Materials and Constructions for Magnetic Cores for Impulsed Transformers

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Abstract – **We present some considerations for construction designing impulsed transformers. The analysis was done on the basis of some most common ferrite materials. It is given some information about these materials and some table values about the dimensions and parameters of the existing magnetic cores. An example, which illustrates how the methodology works, is enclosed.**

I. THEORY

In the contemporary radioelectronics, the usage of impulsed transformers increases. They are used for matching the resistance in impulse circuits and for reversing the impulse polarity. They accomplish the galvanic separation of the impulse circuits when the loading changes. Despite the impulsed transformers (IT) large-scale application, so far there is no a universal methodology for their design. A methodology for designing a IT for monopolar impulses is presented and illustrated by an example in this paper.

IT is calculated and designed by parametres of the single impulse (Fig. 1). Checks on the impulse parameters are done if necessary: time of pulse increasing t_r; pulse length t_p; time of pulse fade t_f, time of pulse restoration t_{rs}; plateau drop ΔU and allowable pulse overshoot [1].

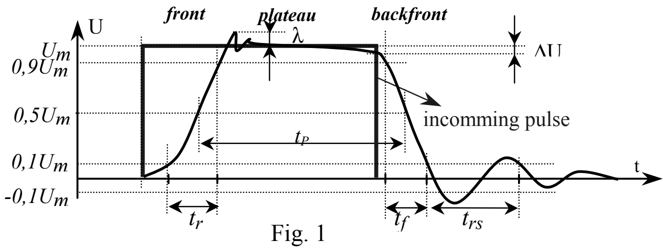

Fig. 1

The output impulses of the real IT have a shape different from the rectangular one (i.e. different from the shape of the input impulse). The rectangular impulse can be developed in a harmonic expansion - it can be viewed as a compound of different harmonic signals with frequency from 0 to ∞. It means that there is no a wider band signal than the rectangular impulse. Each diversion from the rectangular form can be viewed as a contraction of the unlimitedly wide frequency band typical for the ideal transformer. Due to the availability of some capacititances and inductances in a real transformer, the shape of the passing through it impulse is inevitably distorted at the output. The impulse distortion is defined according to the change of their parameters. There usually exist two main requirements to a IT – to transmit the impulses with minimum distortion and a minimum loss of power.

The equivalent scheme of a IT with a steel magnetic core is shown in Fig. 2. Its elements do not have an inductive connection between them. r_1 and r_2' are ohmic resistance of the primary winding and the reduced value of the secondary winding resistance, L_{S1} and L_{S2}' are the distortion inductance of the primary winding and the reduced value of the distortion inductance of the secondary winding. The magnetizing current of the transformer flows through the inductance L_1 of the primary winding, also called the inductance of magnetization. It produces the main magnetic flow in the magnetic core:

$$L_1 = W_1 \frac{\Phi_0}{I_0}. \tag{1}$$

They reflect whirling currents in the magnetic core. These parameters together with a spurious capacitance at a certain frequency create conditions for unwanted resonance phenomena. The other elements are on the analogy of those of the low-frequency transformer: R_i – internal resistance of the pulse signal source ($R_i = U_{output} / I_{output}$); E- electromotive force; R_2' – reduced value of the loading voltage, connected to the secondary winding ($R_2' = R_2/n^2$); $C_{1,2}$ - capacity between the windings; $C_{1,1}$ and $C_{2,2}'$ - total capacity of the primary winding and the reduced value of the total capacity of the secondary winding. The relationship between the inductance increase and the change in the field intensity is called impulse magnetic permeability μ_Δ. The value of the residual induction B_0 in the magnetic core is inversely proportional to the induction in it as well as to the magnetic permeability of the corresponding particular hysteresis cycle, i.e. the high value of B_0 means inefficient usage of the magnetic core. But the more inefficient usage of the magnetic core requires a greater number of loops in the primary winding W_1 in order to receive the necessary inductance of the primary winding. This, from its part increases the distorted inductance and the spurious capacitances of the IT.

