

# Impulse Voltage Distribution in Countershielded Disc VS Interleaved Disc Windings on 500 kV Power Transformer Design

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**Abstract:** Interleaving and countershielding are known as two methods which are commonly used to increase the winding series capacitance. Countershielding has been proven as an effective way to substitute the interleaving as it can be faster and easier to manufacture. The aim of this paper is to find out the most optimum configuration in terms of cost and design by referring to the calculation result of the impulse voltage distribution obtained by interleaved and countershielded winding. A numerical and finite element method (FEM) are used for calculating the series capacitance values as well the voltage distribution along the winding. The result shows that combination of single and double countershielded disc configuration provides an improved impulse voltage distribution and lower voltage stresses compared to the other configuration.

**Key words:** Impulse voltage distribution, interleaved, countershielded, disc winding, capacitance.

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## 1. Introduction

Lightning impulse is one of various kinds of over voltages in power transformer dielectric test. When lightning impulse impinges on the transformer winding, it can produce a considerable voltage gradient that can be resulted in electric breakdown of power transformer insulation [1]. Designing the insulation system of a power transformer for withstanding the overvoltage test, voltage stresses within the winding need to be determined. When a transient voltage impinges on the transformer winding terminal, the initial voltage distribution in the winding will be depending on the winding capacitive network that consisting of ground and series capacitances [2].

The initial impulse voltage distribution in any transformer winding is given by (1)

$$V = A_1 \exp(\alpha) + A_2 \exp(-\alpha) \quad (1)$$

where  $\alpha$  is defined by (2)

$$\alpha = \sqrt{\frac{C_g}{C_s}} \quad (2)$$

$C_g$  and  $C_s$  are the ground and series capacitances, while  $A_1$  and  $A_2$  are constant that depend on the boundary condition. The initial voltage distribution constant,  $\alpha$ , needs to make as small as possible to

improve transient voltage distribution along transformer winding [3], [4]. It can be made closer to ideal linear distribution ( $\alpha \sim 0$ ) and coincident with the final distribution by increasing series capacitances and or reducing its capacitance to ground [2], [5]. However, it will be difficult and less cost effective to reduce ground capacitance. A more cost-effective way is increasing the winding series capacitance by using different types of windings [2]. Some methods which are commonly used for increasing the series capacitance are by interleaving and by countershielding. In countershielded disc design, a certain number of dummy turns are wound-in together with the main turns to generate high turn capacitance in the relevant discs.

Interleaving the turns in such a way can produce high substantial increase in series capacitance. However, it may be very labor intensive and practically will be limited to magnet wire application. The application of continuously transposed cable (CTC) in interleaving method is almost impossible as there are too many number of strands need to be cut and rejoined. Countershielded disc winding tends to produce modest increases in the series capacitance compared with interleaving, requires less labor, and suitable in the implementation of continuously transposed cable. In addition, it can easily make tapered capacitance profile to match the voltage stress profile [6].

This paper presents a numerical calculation of the impulse voltage distribution in a disc winding with interleaving and countershielding. Result of the calculations are compared and analyzed to assign the most optimum configuration.

## 2. Capacitance Model

### 2.1. Continuous Disc

The capacitance model in a continuous disc winding is modeled in Fig. 1 and the layout is shown in Fig. 2. The models consist of ground ( $C_g$ ) and series capacitance ( $C_s$ ). The total series capacitance of continuous disc consists of turn capacitance ( $C_t$ ) and disc capacitance ( $C_d$ ) [2].

