VFT-characteristics of shielding cylinders in power transformers

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Abstract - Axial and circumferencial shielding cylinders are used in power transformers to suppress peaks of the electrostatic field or to avoid capacitive coupling of windings.

If the shields are excited with VFTOs (Very Fast Transient Overvoltages), there will occur transient waves as well between shield and winding respectively transformer tank as between the aluminium strips of the shield. This paper presents the results of experimental and numerical investigations on wave propagation in the shields. A number of parameter variations were done to evaluate the voltage stress of axial and circumferencial shielding cylinders.

I. INTRODUCTION

The demand on insulation in power transformers gets higher and higher. Especially transformers used in system interconnection where the low voltage winding is designed for a high level of voltage are stressed by the electrostatic field. In [1] a new type of an electrostatic shield for application in power transformers is described.

The shield consists of aluminium foil strips sandwiched between two transformerboard protective covers. The attachment of the shield in the transformer can either cause a smoothing of the electrical field between core and windings or a reduction of the capacitive coupling between the high and low voltage winding. (Fig.1)

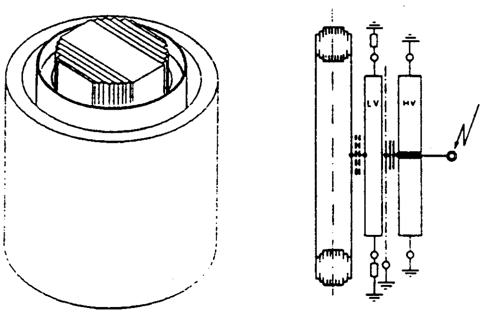


Fig.1 Shielding cylinder with aluminium strips in power transformers

In transformers the aluminium strips can be arranged in two ways. If the strips are axially positioned they have to be interconnected and grounded by one circumferencial braided copper tape. This type is called axial shielding cylinder. (Fig.2a) The other way to arrange the strips is circumferencial with an axial interconnection tape (Fig. 2b).

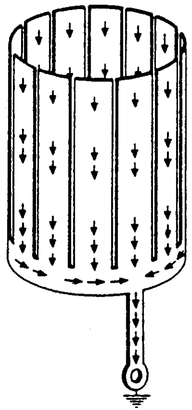


Fig.2a Axial shielding cylinder

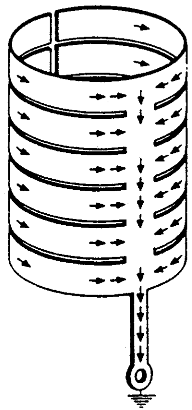


Fig.2b Circumferencial shielding cylinder

Shield parameters:

Width of Strips [mm]	25
Distance between strips [mm]	3
Thickness of strips [mm]	0,2

VFTOs (Very Fast Transient Overvoltages) origin in GIS (Gas Insulated Switchgear) by actuating switches or during ground short circuits. Former investigations have shown that VFTOs propagate in the coaxial GIS as far as peripher mounted working funds i.e. transformers. Because of the excitation with VFTOs transient waves occur as well between shielding cylinder and winding respectively transformer tank as between the aluminium strips of the shielding cylinder. It is the aim of this work to investigate these high frequency effects by using experimental test set ups and EMTP networks.

II. LABORATORY TEST SETUP

The construction of the experimental test set up bases on analogies to a transformer design. Further it is very important to think about electromagnetic compability because the strips of the shield act like an antenna for disturbance signals from environment. A coxial test set up mounted in a coaxial tank makes sure that there will be no failure during measurement caused by outer interference transmitters. The schematic view of the experimental test set up is shown in Fig.3.

