Submicrosecond Pulsed High-Power Transformer Magnetic Cores

V.A. Vizir, A.D. Maksimenko, V.I. Manylov, G.V. Smorudov

Institute of High Current Electronics, Akademichesky 2/3, Tomsk, Russia

Abstract – Analysis and calculations have been performed of the magnetic cores parameters for high power pulsed linear transformers. Formulas are given for calculation of the base core dimension – its diameter depending on pulse parameters and magnetic material of the cores. Technology of the cores manufacturing is described. Parameters of linear transformers, developed in IHCE, and its magnetic cores are given. Typical waveforms are given for the transformer with 1.8 m core diameter.

1. Introduction

Giga- and terawatt transformers of submicro- and nanosecond pulses are made as linear pulsed transformers (LPT) so-called on the analogy of a linear inductive accelerator. In foreign scientific literature such set-up is called as a linear inductive adder. LPT represents by itself a coaxial which central electric conductor is a common secondary winding of concatenate single-turn current transformers. A primary winding look like a volume turn with a magnetic core placed in its cavity: one end of the primary winding is connected with the coaxial sheath (earth), and the second end is applied with a pulse from single primary generators. Secondary voltage (load voltage) is the sum of voltages of the primary windings; the secondary current is equal to primary generators current minus excitation current of a core.

A pulsed generator based on LPT possesses significant advantages as compared with the Marx generators in short pulse forming: it allows obtain of minor inductance, shorter pulses and matching of primary generators with low-resistance load. The most powerful generator based on LPT is a set-up Hermez III with the parameters 16 MV, 800 kA, 30 ns [1].

2. Calculations of the Magnetic Core Parameters

Nanosecond LPT magnetic cores are made from tape permalloys or metglasses. These materials provide minor energy losses for magnetic reversal allowing high efficiency obtain of current transfer from the primary circuit to a load (current efficiency):

$$\eta_I = \left(1 + \frac{I_\mu}{I_L}\right)^{-1}, \qquad (1)$$

here I_μ is excitation current of a core; I_L is load current (secondary winding current).

The LPT magnetic cores are commonly operating in a mode of total remagnetization from a magnetic induction negative value –Bs to a positive one + Bs that is provided by magnetic biasing prior to a pulse. In compliance with a domain theory of magnetization reversal, excitation current is defined from an expression [2]

$$I_f = \frac{S_w \cdot l_c}{\tau}, \qquad (2)$$

where τ is duration of a total remagnetization pulse; l_c is the length of the mean magnetic field line of a core; S_w is the change-over factor, i.e. quantity of electricity necessary for total remagnetization of a ferromagnetic normalized to core length of 1 m.

$$S_w = S_{w0} + S_{we}, \qquad (3)$$

where S_{w0} is a component determined by magnetic viscosity and measured experimentally; S_{we} is a component determined by inductive currents in the ferromagnetic strip and calculated by the formula

$$S_{we} = \frac{Bs \cdot \delta^2}{4\rho}, \qquad (4)$$

where δ is thickness of a magnetic strip; ρ is material resistivity.

In the case of relatively thick tapes ($\delta \geq 0.02$ mm) the inductive component becomes determining. Substituting (4) in (2) taking into account a volt-second integral $U\tau = 2\mathrm{Bs}\, S_c$ (U is primary winding voltage, S_c is cross-section of a core), it is possible to obtain

$$I_\mu = \frac{U}{R_v}, \qquad (5)$$

where resistance of inductive currents is

$$R_{we} = \frac{8\rho S_c}{\delta^2 l_c}. \qquad (6)$$

The same dependence is given in [3], but with a coefficient of 12 instead of 8. One might use this formula for approximate calculation of the average amplitude of magnetization current.

The energy losses for the core remagnetization at total remagnetization [2] are

$$W_c = \frac{2Bs S_c l_c}{\tau}. \qquad (7)$$

Substituting (2) in (1) taking into account that $l_c = \pi d_c$ an expression for the average core diameter may be derived:

$$d_c \le \left(\frac{1-\eta_\mathrm{I}}{\eta_\mathrm{I}}\right)\frac{I_\mathrm{L}\cdot\tau}{\pi\cdot S_w}. \qquad (8)$$

The core diameter value is the most important LPT parameter. That parameter determines power of a pulse transmitted. At the same time this parameter governs the cost of cores that essentially contribute to the cost of a set-up on the whole.