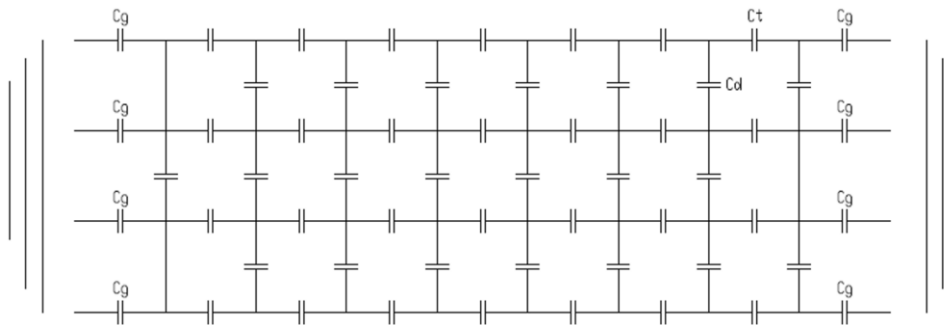


Fig. 1. Capacitance model of disc winding.

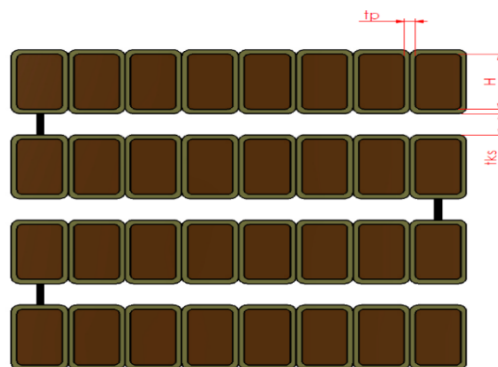


Fig. 2. Layout of disc winding.

The mathematic model and formula of ground capacitance are defined from (3).

$$C_g = \epsilon_o 2\pi R_{gap} H \left[ \frac{f_s}{\left(\frac{t_{cyl} + t_s}{\epsilon_{cyl} + \epsilon_s}\right)} + \frac{(1-f_s)}{\left(\frac{t_{cyl} + t_s}{\epsilon_{cyl} + \epsilon_{oil}}\right)} \right] \quad (3)$$

where,  $\epsilon_o$  is vacuum permittivity (F/m),  $R_{gap}$  is radius gap between windings (m),  $H$  is winding height (m),  $t_{cyl}$  is thickness of cylinder (m),  $\epsilon_{cyl}$  is relative permittivity of cylinder,  $t_s$  is thickness of stick (m),  $\epsilon_s$  is relative permittivity of stick,  $\epsilon_{oil}$  is relative permittivity of oil, and  $f_s$  is the fraction of the space occupied by axial stick.

Equation (4) and (5) provide the turn and disc capacitances [7].

$$C_t = \epsilon_o \epsilon_p 2\pi R_{ave} \frac{(h+2t_p)}{t_p} \quad (4)$$

where,  $\epsilon_p$  is relative permittivity of paper insulation,  $R_{ave}$  is mean radius of winding (m),  $h$  is height of conductor (m), and  $t_p$  is thickness of paper insulation.

$$C_d = \epsilon_o \pi (R_{out}^2 - R_{in}^2) \left[ \frac{f_{ks}}{\left(\frac{t_p + t_{ks}}{\epsilon_p + \epsilon_{ks}}\right)} + \frac{(1-f_{ks})}{\left(\frac{t_p + t_{ks}}{\epsilon_p + \epsilon_{oil}}\right)} \right] \quad (5)$$

where,  $R_{out}$  is outer diameter of winding (m),  $R_{in}$  is inner diameter of winding (m),  $\epsilon_{ks}$  is relative permittivity of radial key-spacer,  $t_{ks}$  is thickness of radial key-spacer (m), and  $f_{ks}$  is the fraction of the disc-disc occupied by radial key-spacer [6]

## 2.2. Interleaved Disc

Continuous disc has disadvantage of having low series capacitance [8]. A simple disposition of turns increases the series capacitance on interleaved winding to obtain near uniform initial voltage distribution [2]. In an interleaved winding  $C_s$  increases considerably if compared with continuous disc, therefore it is used to reduce the severe stress [9].

