DESIGN OF THE 500kA LINEAR TRANSFORMER DRIVER STAGE*

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Abstract

Linear transformer driver (LTD) is a novel fast discharge high pulsed power source. It can realize many LTD stages in series or parallel conveniently, and can directly acquire 100~200ns high power pulse. The pulse maybe realizes to directly drive load without any pulse compressing and forming unit. This paper introduces the latest development of fast LTD technology in abroad. The 100kV/500kA LTD stage with the rise time of 150ns has been designed. The stage is consisting of 20 discharging bricks in parallel. The simplified circuit model of LTD stage is given and the output parameters are simulated with universal circuit simulation software program, and the matched load current of 500kA and the rise time of about 150ns is obtained at the charging voltage of the capacitors about ±80kV.

INTRODUCTION

For carrying out Z-Pinch inertial confinement fusion (Z-ICF), it is required that the electricity power of the pulse driver source must be attained to 1000 TW, electric current 60 MA, rise-time ~ 100 ns[1]. Academician Xianjue Peng in Chinese Academy of Engineering Physics(CAEP) putted forward a concept for the Z-Pinch ignition combine fusion and fission reactor in 2010[2]. It is required that the electric current must be attained to 40 MA, rise-time 200 ~ 300 ns[3] for Z-ICF. Recently, a new technology of Linear Transformer Driver (LTD) technique has been successfully developed in High Current Electron Institute (HCEI) of Russia [3-5] which can provide a high current and voltage in a relatively compact device. The salient feature of the LTD is switching and inductively adding the pulse at low voltage directly from the capacitors by low inductance transfer and soft iron core isolation [5]. High currents can be achieved by feeding each core with many capacitors connected in parallel in a circular array. High voltage can be achieved by inductively adding many stages in series. LTD technology can produce 100 ~ 200-ns high power pulse without pulse compression and pulse forming to direct drive the load. Additional, the quiet gas switches will protect the assembly from mechanical shock of water switch in PFLs, thus increase the life of the assembly. Therefore, the LTD has a good prospect in Z-pinch ICF.

This work was supported in part by the Foundation of National Natural Science of China (Grant No. 51077111) and State Key Laboratory of Electrical Insulation and Power Equipment (EIPE12202).

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Kim and Mazarakis have studied the 1-MA and 500-kA LTD stages in detail, respectively [6, 7]. Based on the 500-kA stage developed by HCEI, Woodworth et al have made improvements to gas switches, capacitors and magnetic toroid cores. These works have increased this stage's output current into a matched load by 65% to 810 kA without any change to its volume. Its peak power approximates to 74.6 GW with the rise time of 100 ns when charged to ±92kV [8].

From 2006, 100-kA and 300-kA/100-ns stages have been developed by Northwest Institute of Nuclear Technology (NINT), China. From then on, much effort has been carried out to improve the operating characteristics of this LTD stage, especially in gas switches and magnetic toroid cores. This paper presents the design of a 500kA stage aimed to investigate the assembly of LTD stage. Driving a matched resistive load, the stage output current peak can attain to exceed 500 kA with an overall rise time of about 200ns in simulation.

DESIGN OF THE LTD STAGE

The Equivalent Circuit and Electric Parameter Estimate of LTD Stage

Figure 1 shows the simply equivalent circuit principle diagram of the LTD stage. S is illustration all parallel switch inside LTD stage. C is illustration the equivalent capacitance of LTD stage. L is total inductance of switch, capacitor and connect bus inductance of LTD stage. R is sum resistance including stage interior resistance and load resistance. The equivalent circuit quadratic differential equation is:

$$L\mathrm{d}i^2/\mathrm{d}t^2 + R\mathrm{d}i/\mathrm{d}t + i/C = 0 \quad (1)$$

Through analytic resolve, in matching load $R=\sqrt{L/C}$, the time of peak current is:

$$t_{\mathrm{peak}} = \frac{2\pi}{\sqrt{3^3}}\sqrt{LC} \approx 1.21\sqrt{LC} \quad (2)$$

The peak current is:

$$i_{\mathrm{peak}} = \frac{2V_0}{\sqrt{3}R}\exp\left(-\frac{\pi}{3\sqrt{3}}\right)\sin(\pi/3) \approx 0.546\,293\,\frac{V_0}{R} \quad (3)$$

The peak voltage is:

$$V_{\mathrm{peak}} = Ri_{\mathrm{peak}} = 0.546\,293\,V_0 \quad (4)$$

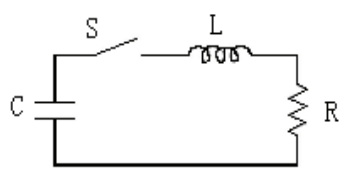

Figure 1: Simply equivalent circuit.

