High-Voltage Pulse Transformer

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Abstract – A high-voltage pulse transformer with a primary voltage of ≤ 20 kV, an output voltage of ≤ 300 kV, and a transformation ratio (number of turns) of 17 was designed. A 16-µF capacitor bank is switched to the primary winding of the transformer in the reverse mode with the use of a TDI1-150k/25 pseudospark switch. The total inductance of the primary circuit is 198 nH (the capacitor inductance is 28 nH, the switch inductance is 96 nH, the inductance of supply cables is 72 nH, the inductance of the primary winding is 2 nH). The secondary winding is self-supported; it consists of KVI-120 cable segments connected to a post insulator with cylindrical steel rods. The inductance of the secondary circuit is 8µH. The transformer was successfully tested in the short-circuit mode, idle mode, and charging mode of a 43.8-nF forming line. Thus, the parameters of the C-L-C circuit reduced to the secondary circuit are 58.2 nF – 65 µF – 43.8 nF. The charging time of the forming line is 3÷4 µs. In the charging mode of the forming line, a batch of 30 pulses with a pulse repetition frequency of 0.3 Hz was obtained.

1. Introduction
The high-voltage pulse transformer is connected in the conventional circuit: its primary and secondary windings are arranged on a toroidal core. The primary winding is a single solid turn; the secondary winding is self-supported and consists of 17 turns uniformly distributed on the toroid. The capacitor bank is switched with a pseudospark switch and is discharged into the primary winding.

2. Design of the high-voltage pulse transformer
The design of the high-voltage pulse transformer is shown in Fig. 1. Eight RK-75-9 cables, of which one runs from a magnetization reversal unit and the others from the primary store, are connected to primary turn 2 through high-voltage leads 1. The primary turn is wrapped around ferromagnetic core 3 of the transformer and is connected to the transformer case. Secondary winding 4 has 17 turns fixed to post insulator 5. One end of the secondary winding is connected to the transformer case, while the other to output unit 8 secured in bushing insulator 6. Inside the transformer, there is active liquid high-voltage divider 7 for measuring the output voltage and Rogowski coil 9 for measuring the output current. The transformer is filled with transformer oil.

The leads of the transformer (see Fig. 2) are connected to steel frame 2 of the ferromagnetic system with eight parallel Al wires 1. The frame also serves as the solid primary turn. Secondary winding 3 consists of KVI-120 high-voltage cable segments with no armature and semiconducting coating. The cable segments are fixed to post insulator 4 with steel rods. Rigid polycarbonate tubes 5 are fit on the cables to give the desired form to the winding. This design of
the winding ensures fast assembly, specifies the required insulation gaps, and eliminates possible turn-to-turn breakdowns and breakdowns into the case.

The ferromagnetic core consists of four cores. The cross-sectional area of the ferromagnetic system is $S = 100 \text{ cm}^2$, the length of the center line is $L_{CP} = 1.2 \text{ m}$, and the induction swing is $\Delta B \sim 47 \text{ [1]}$. The dimensions of a core are $Ø 217 \times Ø 550 \times 18 \text{ mm}$, and its weight is $\sim 25 \text{ kg}$. The weight of the entire ferromagnetic systems is $\sim 100 \text{ kg}$.

The dimensions of the transformer are $765 \times 770 \times 950 \text{ mm}$. The weight of the transformer is $\sim 300 \text{ kg}$.

The capacitor bank of the primary store is discharged into the primary winding of the pulse transformer. The primary store is a bank of 16 capacitors of type $K75-48М – 16 \text{ кВ} – 1 \mu\text{F}$ connected in parallel with a TDI1-200K/25 switch. The capacitor bank and the switch are placed into an air-insulated vacuum-sealed tank in which the active divider for control of the discharge voltage and the Rogowski coil for measurement of the switch current (primary current of the transformer) are also placed. The dimensions of the primary store are $750 \times 700 \times 575 \text{ mm}$. The weight of the store is $\sim 190 \text{ kg}$.