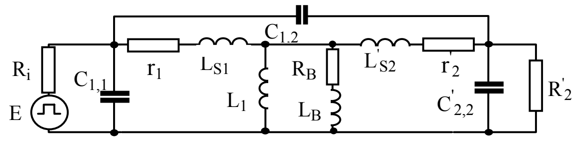

Fig. 2

II. DESIGN METHODOLOGY

When designing a IT some parameters are compulsory to be given: maximum value of the current in the secondary winding I_m, A; load resistance $R_2 \Omega$; impulse duration t_p, s; relative voltage drop on the load at the end of the impulse $p = \Delta U/U_m$; internal resistance of the impulse generator R_i; voltage of the primary winding U_1.V.

A. The transformation coefficient

The transformation coefficient is defined by the expression:

$$n = U_2/U_1.\eta, \tag{2}$$

where $\eta = 0{,}8 \div 0{,}9$ is the coefficient of the transformer performance.

B. Defining the inductance of the primary winding.

The inductance L_1 of the primary winding of the IT influen-

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ces the distortion of the impulse plateau (Fig.2). L_1 is calculated in a way that does not allow the plateau distortion to overcome a previously given value (it is required that at the end of the impulse the relative voltage drop P on the load is $P = \Delta U/U_m \leq 5$ %). The following expression is used:

$$L_1 = \frac{R_e . t_P}{P}, \tag{3}$$

where the equivalent resistance has a value of :

$$R_e = \frac{R_i . \frac{R_2}{n^2}}{R_i + \frac{R_2}{n^2}} . \tag{4}$$

C. Selection of the material and shape of the magnetic core.

Magnetic cores used in the production of a IT are most commonly П-shaped or toroidal (ring-shaped), manufactured from sheet electromechanical steel, permalloy or a ferrite. The value of μ_Δ depends on the intensity of the magnetic field and it should be experimentally defined for each material. Fig.3 shows the dependence of the impulse magnetic permeability μ_Δ for the Э320 cold-rolled sheet steel.

At impulse magnetizing whirling currents appear in the sheet material. They distort the impulse edge and reduce μ_Δ. To receive output pulses with minimum distortion of the edges, the whirling currents in the magnetic core must be minimum, i.e. the following condition must be fulfilled:

$$\tau_B \leq \frac{t_P}{3} . \tag{5}$$

Each sheet material according to its thickness δ is characterized by a specified value of its time constant τ_B. The value of τ_B depends on the specific electric resistance ρ of the magnetic core material and on pulse magnetic permeability μ_Δ:

$$\tau_B = 4.10^{-8} \frac{\mu_\Delta \delta^2}{\rho} . \tag{6}$$

For the sheet electromechanical steels (in which Si quantity is 2.8÷3.8%), $\rho \approx 0.5 \times 10^{-6}$ Ω m, standard values of δ are 0.35; 0.20; 0.15; 0.08; 0.05mm. Strips that are 0.02mm long are used in Permalloy. The real value of the impulse magnetic permeability μ_P which calculates the inductance of the primary winding of the transformer is defined by the expression:

$$\mu_P = A . \mu_\Delta , \tag{7}$$

where A is the coefficient whose value is considered in accordance to the relation t_P/τ_B (Fig.4).

Compared to the sheet magnetically soft materials the ferrite ones have greater specific electric resistance, which makes the influence of the whirling currents insignificantly low and their μ_Δ has to 10 times greater value, and $\mu_P \approx \mu_\Delta$. When using ferrite μ_Δ for each material is defined from the experimentally received dependence $\mu_P = f(\Delta B)$ for a certain impulse duration and impulse-repetition frequency (period $T=1/f$). When using ferrite materials for manufacturing powerful IT not only μ_Δ but also the degree of heating is taken into consideration. As it is due to the losses in the magnetic core, the specific magnetic volume losses become an important parameter $P_Ф$ the dependence of $P_Ф$ from the induction and the impulse length is used for selecting the suitable material for powerful IT manufacturing. These dependences for German ferrite materials T26, N30, T35, T39 and N27 are shown in Fig.5, Fig.6, Fig.7, Fig.8, Fig.9 and Fig.10 [2]. Fig.3 and Fig.4 can be used for the Э320 cold-rolled sheet electromechanical steel.