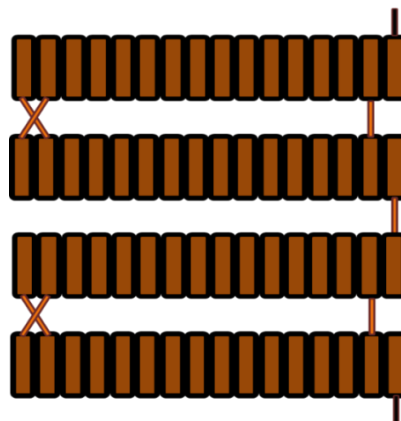


Fig. 3. Layout of interleaved disc.

Fig. 3 shows the configuration of an adjacent interleaved disc winding with one conductor per turn. The series capacitance value of this interleaved winding [10] is given by (6).

$$C_s = \frac{NC_t}{4}(n - 1) \quad (6)$$

where,  $N$  is number of disc with interleaving, and  $n$  is number of conductor in each disc. When there is more than one conductor per turn, it can also be positioned as interleaved to get maximum benefit from the method of interleaving [2].

### 2.3. Countershielded Disc

One of the advantageous of using in-wound shielded conductor is to increase the turn capacitances ( $C_t$ ) without interleaving the main winding's turn. In this winding, the shields, which can be made from copper or aluminum conductor, are placed between the winding's main conductors at predetermined places and insulated from the main turn's conductor. Every shielding conductor from the upper disc (in a pair of discs) is connected to the lower electrostatic shield conductor of the lower disc having the same horizontal position [11]. Fig. 4 shows the configuration of the countershielded disc winding. In this winding design, one shielding conductor is placed between the winding turns and wound-in together with same direction as shown in Fig. 4(a).

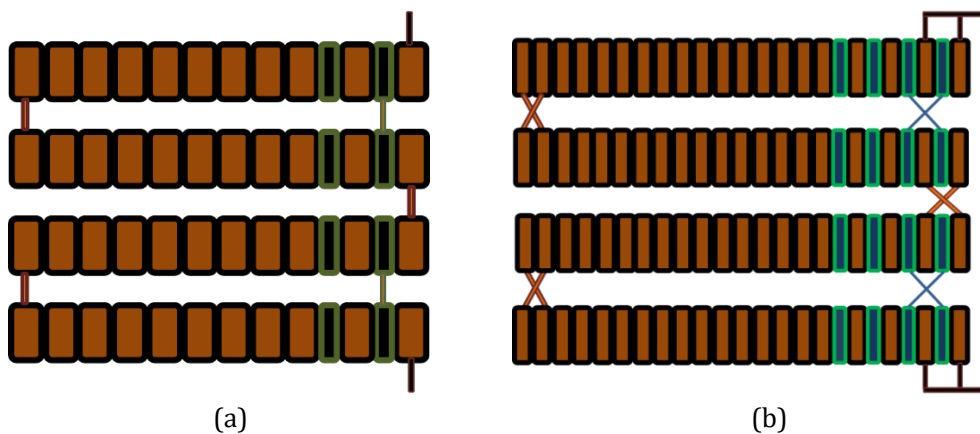


Fig. 4. Configuration of (a) single countershielded and (b) double countershielded discs.

Fig. 4(b) shows the configuration of a double countershielded disc winding. In this model, two pieces of shielding conductors are placed between turns and between parallel conductors of the winding and also wound-in together with same direction. Both shielding conductors are transposed in every two discs (disc pair) to follow the main turn's transposition. The implementation of double shielding configuration is only possible when the winding has an even number of parallel conductors per turn.

### 3. Methodology

The physical windings arrangement of the 500 kV transformer in this study from inside toward the core are configured as TV (Tertiary Voltage), HV\_TAP (HV Tapping), LV (Low Voltage) and HV (High Voltage) as shown in Fig. 5. The main HV winding itself is placed at the outermost diameter and it consists of two axial parts (top and bottom) connected in parallel.

To realize the goal, the simulation of 1550 kVp full wave impulse is applied at the center of the HV winding which is a disc type and has parameters as detailed in Table 1. The simulation is done at principal tap position where whole of the tapping winding is not in service to simplify the calculation. This numerical calculation is done by Pulse software with algorithm as shown in Fig. 6. The output data is plotted by chart in Ms. Excel.

