the saturation of the core even under the most unfavorable conditions. If the mains frequency is different than 50Hz or B_M is different from 1.2T, the coefficient at numerator will be increased by the same percentage value as the increase from 38 to 48 (the percentage increase was checked for cases where B_M=0,8÷1,2T).

e) calculate the number of turns in the primary winding n_1 with the relation:

$$n_1=n_0 \cdot U_1$$

Note:

The resulting value n_1 is rounded up by the addition to the next integer value

f) determine the number of turns in the secondary k, n_{2k} , with the relation:

$$n_{2k} = 1.1 \times n_0 \times U_{2k}$$

Note:

In the above relationship, n_0 has been increased by 10% to compensate for the voltage drop in load on the secondary k. The resulting value for n_{2k} shall be rounded up to the next integer value.

g) determine the magnitude of the primary current, I_1, with the relation:

$$I_1[A] = \frac{P_1[W]}{U_1[V]}$$

h) determine the diameter of the winding conductors d_1 [mm] for primary and d_{2k} [mm], respectively, for the secondary k, with the relation:

$$d_{1;2k}[mm] = 0.65\sqrt{I_{1;2k}[A]}$$

Note:

The above relationship has been obtained for a maximum allowable current density $J_M = \frac{I}{\pi \frac{d^2}{4}} = 3[A/mm^2]$

The resulting value for the conductor diameter, $d_{1;\ 2k}$, is rounded up to the immediately higher standardized diameter shown in Table A6.1 as follows:

for $d_{1;2k} \leq$ 0,7 mm only if the calculated value, with respect to nearest lower standardized value is> 2,5%;

- for 0.7 < $d_{1;2k}$ ≤1mm; if the calculated value, with respect to nearest lower standardized value is > 5%;
- for $d_{1;2k}$>1mm ; only if the calculated value, with respect to nearest lower standardized value is > 10%.

Otherwise, the rounding will be made to nearest lower standardized value.

i) calculate the areas occupied by the primary winding, $A_1[cm^2]$, and secondary winding, $A_2[cm^2]$, in the area window, using the filling coefficients C_1 or C_2 indicated in Table A6.1, depending on the winding procedure adopted, according to the relations:

$$A_1\left[cm^2\right] = \frac{n_1}{C_{1;2}} \qquad \mathrm{A}_2\left[cm^2\right] = \sum_k A_{2k} = \sum_k \frac{n_{2k}}{C_{1;2}}$$

Note:

Filling coefficients were determined experimentally under the series production conditions for each standardized diameter.

j) calculate the total area occupied by windings $A_t[cm^2]$ with the relation:

$$A_t[cm^2] = A_1[cm^2] + A_2[cm^2]$$

k) determine the required dimension for the laminations, in fact the ***a*** parameter, for an optimum filling factor $\gamma_0 = 0,7$ with the relation:

$$a[mm] = \sqrt{\frac{A_t\left[cm^2\right]}{0.03\times 0,7}} = 6.9\times\sqrt{A_t\left[cm^2\right]}$$

Note: If the value determined by the calculation for parameter ***a*** is not standardized, then the nearest standardized value can be chosen, provided that the value of the filling factor fulfills the condition:

$$\gamma_{Standard} \in [0,64 \div 0,76], \qquad \text{where } \gamma_{Standard} = \frac{A_t\left[cm^2\right]}{0.03\times a^2_{Standard}[mm]}$$

l) calculate the thickness of the lamination package b [mm], with standardized laminations, using the relation:

$$b[mm] = \frac{S_{Fe}\left[cm^2\right]}{0.02\times a_{Standard}[mm]}$$

m) evaluate the number of required lamination pieces N depending on their thickness $g_{1,2}$ ($g_1 = 0.35$mm; $g_2 = 0.5$mm)

$$N[number\ of\ laminations] = \frac{b[mm]}{g_{1;2}[mm]}$$

Note:

The number of the obtained pieces N is rounded up (by addition) to the nearest integer value.

Table A6.1 *Standardized diameters and filling coefficients for enameled copper conductors used for windings*

Diameter of standardized conductor [mm]	C_1[turns/cm^2] (with layer insulation)	C_2[turns/cm^2] (without layer insulation)
0.05	13250	16150
0.07	8330	9700
0.1	4460	6100
0.12	3190	4120
0.15	2260	2880
0.18	1730	2050
0.2	1465	1715
0.22	1210	1460
0.25	978	1140
0.28	813	925
0.3	722	807
0.35	530	594
0.4	350	470
0.45	277	371
0.5	224	300
0.55	190	252
0.6	162	209
0.65	142	180
0.7	125	153
0.8	95.5	127
0.9	78	93
1	65	75
1.2	40.5	52
1.5	26.5	33.5
2	15.5	19

Note: In USA wire dimensions are expressed in so called AWG- American Wire Gauge and not directly in wire diameter.