The energy efficiency to load is:

$$\eta_{E(t_{peak})} \approx 0.403\,128 \quad (5)$$

The peak current is decreased 33% and the energy efficiency to load is reduced 20% when stage load is critical damping $R = 2\sqrt{L/C}$ than matching damping. But the load voltage and rise-time of load current is increased. The load voltage and rise-time of load current is:

$$t_{peak} = \sqrt{LC} \quad (6)$$

$$V_{peak} \approx 0.735\,76\,V_0 \quad (7)$$

ESSENTIAL COMPONENT

The Multi-gap Multi-channel Gas Spark Switch

Based on the MGS-I[9-11] used in the 100kA LTD stage; a smaller MGS-II of ±100kV for 300kA/100ns LTD stage has been developed. Similar to the MGS-I, the MGS-II has six electrode gaps, each of which 5 mm and is insulated by dry air at a pressure of 0.3MPa (absolute). Compared with the MGS-I, the diameter of the MGS-II is shrunk by 30% to 98 mm, and the height is shortened by 21% to 127 mm. Fig.3 gives the photos of these two switches. The shrinkage in volume is expected to reduce the LTD loop inductance. Fig.4 shows the short current waveforms of the same brick connected with these two switches, respectively. From Fig.4, the period of the short current is obviously decreased when the brick mounted with MGS-II. So the inductance of MGS-II is smaller than MGS-I. Their mechanical and electrical parameters are shown in Tab.1.

The Store Energy Capacitor

The double-ended capacitors allow the bricks to be packed more tightly relative to single-ended 40nF capacitor used in 100kA/100ns LTD stage, therefore more bricks can be added in the LTD stage, resulting in a lower system inductance. From Tab.1, the store energy capacitor in 500kA LTD stage must be increased capacitance for improvement the load current peak and rise-time. The 80nF/100kV double-ended capacitor has been developed by Ximai electric components Co., LTD, Wuxi, China. The 80nF/100kV has the same configuration with the double-ended 40nF capacitor used in 300kA/100ns LTD stage. The length of the capacitor is added to 292mm from 180mm.

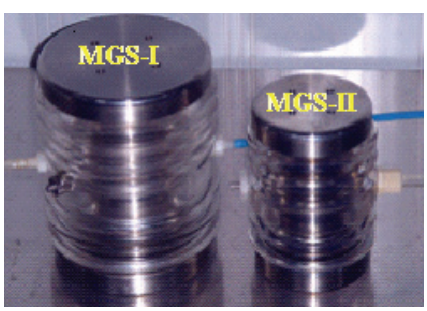

Figure 2: Photo of the multi-gap multi-channel switch.

Table 1: The Parameter of Different Switch

Parameter	MGS-I	MGS-II
Diameter/mm	138	98
Height/mm	156	127
Gas gap	6×5mm	6×5mm
Working voltage	±80kV	±80kV
Working rate	70%	70%
Postpone /ns	39.9	49.6
Jitter /ns	3.75	3.35
One brick inductance/nH	268	245

The Magnetic Core of LTD Stage

In the design of pulse transformers, the saturated magnetic induction intensity Bs, relative magnetic penetrability μ_r and the loss resistance of the magnetic cores are expected to be as high as possible. 2605TCA and DG6 silicon steel have relatively higher B_s and μ_r. Experimental results indicates that the loss resistance of a 2605TCA core sample is about 14 Ω, which is much higher than that of DG6 core sample (3.6 Ω) of the same size [12]. The saturation intensity *Bs* of 2605TCA is 1.56T, and its remnant intensity *Br* is higher than 1.40T. In addition, the time response is about 50ns and the relative magnetic penetrability μ_r=1000, and the packing factor $K_t \geq 0.80$.