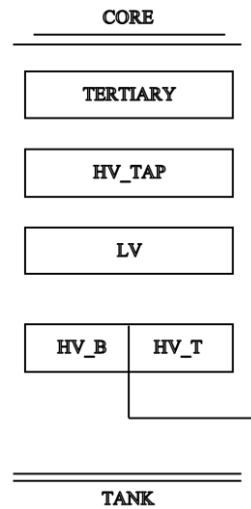


Fig. 5. Arrangement of 500 kV transformer windings.

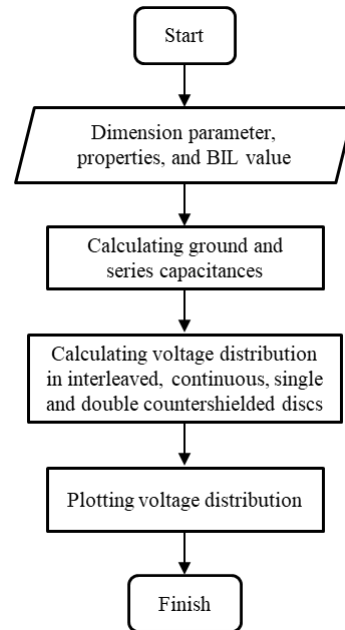


Fig. 6. Flow chart of calculation.

Table 1. The Parameter of Simulated Winding

Description	Quantity and Size
Number of disc in countershielded design	54
Number of disc in interleaved design	52
Number of turn per disc	12
Number of bunch conductor per turn	2
Height of bare bunch conductor	13.0 mm
Thickness of conductor insulation	1.6 mm
Height of shielding conductor	12.6 mm
Thickness of shielding conductor insulation	2.0 mm
Thickness of radial key-spacer	8.0 mm

#### 4. Result and Discussion

According to the result of the Pulse software calculation, the initial voltage distribution of both interleaved and countershielded disc designs are shown in Fig. 7. In this figure, the interleaved disc design shows a more uniform voltage distribution, however it is not the intended design option as it is time consuming. The resulted voltage distributions by double and combined countershielded discs show an acceptable figure even though they are less uniform compared to the interleaved design.

The single countershielded disc design is not suitable in this 500 kV transformer application as the initial voltage distribution as shown in Fig. 7 is far away from linear. The voltage stresses between discs as shown in Fig. 8 are also considerably too high (153.5 kVp) and approaches the design criteria of predefined thickness of paper insulation and radial key-spacer in this study. In addition, the provided design safety margin by this figure is explicitly insufficient.

The comparison of the voltage stresses between discs resulted by interleaved and countershielded disc designs are shown in Fig. 8. In this figure, the interleaved disc design shows a more uniform stresses, however the combination of single and double countershielded disc design has resulted a lower amplitude of voltage stresses. The maximum voltage stress between discs obtained by the calculation are 117.7 kVp in interleaved disc design and 115.3 kVp by combined shielded disc design. In term of design perspective, both options provide a safe design compared to the design criteria of 155 kVp.

