Physical Design of a 300kV Double Windings Pulse Transformer

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In order to develop a repetitive frequency accelerator, a repetitive pulse transformer with output voltage (U_{2m}) of 300kV, average power of 40kW, and more than 500ns pulse duration has been designed and tested. The primary and secondary windings are double coils, which consist of four shunt segments. Its characteristics consists in improving the electric field of windings uniformity. Using an amorphous alloy core helps to improve pulse waveform of output voltage and increase energy transfer efficiency. The experimental results show that the transformer can satisfy designed requirement.

Keywords : pulse transformer, double windings, repetitive frequency, amorphous alloy

1. Introduction

Pulse transformers have lots of advantages, such as high work frequency, good stability, low energy loss, small bulk and light weight⁽¹⁾. Therefore, they are widely applied in repetitive frequency power pulse technology. Compared with Tesla transforms, the iron-cored transformers operating at middle or low frequency can get high coupling coefficient, and more suit for the demand of long pulse source's operation.

With the development of the high power microwave technology research, new demands for the development of repetitive pulsed power source are put forward. American vehicle-load long pulse source achieved a technical qualification of 500kV, 5kA, 100Hz, 500ns⁽²⁾. Meanwhile, Russian has got more advantage in the aspect of the Tesla type accelerator. Moreover, there are several inland units to do related research⁽³⁾. For the sake of researching special problems of high voltage and power pulse transformer which operation at high repetitive frequency, a repetitive pulse accelerator with output voltage of 300kV, repetitive frequency of 100Hz has been designed. The analytical process and experimental result of the pulse transformer, which is the most important part of the accelerator, are described in the paper.

2. Technical Requirement and Target

In view of the hot cathode diode that the accelerator may adopt should connect with the filament power source, optimizing circuit and reliable operation, the secondary winding of the pulse transformer adopt the double winding structure. The filament current circuit consists of two shunt coils. This structure realizes dual functions including pulse discharge in high voltage and AC power supply in low voltage. Prior to the transformer two parallel Blumlein lines are used as pulse forming network (PFN). It is designed requirement that the pulse transformer can work normally when Blumlein PFN operates with any of a single circuit or two parallel circuits and is ensured that the diode can produce

better electron beam with two impedances.

The main technical requirements of 300kV double windings pulse transformer are shown as follows :

- (1) Amplitude of input voltage: $U_{1m}=50\text{kV}$; Amplitude of output voltage: $U_{2m}=300\text{kV}$;
- (2) Peak of pulse current: $I_{2m}=3\text{kA}$; Turn ratio: $n=1:6$
- (3) Pulse width($U_{2m0.5}$): $t_k \geq 500\text{ns}$;
- (4) Risetime ($U_{2m0.1} \sim U_{2m0.9}$): $t_s \leq 150\text{ns}$; Falltime ($U_{2m0.9} \sim U_{2m0.1}$): $t_f \leq 200\text{ns}$;
- (5) Repetitive frequency: $f=100\text{Hz}$;

3. Theoretical Analysis and Numerical Calculation

There are various factors which influence the output waveform of the pulse transformer, primarily including magnetizing inductance L_m , leakage inductance L_s , winding self's stray capacitance C_1 , C_2 and mutual distributing capacitance⁽⁴⁾. The equivalent circuit of the pulse transformer, which converts to primary circuit, is shown in Fig.1. In the figure, U_1 is the input pulse voltage signal; R_1 is the impedance of the forming line; R'_2 is the equivalent resistance of loading; C'_2 is the secondary circuit's distributing capacitance; $U'_2(t)$ is the output voltage. These parameters are all converts to primary circuit. In fact, the lumped components of the equivalent circuit have taken the spray inductance of wires, spray capacitance and resistance of wires into account.

Fig. 1. Equivalent circuit of pulse transformer

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Meanwhile, in order to simplify the analyses, some parameters which influence little are neglected during the numerical analyzing according to the different stage of the pulse function. Limited by the HF characteristic of the parameters, the risetime of output pulse is mainly affected by leakage inductance L_s of the transformer and distributing capacitance C_1, C_2 . Therefore, the function of magnetizing inductance L_m can be neglected when pulse rising. In the course of pulse flat, L_s, C_1 and C_2 are short circuit and open circuit respectively, and the LF characteristic of L_m plays an important function⁽⁵⁾.

(1) Analyze when pulse rising:

Assume that:

$$u = U'_2 / (\alpha U_{1m}), \alpha = R'_2 / (R_1 + R'_2),$$

$$\tau = t / (T_G \sqrt{\alpha}) = t / (\sqrt{\alpha} \sqrt{L_s C'_2}), T_G = \sqrt{L_s C'_2},$$

$$\delta = \frac{\sqrt{\alpha}}{2} \left(\frac{1-\alpha}{\gamma} + \frac{\gamma}{\alpha} \right), \gamma = \frac{\sqrt{L_s / C'_2}}{R_1 + R'_2} = \frac{\rho}{R_1 + R'_2}$$

The differential equation when pulse rising can be described as follows:

$$\frac{d^2 u}{d\tau^2} + 2\delta \frac{du}{d\tau} + u = 1$$

According to the scope of δ , discuss u as follows:

If $\delta > 1$, u is in over damping state with the change of τ ; if $\delta = 1$, u is exponential increasing with the change of τ ; if $\delta < 1$, u is under damping state with the change of τ . In order to get shorter rise time and less overshoot, we chose $\delta = 0.8$. The calculated risetime is $(u=0.1 \sim 0.9)\tau_s = 2.47\mu s$. Then, solving the simultaneous equations shown above, it can be ascertained that leakage inductance $L_s = 400\text{nH}$, distributing capacitance $C'_2 = 18.6\text{nF}$, which meet pulse risetime's condition.