According to Ref. (13), the cross section of the LTD magnetic core is estimated by

$$S = 0.85\tau U_0 / k_t \Delta B_s \quad (1)$$

Where S is the cross section of magnetic cores in cm^2, τ is 1/4 discharge period (μs), U_0 is the primary voltage (kV), K_t is packing factor, and ΔB_s is the biggest magnetic induction value available.

Its total cross section is about 83cm^2, higher than the lowest request of the cross section of magnetic core, 72cm^2. The volt-second integral of the core is about 21.0mVs.

For the magnetic core, the equivalent loss resistance is 70ohm and excitation inductance 10μH, which could be

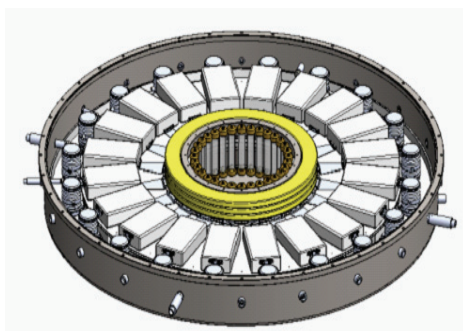

Figure 3: 500KA/150ns LTD stage sans top flange.

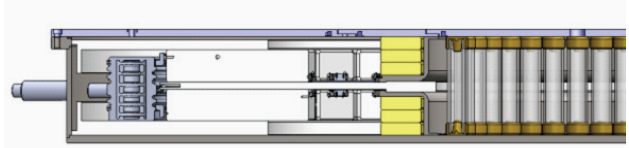

Figure 4: Configuration of 500KA/150ns LTD.

ISBN 978-3-95450-122-9

calculated by

$$R_C = \frac{8\rho S}{\delta^2 l} \quad (2)$$

$$L = \frac{\mu_r \mu_0 S k_t}{l} \quad (3)$$

where S is the cross section of magnetic cores, ρ is the resistively of the magnetic cores material, δ is the thickness of the magnetic foil, K_t is packing factor, and l is the average perimeter of the magnetic cores.

SIMULATION RESULT OF LTD STAGE

The 500kA LTD stage three-dimensional design diagram without the top flange is shown in Fig.3. Fig.4 shows the vertical section of the stage. The stage contains 20 bricks in parallel. Each brick is composed of two low inductance capacitors, a MGS (Multi-gap Gas Switch) and a strip line that transfers the energy to the load. The stage diameter is about 210cm, the height is about 21 cm.

To check the viability of the design, the simplified equivalent electric circuit model of the stage has been built up in the software PSPICE. The parameters were estimated according to the experiment result of one brick short circuit discharged in the LTD stage. The simulation result is shown in Fig.5. Figure 5 presents the matched load current waveform in different charging voltage when capacitor is 80nF. The peak current can obtain 684kA and 764kA in charging voltage ± 90kV and ± 100kV, respective. The current rise-time is about 130ns. The simulation is not considered the magnetic core loss and the influence of the switch jitter. The simulation result indicated that the design can attain required target.

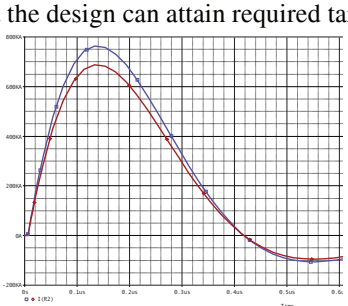

Figure 5: Simulated waveform of the stage with 20 brick and 80nF capacitor in match load (not consider loss).

CONCLUSION

This paper presents the design of a 500 kA LTD stage for current rise-time about 100~200 ns. The stage contains 20 bricks in parallel. Each brick is composed of two low inductance 80nF capacitors, a MGS (Multi-gap Gas Switch) and a strip line that transfers the energy to the load. The stage diameter is about 200cm; the height is about 22 cm. The simulation result indicated that the stage output current peak can attain 500 kA with rise time of about 150ns when driving a matched resistive load. The stage can satisfy for performance test of switch, the performance test of magnetic core, coupling efficiency research, perfect electric circuit simulation model etc. experiment study.

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