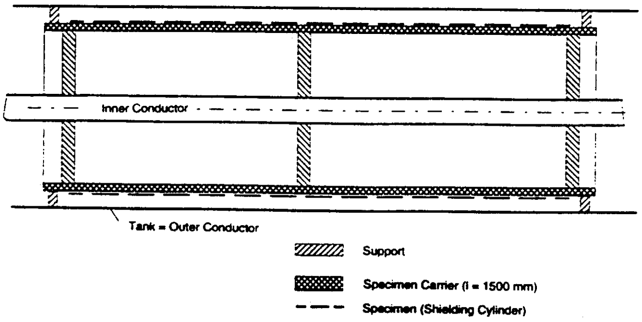


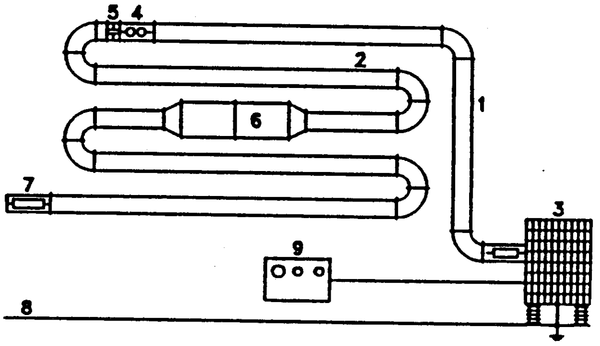
Fig.3 Schematic view of the coaxial test set up

Parameters of the coaxial test set up:

Inner diameter of the tank [mm]	160
Length of the tank [mm]	1600
Diameter of the inner conductor [mm]	10
Diameter of the specimen carrier [mm]	150
Length of the specimen carrier [mm]	1500
Length of the shields [mm]	1400
Wave impedance [Ω]	166,4
Propagation speed [m/s]	3E8

In the test set up the transformer tank is represented by the coaxial tank, the winding is represented by the inner coaxial conductor and the shielding cylinder is represented by the specimen of the shield.

The set up is integrated in a coaxial transient wave model (Fig.4) [2].



1,3...charging device
2...test line
4...SF6-spark gap
5...coaxial capacitor
6...tank with test set up
7,8...ground bar

Fig.4 Coaxial transient wave model with test set up

The transient voltage between one point of the shielding cylinder and ground (tank) is measured by a capacitive field detector. By turning the test set up in the tank it is possible to measure the voltage at each point on circumference of the shield.

III. MEASUREMENTS ON THE SHIELDING CYLINDERS

The investigations are made by comperative measurements on the test set up. The experimental results of the test set up without any specimen of the shields show the reflectionless arrangement of the test set up in the tank and in the coaxial transient wave model (Fig.5).

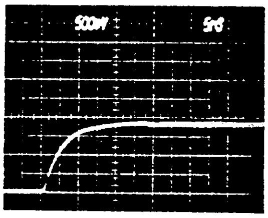


Fig.5 Step voltage on the carrier of the specimen rise time Tr = 10ns

The first specimen of a shielding cylinder is an aluminium foil which is put onto the carrier. If this shielding cylinder is not grounded, the step response of the test set up shows the same result as measured before. In this case the voltage on the shield can be calculated with the ratio of voltage division of the capacity between inner conductor to shield and shield to tank. The aluminium shield grounded at one end shows the transient voltage response as shown in Fig.6.

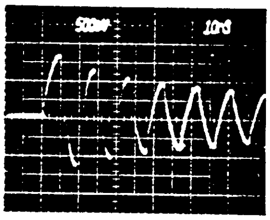


Fig.6 Transient voltage on the aluminium shield grounded at one end

The cycle duration of the transient voltage is determined by the length of the aluminium shield.

$$T = 4 \cdot \frac{length\,of\,shield}{speed\,of\,light} = 4 \cdot \frac{1{,}4}{3 \cdot 10^8} = 18{,}6ns$$

The decrease of the amplitude per period of the transient voltage on the shield is determined by:

$$decrease = \frac{2 \cdot travel\,time}{rise\,time} = 0{,}93$$

A. *Axial shielding cylinder*

The schematic drawing in Fig.7 of the axial shielding cylinder (AX) shows the local determination of the points on the test set up.