Magnetic cores made from thin-layer rolled electric steel are widely used for high-power pulsed microsecond transformers. The Table 1 presents the main parameters of different ferromagnetic materials. As an example, a diameter of a core at $\eta_\mathrm{I} = 0{,}9$, $I_\mathrm{L} = 1$ MA, and $\tau = 0{,}2$ μs calculated from (8) is also cited.

Accordingly it is seen from the data of the Table I that at sufficiently long submicrosecond current pulse it is possible to use thin-layer magnetic steel as a material for magnetic LPT cores having consequently an essential gain in set-up cost. Besides that, due to high saturation induction and high factor of steel packing (0.9 instead of 0.7 for permalloys and amorphous magnetic materials (AMM)) the steel cores even deflate LPT size.

The steel cores do not need annealing both permalloys and AMM. Hence due to relatively small residual induction ($B_\mathrm{r} \approx 1.2$ T) they will need an essential magnetic biasing (~ 1 kA/m) in order to have the total induction drop $\Delta B = 3.8$ T.

3. Linear Transformers with Use of Magnetic Cores

Long ago at the High Current Electronics Institute of SB RAS the LPT having pulse duration of (1÷2) μs have been developed and used with success [4, 5]. During last ten years, series of LPT operating in a submicrosecond range have been developed. Pulse parameters of such LPT stages and parameters of their magnetic cores are shown in Table II. The pulse duration is given at half-height. All the cores are made from magnetic steel ES-3425 of 0.08 mm in thickness and 18 mm in width. Fig. 1 shows pulse oscilloscope traces of the stage 5: U_L – active load voltage; I_L – load current; I_1 – magnetization current of a core; VS – volt-second integral U_L. The stage operated in demagnetization mode at demagnetization current pulse applied in a pause between pulses. Induction drop is $\Delta B = B_\mathrm{r} + B_\mathrm{s} = 3.1$ T. It is seen that the core saturation starts in 250 ns.

Table 1. Parameters of different ferromagnetic materials

Magnetic material	Parameters			
	Bs, T	ρ, Ω·m	S_w, K/m	d_c, m
Permalloy 50НП (δ = 0,02 mm)	1.5	$0.5\cdot10^{-6}$	~ $500\cdot10^{-6}$	15
Amorphous magnetic material 2НСР (δ = 0.025 mm)	1.5	$1.2\cdot10^{-6}$	~ $300\cdot10^{-6}$	24
Electric steel ES-3425				
(δ = 0,05 mm)	1.9	$0.5\cdot10^{-6}$	~ $2400\cdot10^{-6}$	3.0
(δ = 0,08 mm)	1.9	$0.5\cdot10^{-6}$	~ $6000\cdot10^{-6}$	1.2

Table 2. Pulse parameters of LPT stages and parameters of their magnetic cores

No.	Stage parameters						Refs.
	U_I, kV	I_L, MA	τ, μs	d_c, m	S_c, cm^2	η_I, r.u.	
1	60	1	0.7	0.25	110	0.99	[6]
2	50	0.18	0.6	0.37	80	0.99	[7]
3	100	0.2	0.2	0.37	60	0.95	[8]
4	105	0.5	0.16	0.92	46	0.88	[9]
5	125	0.65	0.18	1.85	60	0.75	[10]

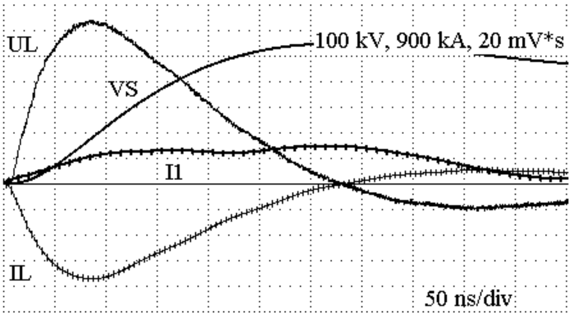

Fig. 1. Pulse oscilloscope traces of the stage 5: U_L – active load voltage; I_L – load current; I_1 – magnetization current of a core; VS – volt-second integral U_L

