Central Power Research Institute

Vol. 19(2)/127-131, December 2023
ISSN (Print) : 0973-0338
DOI : 10.33686/pwj.v19i2.1137

Power Research

Shielding Effectiveness of HV-HF Transformer for Accelerator Applications

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Abstract

High-voltage high-frequency transformers are employed in DC accelerators. The high frequency produced by the inverter at lower voltage is stepped up to several tens of kilovolts using step-up transformers. These transformers are subjected to high-frequency transients from high-voltage multiplier columns. Electrostatic shielding is very effective in common mode noise reduction. However, in accelerator applications, shielding effectiveness obtained using conductive shields is found compromised in practice. This paper investigates the reasons behind this phenomenon and explores remedial measures.

Keywords: High Voltage, Multiplier, Shielding, Transients

1. Introduction

DC electron beam accelerators are used in many cost-sensitive applications due to their high efficiency. A DC electron accelerator rated for 1 MeV, 100 mA is being developed at Electron Beam Centre, Kharghar employing a high voltage power supply based on symmetrical Cockcroft-Walton multiplier topology. This multiplier requires a power input of 45 kV-0-45 kV at 10 kHz. The high-frequency supply is produced by an inverter–a step-up transformer combination. The low voltage output from the solid-state inverter necessitates a step-up ratio of 180 for the transformer. The high-frequency transformer uses manganese-zinc ferrite stacks for the core and litz wire for the primary and secondary. The secondary winding uses multi-sections to control parasitic capacitance to reduce high-frequency circulating currents. The use of low-voltage semiconductor devices in the inverter imposes stringent requirements on the step-up transformer in terms of attenuation of common mode and differential mode transients from the high voltage multiplier.

2. Transients

The origin of transients in the DC accelerator is the high voltage breakdowns in the multiplier or accelerating tube. The power input to the multiplier is protected using spark gaps set to trigger at 55 kV DC. Breakdowns in the multiplier lead to different waveforms with rise times ranging from 20 ns to 2 microseconds depending on the discharge path. The peak value of the waveform increases up to 110 kV for shorter rise time pulses as the breakdown voltage of the spark gap is a function of the rise time. Frequently observed common mode waveform appearing at the transformer secondary terminal during discharges in the multiplier is shown in Figure 1. The symmetrical multiplier has several components and corona guards connected to each side of the column resulting in variation in parasitic capacitances resulting in differences in waveforms at each side of the transformer. The fall time is always controlled by the spark gap and associated inductance and capacitances in the interconnection to the transformer. Variations in parasitic capacitances and jitter in spark gaps triggering

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lead to differential mode voltage of up to 110 kV with a time duration of several hundreds of nanoseconds. The differential mode voltage for spark gap triggering at 70 kV is shown in Figure 2.

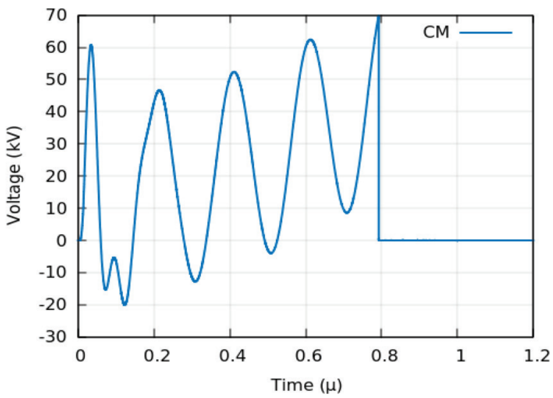

Figure 1. Common mode transient at HV terminals.

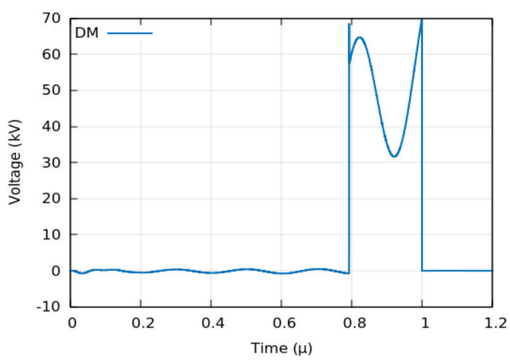

Figure 2. Differential mode voltage across the transformer.

The differential mode voltage appears across the transformer when one spark gap is only conducting, and this condition depends on the capacitance asymmetry in the multiplier column. Even though large amplitude differential voltage appears across the secondary, its effect on primary voltage is not of major concern due to the presence of a tank circuit connected across the primary. In contrast, the common mode voltage of more than 100 kV at the secondary must be attenuated to less than 1 kV to protect sensitive components in the low-voltage system.