The most suitable Russian ferrite for making IT magnetic cores are nickel-zinc ones with steel quality 300ННИ, 350ННИ1, 450ННИ, 1000ННИ, 1100ННИ and manganese-zinc 1100НМИ. Data on the basic parameters of these ferrite materials are included in Table1, additional parameters – in Table2. The dependence μ_Δ on the temperature is shown in Fig.11. The dependence of the specific magnetic volume losses on the induction in the magnetic core at different pulse length is shown in Fig. 12, 13 and 14 for ferrite 1000ННИ, 450ННМ and 1100НМИ [3]. The dependence of μ_Δ on the pulse length is shown in Fig.15.

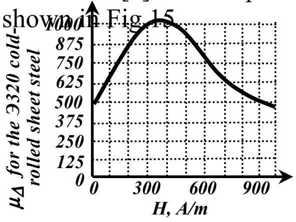

Fig.3

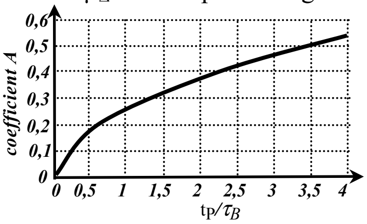

Fig.4

TABLE 1
DATA ON THE BASIC PARAMETERS OF THE FERRITE MATERIALS FROM 5TH GROUP

Quality	μ_P at t_P=1÷3μs and f_P=0,5÷5kHz	Optimal value for $H_И$, A/m	$\Delta\mu_P/\mu_P$, %, at temperatures in the range of:	
			-60÷+20 °C	+20÷+80 °C
300ННИ	300±50	80÷240	-30÷+30	-30÷+30
300ННИ1	300^{+80}_{-50}	64	-4÷+8	-4÷+8
350ННИ	350±75	80	-	-30÷+30
450ННИ	450±50	240	-25÷0	0÷+10
1000ННИ	1000^{+300}_{-250}	64	-30÷0	-30÷0
1100ННИ	1100±250	80	-50÷0	-50÷0
1100НМИ	1100±150	80	-25÷+25	-25÷+25

D. Selection of a magnetic core.

The minimal capacity that a magnetic core must have is defined by this formula:

$$V_{CT} = \frac{\mu_0 \mu_P U_I^2 t_P^2}{\Delta B^2 L_1}, \ m^3 \tag{8}$$

where $\Delta B = (\Delta B)_{max}$ and the corresponding value of the ferrite material N27 are reported in the diagram in Fig. 9.

TABLE 2
DATA ON THE ADDITIONAL PARAMETERS OF THE FERRITE MATERIALS FROM 5TH GROUP

quality	f_{KP}, MHz at $tg\delta_\mu$=1	μ_{max}	H_0, A/m at μ_{max}	B, T	B_r, T	H_C, A/m	$\Delta\mu_P/\mu_P$, %, at temperatures in the range of:		ρ, Ω.m	Shape of the magnetic core
							-60÷20°C	20÷100°C		
300ННИ1	2,0	400	160	0,22	0,06	96	-2,0÷+1,0	-2,0÷+1,0	10^4	Toroidal
350ННИ	2,5	1000	80	0,26	0,12	48	3,0÷24,0	4,0÷17,0	10^7	Toroidal O-shaped
450ННИ	1,0	2100	56	0,37	0,16	40	8,0÷14,0	6,0÷18,0	10^3	Toroidal П-shaped
1000ННИ	0,5	3000	32	0,30	0,09	16	4,0÷9,0	2,0÷6,0	10^3	Toroidal
1100ННИ	0,4	3000	32	0,27	0,08	20	3,0÷6,0	2,0÷4,0	10	Toroidal
1100НМИ	0,3	3000	32	0,40	0,15	24	1,0÷3,0	1,0÷3,0	0,1	Toroidal