4. Technology of the Magnetic Cores Manufacturing

Magnetic cores were coiled round by using specially outfitted machine tools. The cores of up to 1 m in diameter were coiled round by using a machine having a horizontal axis of coiling. Simultaneously with coiling, removing of the edge protuberances by rolling of a tape between the rollers was made. At the same time, tape windings were isolated by coiling between them polypropylene or lavsan strips (10 ± 12) μm in thickness and 20 mm in width so that the strips were advanced above the tape for 1 mm. The packing factor of the cores with steel was 0,9 for the cores with a diameter of up to 400 mm, and it was less as ~ 0.85 for the cores of 1 m in diameter. Coiling speed of the cores was ~30 kg/hour. The cores of 1850 mm in diameter were coiled by using a machine having a vertical axis with a special mandrel. Coiling speed was ~ 10 kg/hour. The packing factor was ~ 0.8.

Core resistance being measured from the internal diameter to the external one differed from a calculated value no more than by ~ 5%. In cases of core resistance decreasing by 10%, the cores were recoiled. Single cores were tested for electric strength by a pulse application between the external and internal diameters with duration of 1 μs and amplitude 2 times above the operating one. In the cases with decreased core resistance, sparks were observed on the core surface leading to resistance decrease. Such cores needed to be recoiled too.

Cores with diameter 0.5 m and more do not possess enough mechanical strength required for transportation and assembling in the transformer. Mechanical strength was enhanced by gluing of the side surfaces by some method. The simplest one is remelting of running out edges of the insulation film by hot air purging. But it works out only for cores up to 1 m diameter. Covering of a large side surfaces by melted polymers (caprolon, polyethylene) was tested also. The biggest cores (1.8 m diameter) were strengthened with the epoxy compound gluing with 3 mm layer thickness.

References

[1] J.J. Ramizez, K.R. Prestwich, D.L. Johnson et al., *in: Proceedings of the 7th Intern. conf. of High Power Particle Beams*. Karlsruhe, Germany, July 4–8, 1988, pp. 143–146.

[2] L.A. Mejerovich, I.M. Vatin, E.F. Zaitsev, V.M. Kandykin, *Magnetic pulsed generators*, Moscow, Sovetskoje Radio, M., 1968.

[3] S.S. Vdovin, *Pulsed transformers design*, Leningrad, Energija, 1971.

[4] V.A. Vizir, A.S. El'chaninov, V.F. Feduschak et al., Pribori i tekhnika eksperimenta, 95–98 (1968).

[5] A.V. Luchinskii, N.A. Ratakhin, V.F. Feduschak, A.N. Shepelev, Izvestija vysshikh uchebnykh zavedenii. Fizika **40**, No. 12, 67–75 (1997).

[6] B.M. Kovalchuk, V.A. Vizir, A.A. Kim et al., Izvestija vysshikh uchebnykh zavedenii, Fizika **40**, No. 2, 25–37 (1997).

[7] B.M. Kovalchuk, A.A. Kim, E.V. Kumpjak, N.V. Zoi, V.B. Zorin, *in: 13th IEEE Intern. Pulsed Power Conf.*, Las Vegas, Nevada, 2001, p. 1488–1490.

[8] A.A. Kim, B.M. Kovalchuk, V.G. Bastrikov, et al., *in: 13th IEEE Intern. Pulsed Power Conf.*, Las Vegas, Nevada, 2001, p. 1491–1494.

[9] A.N. Bastrikov, V.A. Vizir, A.A. Kim, B.M. Kovalchuk et al., *in: Proc. of Intern. Conf. Megagauss IX*, Sarov, 2002, p. 46.

[10] A.N. Bastrikov, A.A. Kim, B.M. Kovalchuk et al., "100-GW fast LTD stage", *Proc. of the present Symposium*.