3. Winding Design

High-frequency operation of the transformer requires minimization of the parasitic capacitances and leakage inductances. Parasitic capacitances in the windings create circulating currents resulting in dielectric and copper losses. Leakage inductance leads to voltage drop with loading. The leakage inductance and parasitic capacitance form resonances in the transformer. Operation of the transformer near resonance creates wide voltage variation with loading, which is undesirable for high-voltage systems.

The parasitic capacitances in the transformer are minimized by reducing the winding width and increasing the number of layers[1]. To utilize the window height, the winding must be arranged in many sections. The effective capacitance is derived from the total electrostatic energy storage in the winding considering the voltage distribution. Capacitance for a single-section multi-layer winding is given by Equation (1).

$$C_e = \frac{C_s}{3l^2} + \frac{4C_l\left(l-1\right)}{3l^2} \tag{1}$$

Where C_s is the shield to adjacent layer capacitance, C_l is the capacitance between layers and l is the number of layers. Multiple sections are useful to reduce capacitances for windings with many turns. However, with multiple sections direct capacitance between edge layers and the core or shield forms additional capacitance. In addition to the winding capacitance, the high voltage connections, output side field control rings and bushing create additional capacitances. To minimise effective capacitance, gaps between conductors with large potential differences should be increased.

Minimisation of leakage inductance requires satisfying contradictory requirements. To minimize stored energy in the uncoupled magnetic flux it is required to reduce the inter winding spacing. Equation (2) describes leakage inductance reflected in the primary.

$$L_l = \mu_0 N_1^2 \frac{L_w}{b_w}\left(\frac{h_1+h_2}{3}+h\right) \tag{2}$$

Where L_l is the leakage inductance referred to as primary, N_1 is the humbler of primary turns, L_w is the winding width, b_w is the winding width, and h_1, h_2 and h are the inter-winding distances. A compromise between the higher electric fields and lower leakage inductances is obtained by adopting bucket-shaped winding where the distance between windings is increased as the voltage level goes up. Even though this scheme is adopted for pulse transformers, it is difficult to use for medium-frequency applications involving many turns.

Being a multi-layer high-frequency transformer, it is important to reduce high-frequency resistive losses in the windings due to skin and proximity losses. Hence both the primary and secondary are wound with Litz wire. The inter-layer insulation is provided by Mylar sheets and the bobbin is made of Delrin. The high-voltage winding is arranged as a multi-section solenoid with high-voltage connections at both ends. Gaps between secondary sections and grounded surfaces like core and primary are kept uniform. Mineral transformer oil is used as the major insulation in the transformer.

4. Voltage Distribution

During normal operation, potentials in the transformer are linearly distributed. For high operating frequencies, the linear distribution is disturbed because of the presence of leakage inductance and parasitic capacitance[2]. For an operating frequency of 10 kHz, the transformer under consideration does not exhibit considerable deviations from linear distribution. During externally imposed high-frequency transients, capacitances in the windings dominate due to delays involved with the inductive elements. The capacitive network formed is shown in Figure 3. The large inter-turn capacitance reduces to a negligible level due to the large number of such capacitances in series. The layer-to-layer capacitance is more significant due to the large area and smaller spacing. The direct coupling capacitance between primary and secondary is formed through the oil-filled gap.

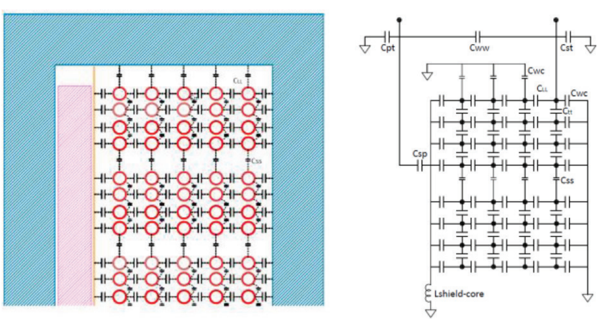

Figure 3. Winding of step-up transformer and equivalent circuit.

At high frequencies, the transformer behaves more like a capacitive ladder network formed by the intersection of capacitance and capacitance to ground[3]. When the transformer is made of many disc coils, the behaviour of such a ladder network for the initial period of a step function excitation is given by Equation (3).

$$V_x = \frac{V_0 sinh\left(\frac{\alpha x}{l}\right)}{\sinh(\alpha)} \tag{3}$$

Where V_0 is the voltage at the HV terminal, α is a factor indicating spatial non-linearity of voltage distribution and l is the length of winding. Power frequency transformers employ techniques using capacitive grading to properly distribute the transient voltage across the windings[4]. It is difficult to employ this solution, due to field enhancement and capacitive currents at high frequencies.