(2) Scope of magnetizing inductance L_m The value of L_m is chosen on the condition of guaranteeing the certain flattop of waveform and falltime. It usually can be chosen by the following formula:

$$L_m \geq t_k R_1 R'_2 U_2 / (R_1 + R'_2) \Delta U_2 = 70\mu H$$

Fig.2 shows the simulated result by using PSPICE program. From the figure, it can be seen that risetime, falltime and half-width of the pulse reached the requirements of designed target.

Fig. 2. Simulated output waveform by PSPICE

4. Structure Design and Parameter Computation

According to the Blumlein PFN's operated requirement, two independent primary windings are twined round the transformer's two iron pillars, each of which consists of two symmetry shunt coils. Meanwhile the high voltage ends are located in the middle of the iron pillars. The secondary taper windings also consist of four symmetry shunt coils, and the high voltage ends of each two coils merge into a winding to connect with filament transformer. The coil's distances of the primary winding increases with the increase of voltage. This structure can greatly improve the electric field uniformity in main gap, and greatly improve material insulation stability under high repetitive frequency pulse condition.

The structure of double windings four symmetry shunt coils of high voltage pulse transformer (shown as Fig.3) have following characteristics (1) The high voltage ends are located in the middle of the iron pillars, which guarantee the electric field to transits evenly, and at the same time the insulated requirement of the cores is reduced. (2) It can be realized that two pulse sources can act on the transformer alternately, which can improve the repetitive ability of modulator. (3) It reduces leakage inductance and distributing capacitance, and optimizes the weight and volume of the transformer.

It is generally considered that when pulse repetitive frequency exceeds 100 Hz, the insulation property of transformer oil will drop 40%~50%, and even more. Therefore, the coils are laid into the cave of the organic glass skeleton, and grading ring is used at high voltage port.

The primary winding is twined in combining every 7 wires, and the distance to the core $\Delta_1 = 10\text{mm}$; the secondary is twined just in single wire, and the max distance to the primary $\Delta''_{12} = 35\text{mm}$.

For closed core pulse transformer, the magnetizer is required to choose the magnetic materials which have high B_s , low B_r , and H_c . Amorphous alloy, which has fine performance, is chosen. Its efficient relative permeability is about 2000, and its rectangle BH hysteresis curve is propitious to connect DC demagnetizing circuit. If the materials is applied demagnetizing current, the increment of magnetic inductance $\Delta B_{\max}$ can reach 1T on repetitive pulse condition. Considering that the core works in nonlinear condition and the turns of the primary winding is unsuitable being too high,

Fig. 3. Schematic diagram of the pulse transformer

Fig. 4. The forming line equivalent circuit (the forming line parameters of every unit: $L_i=69\text{nH}$, $C_i=9\text{nF}$)

Fig. 5. The simulated output waveform

the area of square section is taken to be $S=100\text{cm}^2$ after calculating.

The turns of winding: $N_1=U_{1m}t_k/(\Delta BSK_T)=3$, and $N_2=19$.

Leakage inductance, magnetizing inductance and distributing capacitance of the designed transformer can be calculated according to the transformer's structural parameter:

$L_{sB}=390\text{nH}$, $L_m=123\mu\text{H}$, $C_{1B}=0.21\text{nF}$, $C_{12B}=2.12\text{nF}$.

Taking the effect of lead wires to distributing parameters into account, numerical simulation is done by applying every parameter to the forming line equivalent circuit (Fig.4), then the output waveform can be obtained and shown in Fig.5.

5. Experimental Result

Based on the results of theory analysis and numerical calculation, a pulse transformer has been developed, and its mainly parameters as follows: $L_s=420\text{nH}$, $L_m=150\mu\text{H}$, $n=(L_2/L_1)^{1/2}=6.3$.

Using the pulse produced by Blumlein PFN as input voltage and a water resistance (115Ω) as load, experiments have been done on single pulse and repetitive pulse conditions. The designed targets that output voltage greater than 300kV on single pulse condition and $U_{2m}=300\text{kV}$, $f=100\text{Hz}$ on repetitive pulse condition

Fig. 6. Waveforms on a single pulse condition

Fig. 7. Waveforms of the transformer when $f=100\text{Hz}$

have been achieved.

The waveforms of a single pulse are shown as Fig.6. The curves 1, 2 and 3 in Fig7 respectively show the voltage waveforms of primary winding and secondary windings, and the current waveforms of secondary windings. From the waveform we can see:

$U_{1m}=50.6\text{kV}$, $t_{s1}\approx 270\text{ns}$; $U_{2m}=303\text{kV}$, $t_{s2}\approx 300\text{ns}$; $t_k\approx 500\text{ns}$.

Then, we can calculate the risetime of the transformer $t_s=131\text{ns}$, and the transformer ratio $U_{2m}/U_{1m}=6$.

From the test waveforms, it can be found out: (1) Because parameters are designed relatively reasonable, and magnetic material's performance is well-chosen, the pulse transformer developed has fine responding characteristics; (2) The insulation problem when the transformer operates on repetitive pulse condition can be solved efficiently by using double winding structures; (3) The higher overshoot of waveform shows that load impedance is smaller than matching value. The reason is the transformer in entire loop has not well matched with the artificial line. At the same time it also causes the measured value of turn ratio is less than the designed value. Moreover, the self resistance value of water resistance load changes with temperature and pulse polarity, which also influences the output waveform.

Such test results show that the designed transformer has reached the technical target of designed requirement, and it can export an average power of 40kW when repetitive frequency is 100Hz. It can be seen that the design scheme is reasonable and feasible.

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