On the basis of the calculated by (8) minimum necessary value of V_{CT} from tables a standard magnetic core is selected. If there is no a magnetic core with the calculated V_{CT} a magnetic core whose capacity is bigger and closest to that is selected. Constructional parameters are reported for the selected standard magnetic core.

In Fig.16 are shown some ferrite П - shaped magnetic cores – german production. These magnetic cores, which are called U-Kerrn and I-Kerrn, have exceptional wide application for the production of IT. Data for this type of magnetic cores can be found in Table 3.

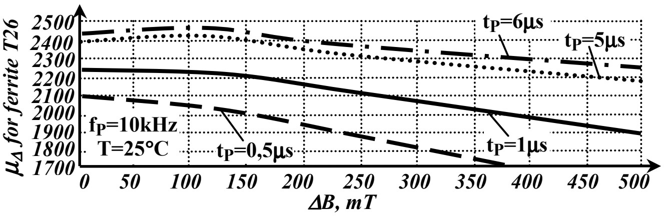

Fig. 5 Dependence of the specific magnetic capacity losses on the magnetic induction in a ferrite T26 magnetic core at different pulse length

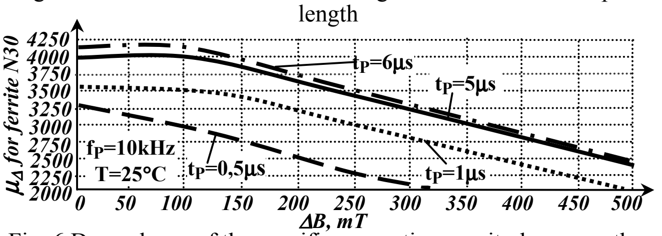

Fig. 6 Dependence of the specific magnetic capacity losses on the magnetic induction in a ferrite T30 magnetic core at different pulse length

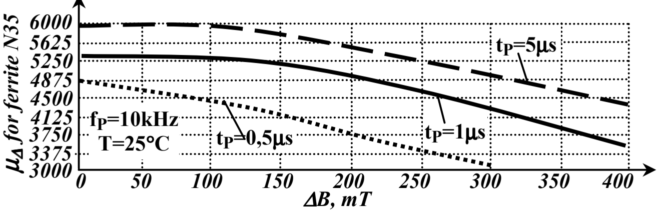

Fig.7 Dependence of the specific magnetic capacity losses on the magnetic induction in a ferrite T35 magnetic core at different pulse length

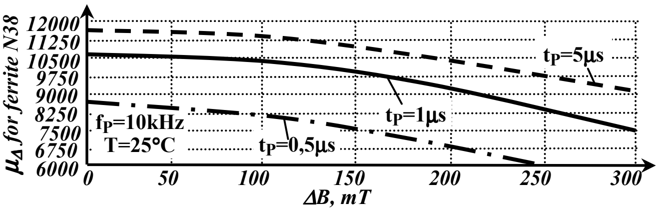

Fig.8 Dependence of the specific magnetic capacity losses on the magnetic induction in a ferrite T38 magnetic core at different pulse length