For medium frequency applications under consideration, the number of sections required are limited to less than 8 and in such cases the exponential voltage distribution deviates to stepped values as shown in Figure 4.

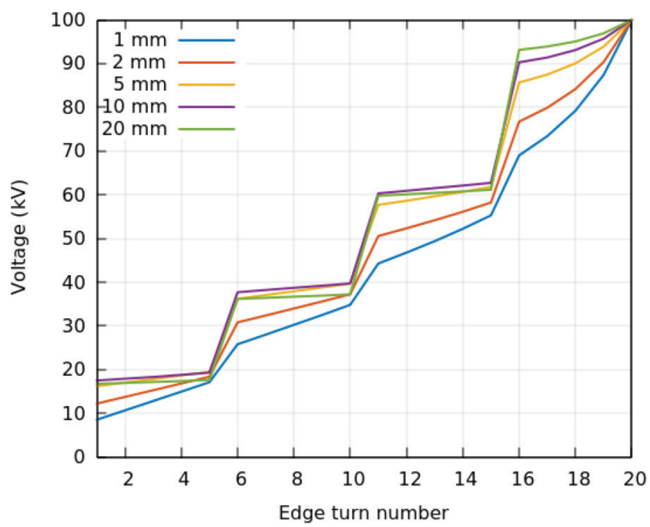

Figure 4. Test setup to measure shielding effectiveness.

The voltage distribution shown is for a 4-section secondary winding with 9 layers in each section and 5 turns per layer. When the section-to-section spacing is minimal, the voltage distribution tends to follow the exponential distribution. Large differences in voltage level appear across sections with larger inter-section gaps, while turns inside a section are nearly at the same potential. This helps the transient to confine to the section connected to the high voltage terminal, effectively reducing the capacitance to shield as indicated by the current drawn from the source as shown in Figure 5.

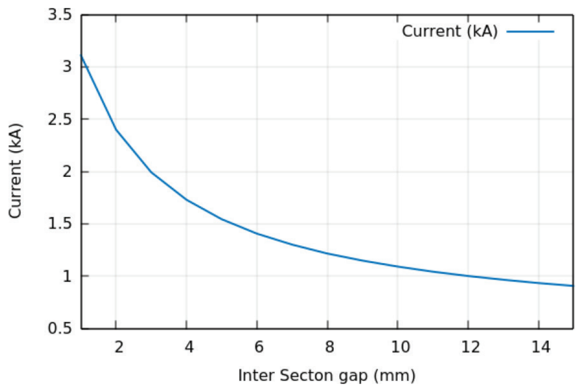

Figure 5. Transient current as a function of inter-section gaps.

5. Shielding Effectiveness

Electrostatic shields are used to suppress transients in transformers[5]. While transformers without shields form considerable direct primary to secondary capacitance, the addition of a shield diverts the current produced by the capacitance to the ground. Shields placed in high-frequency transformers are shaped in such a way that electric field enhancement should be under safe limits. The electric field enhancement by a shield placed between the primary and secondary is shown in Figure 6.

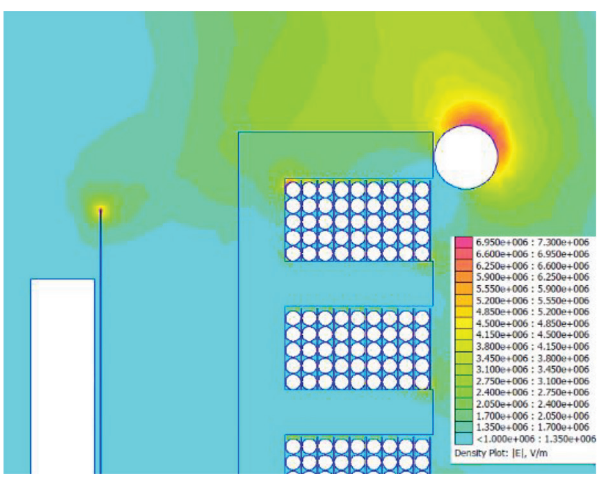

Figure 6. Electric field distribution with a shield.

The electric field stress on the shield approaches as much as the maximum electric field in the transformer located on the corona guards. As the shield is made of foil with a thickness of 50 to 100 µm, actual electric fields may increase considerably from simulation results due to manufacturing deviations. Hence a more relaxed electric field stress of 25kV/cm is desired on the shield. The electric field enhancement is minimized by extending the shield further away near to core. The reduction in electric field due to shield extension is shown in Figure 7. The shield extension increases the current passing through the shield due to higher capacitance configured to the high voltage end section of the transformer, thus degrading shielding effectiveness.