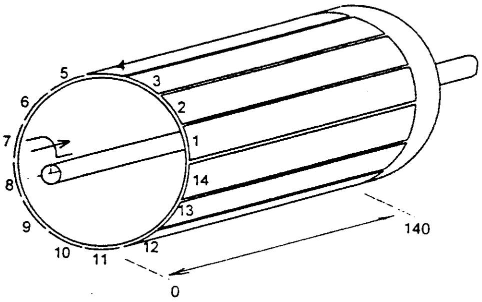
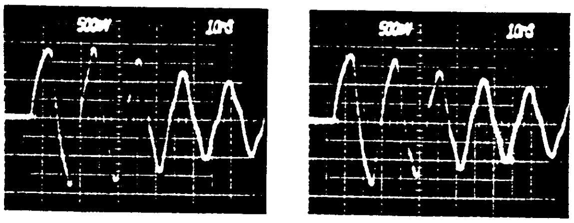
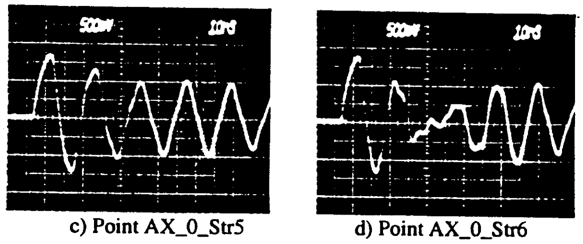


Fig.7 Local determination of the axial test set up

At first the axial strips (Str) are interconnected with a braided copper tape at position AX_140 and grounded with a short earth lead (l=15mm) at position AX_140Str7-8. There are differences in the transient voltage responses between adjacent strips on the axial shielding cylinder (Fig.8). The cycle duration is about 27ns.



a) Point AX_0_Str3 b) Point AX_0_Str4



c) Point AX_0_Str5 d) Point AX_0_Str6

Fig.8 Transient voltage response of the axial shielding cylinder at various points on circumference with a short earth lead

For testing the influence of the length of the earth lead the following measurements were made with a 250mm long earth lead. A characteristic transient voltage response is shown in Fig.9.

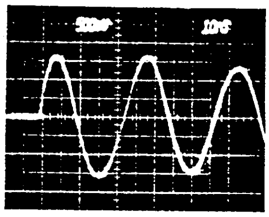


Fig.9 Characteristic transient voltage response of the axial shielding cylinder with a 250mm long earth lead

Adjacent strips show the same behavior. The cycle duration is 50ns.

B. *Circumferencial shielding cylinder*

The schematic drawing in Fig.10 of the circumferencial shielding cylinder shows the local determination of the points on the test set up.

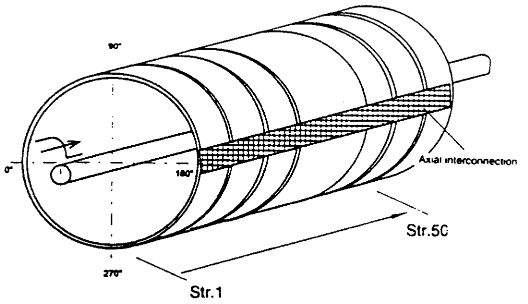
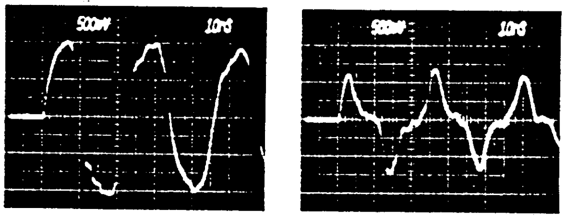


Fig.10 Local determination of the circumferencial test set up

In this reference system the strips (Str) are interconnected at position 180° and grounded at position Z_Str50 with a short earth lead (l=15mm). The strips are slotted at position 0° avoiding a short circuit in the transformer. Fig.11 shows the transient voltage response at different points on the circumferencial test set up. The cycle duration is 47ns.



a)Point Z_Str1_180 b) Point Z_Str36_180

Fig.11 Transient voltage response of the circumferencial shielding cylinder at various axial points with a short earth lead

The circumferencial test set up with a 250mm long earth lead shows a similar behavior as before.

These measured transient waveforms make up the base for comparing the equivalent circuit diagrams with the experimental set up.