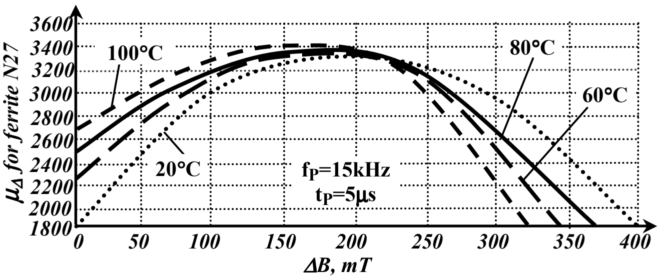

Fig.9 Temperature dependence of the pulse magnetic permeability at optimal magnetic-field strength of the pulse magnetizing subfield, tP= 5μs and fP= 15kHz

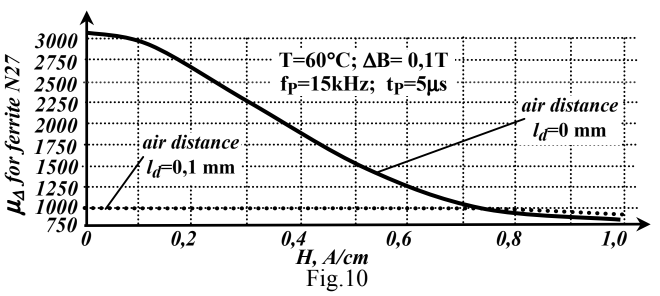

Fig.10

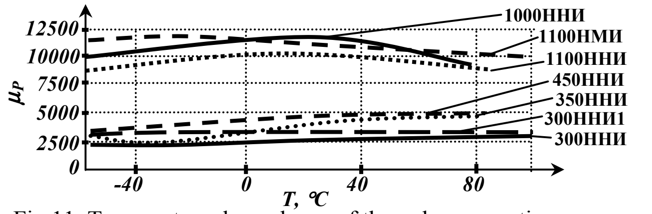

Fig.11. Temperature dependence of the pulse magnetic permeability at optimal magnetic-field strength of the pulse magnetizing subfield, tP= 3μs and fP= 5kHz

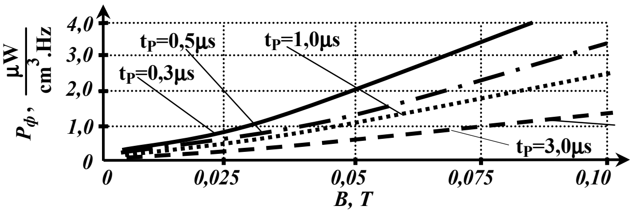

Fig.12 Dependence of the specific magnetic capacity losses on the magnetic induction in a ferrite 1000ННИ magnetic core at different pulse length

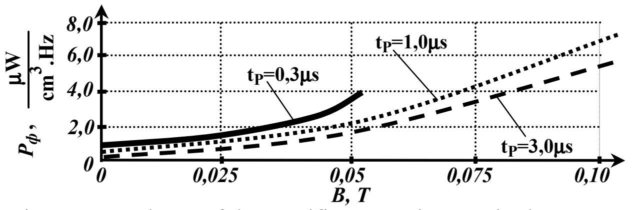

Fig.13 Dependence of the specific magnetic capacity losses on the magnetic induction in a ferrite 450ННИ magnetic core at different pulse length

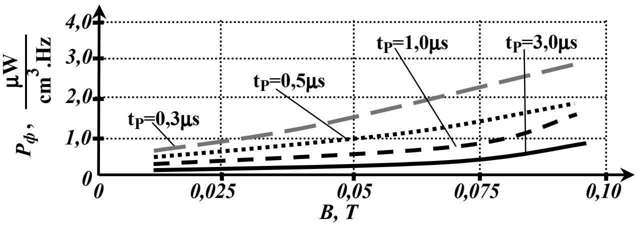

Fig.14 Dependence of the specific magnetic capacity losses on the magnetic induction in a ferrite1100НМИ magnetic core at different pulse length

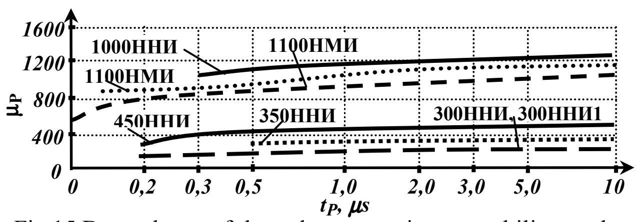

Fig.15 Dependence of the pulse magnetic permeability on the pulse length at magnetic-field strength of 80A/m and frequency of the pulse train of f_p=5kHz.