A photo of the high-voltage pulse transformer with the primary store fitted underneath the transformer is shown in Fig. 3.

![Fig. 3. Photo of the high-voltage pulse transformer (1) with the primary store (2).](image)

4. Electrical parameters

The circuit of the setup is shown in Fig. 4. The capacitance and the inductance of the capacitors of the primary store are $C_{1...16} = 1.05 \mu\text{F}$ and $L_{1...16} = 0.45 \mu\text{H}$, respectively. The inductance of the switch is $L_{SW} = 96 \text{ nH}$. The inductance of the cables connecting the primary store with the pulse transformer is $L_{CAB} = 72 \text{ nH}$. The inductance of the primary winding is $L_{S1} = 2 \text{ nH}$. The total inductance of the primary circuit is $L = 198 \text{ nH}$. The inductance of the secondary winding of the transformer is $L_{S2} = 8 \mu\text{H}$. The capacitance of the forming line is $C_L = 43.8 \text{ nF}$. The parameters of the $C-L-C$ circuit reduced to the secondary circuit are $58.2 \text{ nF} – 65 \mu\text{H} – 43.8 \text{ nF}$. The impedance of the generator is $\rho = 33 \Omega$. The charging time of the forming line is $4 \mu\text{s}$.

![Fig. 4. Circuit of the setup](image)

Results

The pulse transformer was tested in the short-circuit mode (the charge voltage is $U_0 = 16 \text{ kV}$). Typical waveforms of the primary and secondary currents in this mode are shown in Fig. 5.

![Fig. 5. Waveforms of the primary ($I_1$) and secondary ($I_2$) currents for the transformer in the short-circuit mode](image)

The pulse transformer was also tested in the idle mode with decreased discharge voltage ($U_0 = 10 \text{ kV}$). Figure 6 shows typical waveforms of the input and output voltages and of the primary current in this mode.

We also obtained a batch of 30 pulses with a frequency of 0.3 Hz during the operation of the transformer in the charging mode of the forming line ($U_0 = 12 \text{ kV}$). Waveforms of the current and voltage for one of 30 pulses are shown in Fig. 7 and for all 30 pulses in Fig. 8.
Oral Session

Fig. 6. Waveforms of the input ($U_1$) and output ($U_2$) voltages and of the primary current ($I_1$).

Fig. 7. Waveforms of the input and output currents and voltages for one of 30 pulses in the charging mode of the forming line.

We also obtained a batch of 30 pulses with a frequency of 0.3 Hz during the operation of the transformer in the charging mode of the forming line ($U_0 = 12$ kV). Waveforms of the current and voltage for one of 30 pulses are shown in Fig. 7 and for all 30 pulses in Fig. 8.

It can be seen in Fig. 8 that the shape and the amplitude of the output voltage and current display high stability throughout the batch of 30 pulses.

The energy stored in the primary store is $W_1 = C_1 U_0^2/2 = 1200$ J. The energy transferred to the forming line (see Fig. 7) is $W_2 = C_1 U_2^2/2 = 920$ J. The generator efficiency is 76%.

Conclusion

The high-voltage pulse transformer with an output voltage up to 300 kV and a rise time no longer than 4 $\mu$s at a capacitive load was designed. The transformer was successfully tested in the short-circuit mode, in the idle mode, and in the charging mode of the forming line (the capacitance of the line was 43.8 nF). The parameters of the $C$–$L$–$C$ circuit reduced to the secondary circuit are $58.2$ nF – $65$ $\mu$F – $43.8$ nF. The charging time of the forming line is 4 $\mu$s. The generator efficiency is 76%. The batch of 30 pulses with a frequency of 0.3 Hz was obtained during the operation of the transformer in the charging mode of the forming line.

References

[1] Cold-rolled anisotropic electrical steel tape (RF Standard 21427.4-78).