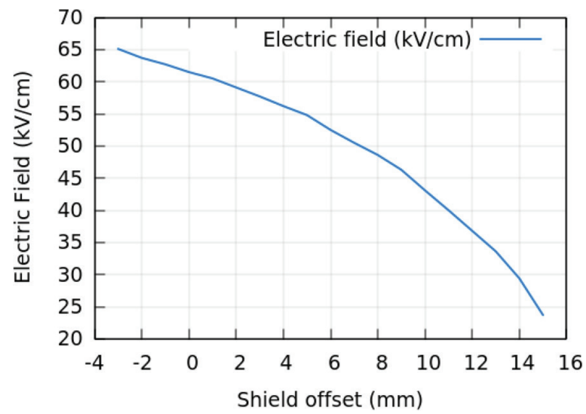

Figure 7. Electric reduction with shield offset.

Similarly, field enhancement due to presence of sharp edges of the shield must be considered near the winding extensions connected to high-voltage terminals. This requirement forces large windows to be placed in the shield for routing the high-voltage leads to terminals. In addition, closed shields are very difficult to implement in high-power transformers as they restrict convection currents leading to heat transfer problems. In essence, the large penetrations in the shields degrade the shielding effectiveness in the high-frequency high voltage transformers.

6. Measurement

Measurement of shielding effectiveness is obtained from the relative reduction in common mode current at the secondary with and without the shield. By using current in place of voltage, ambiguities associated with impedance variation are removed. For measurement, the primary terminals are shorted and common mode current is injected using a function generator. The current passing through the secondary is measured using a high-frequency current probe or shunt. The secondary terminals should be nearly at the ground potential so that the potential does not influence the current passing through the terminals. A spectrum analyser is used to measure the output current amplitude. The scheme used to measure shielding effectiveness is shown in Figure 8. Switch T_1 schematically represents multiple connections from shield to ground. All shield connections to the ground are removed to minimize capacitively coupled current to the ground. With this configuration current passing to ground through the secondary terminals is measured. The experiment is repeated with the shield connections in place.

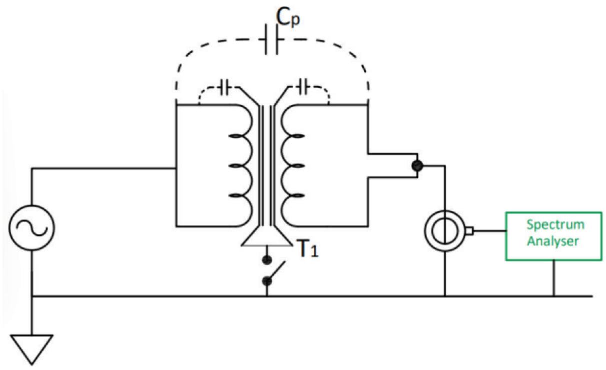

Figure 8. Test setup to measure shielding effectiveness.

The measured shielding effectiveness for a transformer employing 4 secondary sections for each high voltage output and single layer of primary is shown in Figure 9. The shielding effectiveness degrades at high frequency mainly because of the connection inductance of shield with ground.

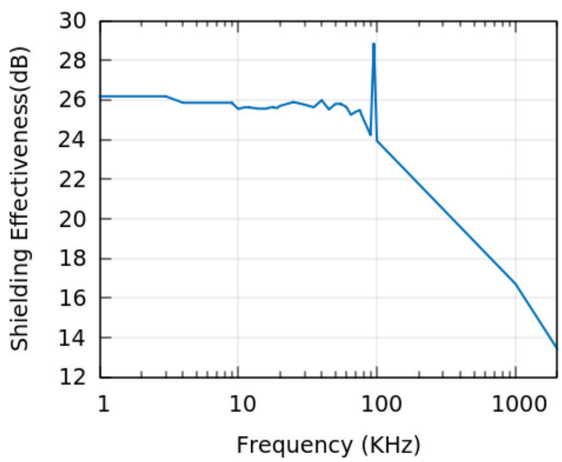

Figure 9. Measurements of common mode attenuation.

Shorter and wider ground connections from the shield improve the shielding effectiveness at high frequencies.

7. Conclusion

Electrostatic shields help suppress the propagation of transients to the protected side of a transformer. Constraints in high frequency high voltage transformer design impose large penetrations in the shield resulting in degradation in shielding effectiveness. Electric field enhancement caused by shield edges is reduced by carefully shaping the shield. Grounding connections behaves as large impedance at high frequency, further reducing the shielding effectiveness. This problem is minimized by multiple parallel connections and by using low impedance ground place.

8. References

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