International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

June 2013 | Issue 15 | Volume 5 | Number 2 | Pages 22-28

INFLUENCE OF TRANSFORMER LAYER WINDING PARAMETERS ON THE CAPACITIVE CHARACTERISTIC COEFFICIENT

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Abstract- With changing the parameters of layer winding in transformers, capacitive characteristic coefficient of winding will be changed. Since, impulse voltage distribution (IVD) along a winding is depended on this coefficient, so analyzing this coefficient is important in transformers. This paper study and analyze a transformer with layer winding and rectangular cross-section. In this study, the influence of changing the layer winding transformers parameters (LWTP) on capacitive characteristic coefficient is going to be analyzed which may be a new research in this study. Also, in this study the equations for capacitances between winding turns in different layers and also equations for capacitances between turns and core in different layers are derived. The presented relationships are dependent on the parameters of the transformer winding, so changing these parameters will change turn-turn capacitance (TTC) and turn-core capacitance (TCC) and finally change the capacitances of the total series and parallel of the winding. The aim of this paper is to illustrate the effect of parameters deviations on the capacitances of the total series and parallel of the winding and show these effects on the results of the capacitive characteristic coefficient of the winding.

Keywords: Capacitive Characteristic Coefficient, Impulse Voltage Distribution, Layer Winding Transformers Parameters.

I. INTRODUCTION

The various kinds of over voltages in power systems are as follows: switching, lightning shock and short circuit in power network. Lightning as the most significant external source producing transient overvoltage in power systems is of great significance [1]. When a lightning over voltage impinges on the transformer winding terminals, produces considerable voltage gradient at the first of the winding, which can be resulted in electric breakdown of the transformer insulation. So, protection of power transformers in lightning over voltages is very important.

Because of high frequency of the lightning over voltage, impact of capacitances of the winding cannot be ignored [2-4]. The amounts of these capacitances have an important effect on the impulse voltage distribution (IVD) and the stresses along the windings. To optimize the amounts of capacitances of capacitive network of the winding, the safety of the operation of the power transformer can be certified. The life of transformers has a considerable economic impact on the operation of electrical systems [5].

In order to estimate the IVD along the transformer winding, the knowledge of the effective series and parallel capacitances is essential [4]. The capacitors between winding turns are known as series and the capacitors between turns and core are known as parallel capacitors.

According to Figure 1, the voltage of any point in capacitive network of the winding in the time of the strike of impulse voltage U with assuming the grounded transformer winding is deduced from Equation (1) [4]:

$$V(x) = U\left(\frac{e^{\alpha x} - e^{-\alpha x}}{e^{\alpha l} - e^{-\alpha l}}\right) \tag{1}$$

which,

$$\alpha = \sqrt{\frac{C_p}{C_s}} \tag{2}$$

In Equation (1), U is the amplitude of the applied impulse voltage to the winding terminal, l is the total length of winding, x is the coordinates of point for calculating the voltage. In Equation (2), C_s is the total series capacitance of the winding and C_p is the total parallel capacitance of the winding.

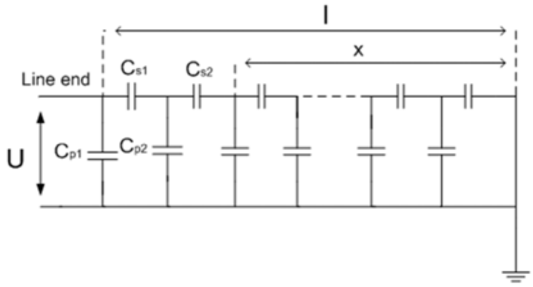


Figure 1. Capacitive network of the transformer winding in time of the strike of the impulse voltage U

Capacitive characteristic coefficient of the winding (α) shows the rate of uniformity of IVD along the transformer winding [2]. This coefficient is dependent on the total series and parallel capacitances of the winding. Total series capacitance of the winding is equivalent to the capacitances of turn-turn and total parallel capacitance of the winding is equivalent to the capacitances of turn-core.

Figure 2 shows, the curve of the initial IVD on a grounded winding for different α [2]. According to Figure 2, by increasing capacitive characteristic coefficient of winding (α), the IVD along a winding will be nonlinear.

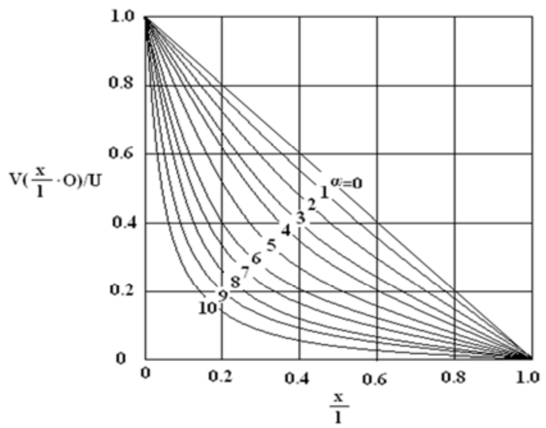


Figure 2. Impact of α on the initial impulse voltage distribution [2]

According to Equation (2), with increasing the proportion of total parallel capacitance to the total series capacitance of the winding, the coefficient of α will be increased. So, by increasing C_s and decreasing C_p the coefficient of α will be decreased and it will be caused to provide a uniform and linear IVD along the winding.