A6.3.4. Example of designing a single-phase, low power network transformer

It is required to design a mains transformer with the following initial data: U_1=220V; f=50Hz; U_{21}=6.3V; I_{21}=0.3A; $U_{22}=U_{23}$=15V; $I_{22}=I_{23}$=2.54A; B=1.2T; Both "with layer insulation" and "without layer insulation" winding processes will be considered. The calculations are carried out according to the design methodology indicated, as follows:

a) evaluate the total absorbed power from the secondary, P_2:

$$P_2=6.3\times0.3+2\cdot15\times2.54=78.09\text{W}$$

b) calculate the power absorbed in the primary, P_1 for η=0.85;

P_1=78.09/0.85=91.87W

c) determine the magnetic core cross section, S_{Fe};

$$S_{Fe} = 1.2 \times \sqrt{91.87} = 11.5 cm^2$$

d) calculate the number of turns/V, n_0, required:

n_0=48/11,5=4,173 sp/V

e) determine the number of turns in the primary winding, n_1:

n_1=4,173·220=918,06 sp.

Note:

The obtained value can be rounded to n_1 = 920 turns so that it is easily memorized and tracked by the coil machine operator, the tolerance allowed in this case being less than 1%, which is acceptable;

$$t = \frac{920 - 918.06}{918.06} \cdot 100\% = 0.21\% < 1\%$$

f) calculate the number of turns required for the three secondary windings:

n_{21}=1.1×4.173×6.3=28.91 sp

n_{22}=n_{23}=1.1×4.173×15=68.85 sp

Note:

Calculated values are rounded to n_{21} = 29 sp and n_{22}=n_{23}=69 sp, respectively

g) evaluate the current in the primary winding, I1:

I_1=91.87/220=0.417A

h) calculate the diameters of the primary winding conductors, d_1 and secondary, d_{2k}:

$$d_1 = 0.65 \times \sqrt{0.417} = 0.419 mm$$

$$d_{21} = 0.65 \times \sqrt{0.3} = 0.365 mm$$

$$d_{22} = d_{23} = 0.65 \times \sqrt{2.54} = 1.035 mm$$

On the basis of the indications given in the design methodology, the standardized diameters are chosen:

d_1=0.45 mm; d_{21}=0.35 mm; d_{22}=d_{23}=1 mm

i) calculate the areas occupied by windings in the area window in both winding processes:

- with layer insulation - $A_1 = \frac{920}{277} = 3.321 cm^2$

$$A_2 = \frac{29}{530} + 2 \cdot \frac{69}{65} = 2.177 cm^2$$

- without layer insulation - $A_1^{'} = \frac{920}{371} = 2.479 cm^2$

$$A_2^{'} = \frac{29}{594} + 2 \cdot \frac{69}{75} = 1.888 cm^2$$

j) evaluate the total areas occupied by windings in both cases:

A_t=3.321+2.177=5.498 cm^2;

$$A_t^{'} = 2.479 + 1.888 = 4.367 cm^2$$

k) calculate the laminations dimensions in both cases:

$$a = 6.9 \times \sqrt{5.498} = 16.17 mm$$

$$a' = 6.9 \times \sqrt{4.367} = 14.41 mm$$

We choose the standardized laminations E16 and respectively E14 and the filling factor is checked with this standardized values, $\gamma_{Standard}$:

$$\gamma_{Standard} = \frac{5.498}{0.03 \times 16^2} = 0.71$$

$$\gamma_{Standard}^{'} = \frac{4.367}{0.03 \times 14^2} = 0.74$$

The lamination sizes are accepted because $\gamma_{Sstandard}$ and $\gamma'_{Standard} \in [0.64 \div 0.76]$.

l) calculate the thickness of the laminations package b and b' using the selected standardized laminations sizes:

$$b = \frac{11.5}{0.02 \times 16} = 35.93 \text{mm}$$

$$b' = \frac{11.5}{0.02 \times 14} = 41.07 \text{mm}$$

m) determine the number N of lamination pieces required in both cases, for g_1=0.35mm:

$$N = \frac{35.93}{0.35} = 102.65 \text{ pieces}$$

$$N' = \frac{41.07}{0.35} = 117.34 \text{ pieces}$$

The obtained values are rounded up by addition to N=103 and respectively, N'=118.