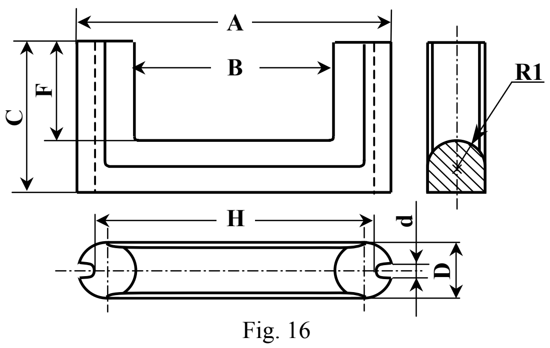

Fig. 16

TABLE 3
PARAMETERS OF SOME OF THE MANUFACTURED IN GERMANY
Π-SHAPED CORES MADE OF FERRITE MATERIAL SIFERRIT N27

Shape of the core	TYPE	MARK IN **DIN 41296**	DIMENSIONS, mm A	B	C	F	H	D	l_{CT}	Q_{CT}, mm^2	V_{CT}, mm^3	G_{CT}, g
Π-shaped (U-Kerne)	U 59	B67333	59	26,5	36,9	21,5	50,5	17	189	210	39690	200
Π-shaped (U-Kerne)	U 57	B67334	57,5	26,9	28,4	16	49,8	15,9	168	170	28560	140
Π-shaped (U-Kerne)	U 64	B67335	64	35,5	29,5	18	56,7	13,8	190	140	26600	127
Π-shaped (UI-Kerne)		B67336	57 57	27 27	44,4 12,9	31 0,5	49,6 50	15,6 15,6	168	170	28560	140

III. AN EXAMPLE OF A IMPULSED TRANSFORMERS DIMENSIONING

Task. Design a IT following the initial data given below.

Initial data: internal resistance of the impulse signal source R_i=40Ω; loads resistances R_2=200Ω, R_3=20Ω, R_4=2,3Ω; peak value of the input impulse voltage U_1=300V; peak value of the currents in the secondarys windings I_2=0,55A, I_3=0,85A, I_4=2,2A (Fig. 18); frequency of the pulse sequence fp=15kHz; impulse duration t_P=5μs; relative voltage drop on the load R2 at the end of the pulse 2% ($p \leq 2\%$);

Technical, constructional, technological and financial specifications, data on the performance conditions and regime: a IT is going to work under normal weather conditions, indoor, in a continuous operating regime. It must be dimensioned optimally with minimum weight and volume.

Initial electrical calculations

The average value is chosen in the recommended range η=0,8÷0,9. We accept η=0.85.

The peak voltage value of the input impulses is calculated U_2, U_3 and U_4:

$U_2 = I_2.R_2 = 0{,}55.200 = 110$V; U_3=17V; U_4=5,06V

We use an expression (2) to find the coefficient of IT:

$$n_2 = \frac{U_2}{U_1.\eta} = \frac{110}{300.0{,}85} = 0{,}4314; \qquad n_3 = 0{,}0667; \qquad n_4 = 0{,}02.$$

We calculate the reduced value of the load resistance:

$$R'_2 = \frac{R_2}{n_2^2} = \frac{200}{0{,}4314^2} = 1074{,}7\ \Omega; \quad R'_3 = 4495{,}5\Omega; \quad R'_4 = 5750\Omega.$$