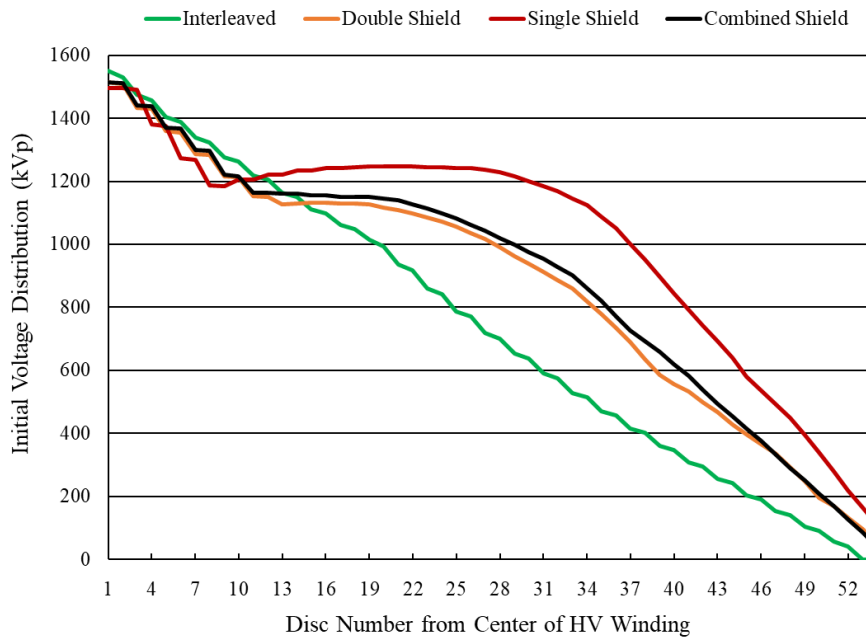


Fig. 7. Initial voltage distribution along the winding.

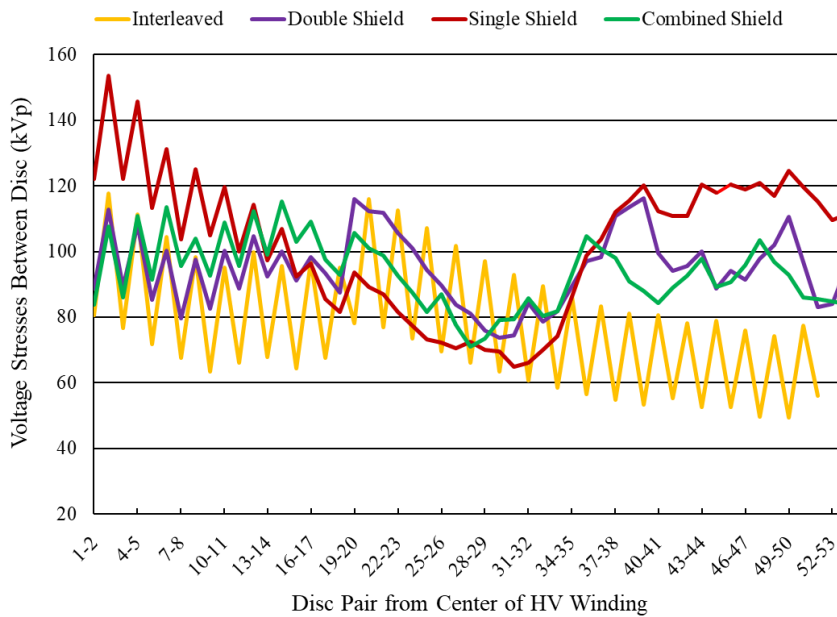


Fig. 8. Voltage stresses between discs.

## 5. Conclusion

Using combination of single and double countershielded disc configuration provides better impulse voltage distribution and lower amplitude of voltage to ground compare to single configuration either double or single countershielded. The interleaved disc design shows more linear distribution, however it becomes less favorable due to difficulties to manufacture and less cost effective. The implementation of the interleaved design is also limited to magnet wire or bunch conductor. In the application of large power transformer where the CTCs are widely used, the countershielding design is the only solution.

The extended study of countershielded disc design by triple shields arrangement may be interesting

typically for large power transformer design and higher voltage level. Providing multiple shielding is the most effective solution in increasing the series capacitance as adding the number of shielding turns will generate a higher voltage stresses at the shield ends.

### Conflict of Interest

The studies reported in this publication were supported by grant from CG Power Systems Indonesia. Although a non-financial conflict of interest was identified for management based on the overall scope of the study and its potential benefit to CG Power Systems Indonesia, the research findings included in this publication may not necessarily related to the interests of CG Power Systems Indonesia.

### Author Contributions

Moh. Slamet Wahyudi brought the idea, developed the theory, and performed the computation. Rudy Setiabudy verified the analytical methods and supervised the findings of this work. All authors discussed the result and contributed to the final manuscript.

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