IV. NUMERICAL CALCULATION

A. *Theoretical basics [3],[4]*

A strip line is defined as a double line which consists of two strips having a width *b* arranged on a dielectric material at a distance *s*. If the inhomogenity of the dielectric material can be neglected, the wave impedance is calculated as follows:

$$Z = \frac{\pi}{\ln\left[2\,\dfrac{1+\sqrt[4]{1-\left(\dfrac{s}{s+2b}\right)^2}}{1-\sqrt[4]{1-\left(\dfrac{s}{s+2b}\right)^2}}\right]}\cdot\sqrt{\frac{\mu}{\varepsilon}}$$

$$\text{with } \frac{s}{s+2b} < \frac{1}{\sqrt{2}}$$

The wave impedance of the coaxial transmission line is determined by the following equation.

$$Z = \frac{1}{2\pi}\cdot\sqrt{\frac{\mu}{\varepsilon}}\cdot\ln\frac{Da}{Di}$$

If a coaxial conductor is placed in a coaxial transmission line, there will be a serial junction of two transmission lines for the incoming transient wave at the point of discontinuity.

B. Axial shielding cylinder

B.1 Equivalent circuit diagram

The equivalent circuit diagram for the axial shielding cylinder in the experimental set up has to be adapted for the calculation in the ElectroMagneticTransientProgram EMTP. The axial test set up is represented by parallel branched transmission lines.

Parameters of the equivalent circuit diagram:

$Zi^*+Za^* = 166\Omega$ $Zi = n.Zi^*$
$Zstr = 112\Omega$ $Za = n.Za^*$
Le,Lk = 0,72μH/m (inductivity of the lead)
n = 10 (number of parallel branched transmission lines)

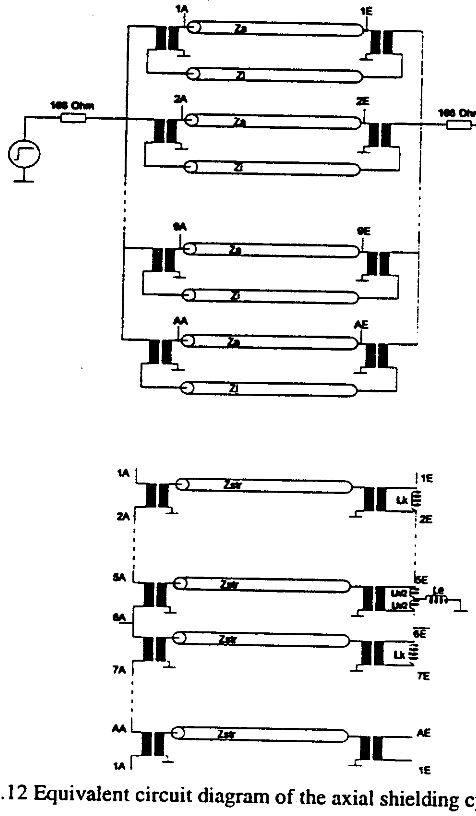
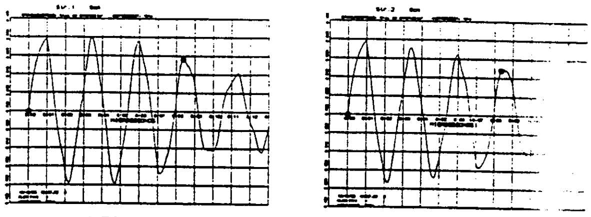


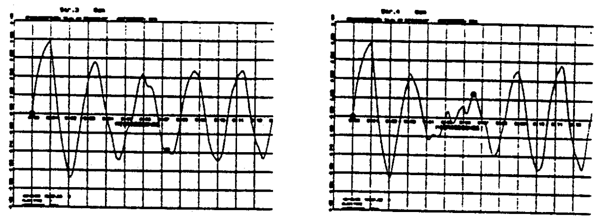
Fig.12 Equivalent circuit diagram of the axial shielding cylinder

B.2 Calculation results

For the evaluation of the equivalent circuit diagram the transient voltage response of the test set up is calculated. Fig.12 shows the voltage-time-caracteristics of four adjacent strips. The results of the numerical simulation are nearly congruent with the measured results (compare with Fig.8).



a) Plot AX_Str1 b) Plot AX_Str2



c)Plot AX_Str3 d)Plot AX_Str4

Fig.13 Calculation results of the axial shielding cylinder at various points on circumference

B.3 Further investigations

Several parameter variations were made. The first conclusion is that the point where the earth lead is connected to the axial shielding cylinder does not influence the peak voltage on the shield.