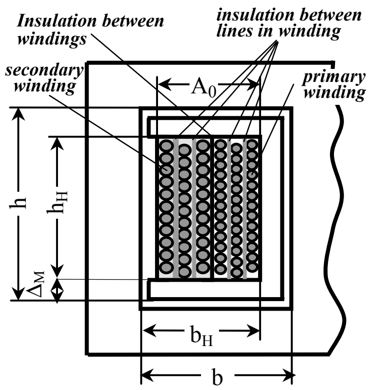

Fig. 17

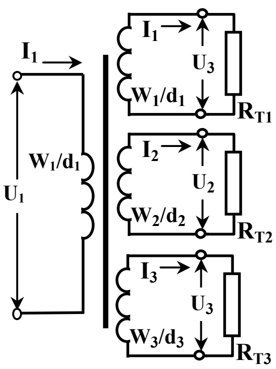

Fig. 18

Using (4) we calculate the equivalent IT resistance:

$$R_e = \frac{R_i.R'_{2\Sigma}}{R_i + R'_{2\Sigma}} = \frac{40.753{,}7}{40 + 753{,}7} = 38\ \Omega$$

With (3) we calculate the inductance L_1 so that the plateau distortion does not exceed the previously given value, i.e. the relative voltage drop on the load R_2 R_3 and R_4 at the end of the impulse is less than 2% ($P = \Delta U/U_m \leq 2\%$).

$$L_1 = \frac{R_e.t_P}{P} = \frac{38.5.10^{-6}}{2/100} = 0{,}0095\,\text{H}\ ,$$

Initial constructional calculations.

According to the task the IT must have minimum weight and volume and be suitable for a continuous performance regime. That is why we chose a toroidal shape of the magnetic core. By doing this we achieve the best possible usage of the magnetic properties of the material. The current of the idle running and the scattering of the magnetic energy will be minimumal. The toroidal shape will provide minimum influence of the external magnetic fields.

We choose a ferrite for making the magnetic core. Ferrite have significantly greater specific electrical resistance than the sheet magnetically soft ones, i.e. their influence is small enough to be neglected. As the value of μ_P for a certain material is experimentally defined, depending on the magnetic-field strength, we choose a ferrite N27 for which we have an experimentally received dependence $\mu_P = f(\Delta B)$, reported for the impulse length $t_P = 5\mu s$, and frequency of repetition f_P =15kHz (Fig. 9). We choose a sufficiently high value of the induction, at which μ_P has still high values, for example $B = 0{,}22T$ (this tentative value must be specified). For $B = 0{,}22T$ we report the value μ_Δ = 3230

Using the formula (8) we can calculate the minimum value of the magnetic core volume:

$$V_{CT} = \frac{\mu_0 \mu_P U_1^2 t_P^2}{\Delta B^2 L_1} = \frac{4\pi 10^{-7}.3230.300^2.(5.10^{-6})^2}{0{,}22^2.0{,}0095} = 19852\,\text{mm}^3$$

$\Delta B = (\Delta B)_{MAX}$ and the responding value of μ_P for the ferrite N27, are shown in the diagram in Fig.9. By the calculated value of V_{CT}=19852, from table 3 we choose a standard magnetic core U64. The table values of the selected magnetic core are written: A=64mm; B=35,5mm; C=29,5±0,2mm; d=3,6mm; D=13,8±0,2 mm; H=56,7±1mm; F=18 mm; l_{CT}=190 mm; r_1=6,5mm; Q_{CT}=140 mm^2; V_{CT}=26600 mm^3; G_{CT}=127 g.

IV. CONCLUSION

50 IT with different parameters and design have been produced by using the suggested method. Their parameter measurement shows that the deviation from the given values is most frequently about 1,8÷3% and does not exceed 4% for any of the transformers. The received results assured us to conclude that the suggested methodology of a IT design with monopolar impulses is convenient for usage and gives the required accuracy. If a greater accuracy is necessary the parameters of the test sample must be measured and according to those results some corrections in the construction can be done.

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