So, in the design of transformers for high voltage operations, it will be attempted that the total series capacitance of winding will has the largest possible value. In this case IVD along the winding will be uniformed, and also the insulation of wires in the beginning of the winding will be protected.

As mentioned above, to minimize the damage to the winding in the time of the strike of impulse voltage, the coefficient of α must be the smallest possible value. Methods of interleaving the winding turns and use of the electrostatic shielding in the windings are used for increasing the total series capacitance of the winding and linearization of the initial IVD on the winding or decreasing of α [6-9].

In [10], the amount of total series capacitance in the windings with shield and without shield is compared with various methods. In [11], presents a comprehensive procedure for calculating all contributions to the self-capacitance of high voltage transformers and provides a detailed analysis of the problem, based on a physical approach. Also in [12], a novel procedure to determine the series capacitance of a transformer winding, based on frequency-response measurements, is reported. Also there are different methods for calculating the series and parallel capacitances (turn-turn and turn-core capacitances) of capacitive network of the winding [13-16]. Series and parallel capacitances in capacitive network of the winding are dependent on the parameters of the winding. So these parameters can be affected the amount of total series and parallel capacitances of the winding and finally can be useful in making the distribution of initial impulse voltage more uniform.

In this paper, the influence of the winding parameters on the total series and parallel winding capacitances has been studied. With the results of this paper, we can understand how the winding parameters will be changed in order to decreases the capacitive characteristic coefficient of the winding. Also we can understand which parameters will have a more effect to increase the total series capacitance and decrease the total parallel capacitance of the winding. In this paper, capacitive network of the layer winding with rectangular cross-section is studied. The winding of a typical transformer with specified parameters has been simulated by using Matlab software.

II. CALCULATING SERIES AND PARALLEL CAPACITANCES

A. Series Capacitance

In this section, equations for series capacitors (turn-turn capacitors) will be presented. Figure 3 shows a coil with rectangular winding. For calculating the capacitance, the curvature of the turns was neglected and it was assumed that the conductors are straight with unlimited length. Two conductors with rectangular cross-section which are straight and parallel are equivalent to two parallel planes. From the parallel-plane capacitor equation, one obtains the following:

$$C = K.\varepsilon_0 \frac{A}{d} \tag{3}$$

where A is the cross-section of parallel planes, d is distance of between two parallel planes, ε_0 is the permittivity of vacuum (8.85×10^{-12} F/m) and K is a constant for winding leakage effects.

In the next steps, Equation (3) will be more accurate so that winding parameters will be included. In this method [13-16], distance between two adjacent turns or the turn and core are divided into different parts. According to Figure 4, distance between two adjacent turns is divided into 3 regions. First region is the insulating coating of the first turn, second region is the insulation between adjacent turns and the third region is the insulating coating of the second turn.

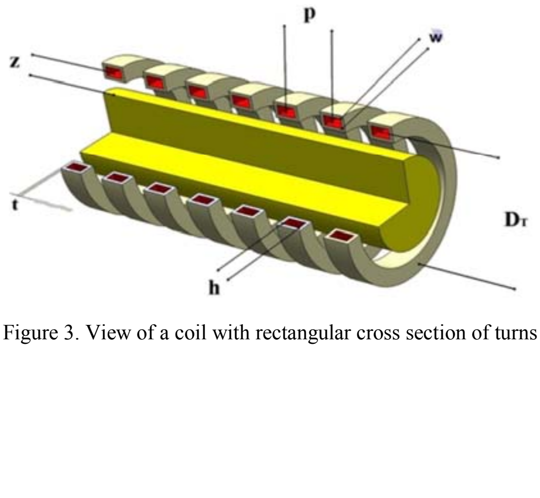


Figure 3. View of a coil with rectangular cross section of turns

The capacitance for the insulating coating of each wire (capacitance of the first and third regions) is calculated from Equation (4) that is derived using Equation (3).

$$C_{ic} = \varepsilon_0 . \varepsilon_r . \frac{\pi . D_T . w}{t} \qquad (4)$$

The parameters of Equation (4) are shown in Figure 3. In this equation, D_T is the average diameter of the turn, w is the width of turn’s cross-section without insulating coating and t is the thickness of the insulating coating on one side and ε_r is the relative permittivity of the insulating coating of each wire.

In the transformers winding, the insulation between two turns is usually oil. The capacitance between two adjacent turns in the area of covered by oil (capacitance in the second region) is calculated from Equation (5):

$$C_{oil} = \varepsilon_0 . \varepsilon_{r(oil)} . \frac{\pi . D_T . w}{p - h - 2t} \qquad (5)$$

where p is winding pitch or distance between centers of the cross-sections of the adjacent turns, h is the height of turn’s cross-section without insulating coating and $\varepsilon_{r(oil)}$ is the relative permittivity of oil.