The differential voltages between adjacent strips stress the shielding cylinder and can cause partial discharges in the shield. With reference to the capacitive coupled voltage on the shield the maximum differential voltage between two strips is about 16%. With reference to the excitation voltage this value is 5%.

By varying the length of the earth lead the frequency distribution of the shield can be described as follows (Fig.13).

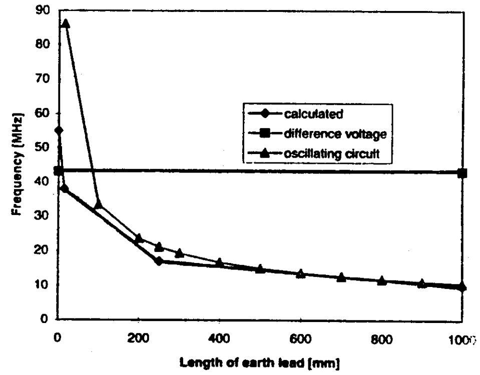


Fig.14 Frequency behavior of the axial shielding cylinder and the LC-oscillating circuit

•In general it was found that the LC-oscillating circuit consists of the inductivity of the lead and the capacity of the shield against ground.

•The frequency of the difference voltages between adjacent strips is independent of the length of the earth lead and is determined by:

$$f = \frac{speed\ of\ light}{4 \cdot length\ of\ strips}$$

•Increasing the length of the earth lead the LC-circuit determines the frequency of the transient voltage response. Subsequently the differential voltages between strips disappear.

•Decreasing the length of the earth lead the frequency behavior of the shield is mainly characterized by the transient waves between the strips.

C. Circumferencial shielding cylinder

C.1 Equivalent circuit diagram

The circumferencial shielding cylinder in the tank acts like a delay transmission line with periodical structure. Applying theoretical basics of the "tape ladder line" it is quite simple to make up an equivalent circuit for calculation on EMTP.

Parameters of the equivalent circuit diagram:

Zi+Za = 166Ω
Zstr = 112Ω
Propagation speed = 2,4E8m/s
Le = 0,72μH/m

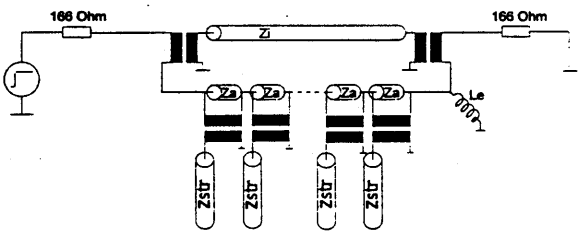
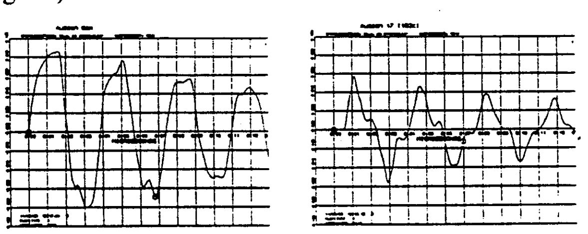


Fig.15 Equivalent circuit diagram of the circumferencial shielding cylinder

C.2 Calculation results

The calculated transient voltages at the circumferencial shielding cylinder (Fig.16) approximate the measured ones in a sufficient way (compare with Fig. 11).



a) Plot Z_Str1 b) Plot Z_Str36

Fig.16 Calculation results of the circumferencial shielding cylinder at two axial points

C.3 Further investigations

Several variations of parameters showed, that the length of the earth lead is not decisive for the quantity of the differential voltages between the strips. Using a circumferencial shield only the axial delay time of the transient wave influences the dielectric stress of the shield. The maximum voltage occuring in this investigation was about 11% with respect to the capacitive coupled voltage on the shield.

V. CONCLUSION

The present work details the transient characteristics of shielding cylinders in power transformers. The measured transient voltages formed the base for the development of general applicable equivalent circuit diagrams. The differential voltages between adjacent strips match values up to 16% with respect to the capacitive coupled voltage on the shield and they can cause partial discharges. Depending on the geometric dimensions of the shield frequencys from 10MHz to 60MHz were calculated.

Finally it was veryfied that EMTP is a very useful tool to investigate the VFT-behavior of the shields

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