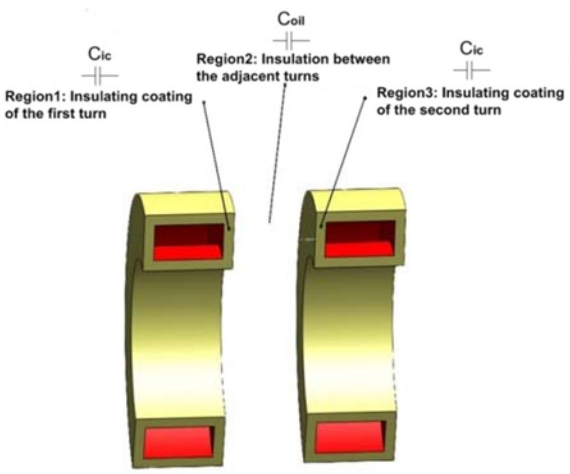


Figure 4. Regions between two adjacent turns

In the space between two adjacent turns in the transformers winding only the oil is considered and the other insulations are ignored. In the distance between two adjacent turns, the capacitance associated with the first, second and third region, make up a series composition which is shown in Figure 5.

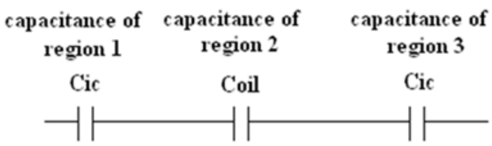


Figure 5. Series combination of capacitances in the distance of two adjacent turns

This series combination can be shown as Equation (6):

$$C_{tt} = \frac{C_{ic} . C_{oil}}{C_{ic} + 2C_{oil}} \qquad (6)$$

It is important to note that the capacitances of associated with the first and third regions are equal. By substituting Equations (4) and (5) in Equation (6), the total capacitance between two adjacent turns (turn–turn capacitor) is calculated by Equation (7):

$$C_{tt} = \varepsilon_0 . \varepsilon_{r(oil)} . \frac{\pi . D_T . w}{p - h - 2t\left(1 - \frac{\varepsilon_{r(oil)}}{\varepsilon_r}\right)} \qquad (7)$$

B. Parallel Capacitance

To calculate the parallel capacitance (turn-core capacitor), like section A the curvature of the turns are ignored and the core is considered as a plane. Also in this section Equation (3) is used and developed for this consideration. In this method [13-16], the distance between a turn and core is divided into two regions. According to Figure 6, first region is the insulating coating of the turn and the second region is the insulation between turn and core (oil). In this section, to calculate the capacitance of first region (the capacitance of insulating coating of the turn) is used from Equation (8):

$$C_{ic} = \varepsilon_0 . \varepsilon_r . \frac{\pi . D_T . h}{t} \qquad (8)$$

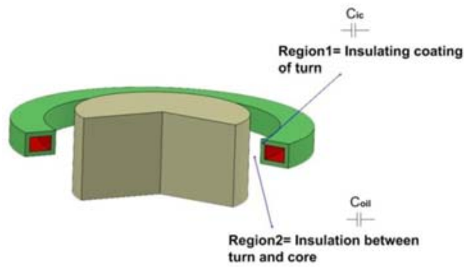


Figure 6. Regions between turn and core

The capacitance of the second region which is filled by oil is calculated according to Equation (9):

$$C_{oil} = \varepsilon_0 . \varepsilon_{r(oil)} . \frac{\pi . D_T . h}{Z - (\frac{w}{2}) - t} \qquad (9)$$

The parameters of Equation (9) are shown in Figure 3. In this equation, Z is distance between the center of turn’s cross-section and the outer surface of the core. According to Figure 7, in the distance between the turn and core capacitance associated with the first region, it makes a series combination with the capacitance associated with the second region.

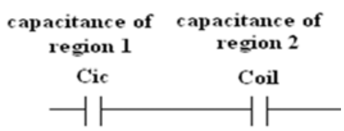


Figure 7. Series combination of capacitances in the distance between turn and core

This series combination can be shown as Equation (10):

$$C_{tc} = \frac{C_{ic} . C_{oil}}{C_{ic} + C_{oil}} \qquad (10)$$

It should be noted that in this section, there is only one capacitor C_{ic}, but in section A there were two capacitors C_{ic}, which were series. So by substituting Equations (8) and (9) in Equation (10), the total capacitance between the turn and core (turn-core capacitor) can be by calculated by Equation (11):

$$C_{tc} = \varepsilon_0 . \varepsilon_{r(oil)} . \frac{\pi . D_T . h}{Z - \left(\frac{w}{2}\right) - t\left(1 - \frac{\varepsilon_{r(oil)}}{\varepsilon_r}\right)} \quad (11)$$

Equations (4)-(11) are based on references [13-16].

III. EQUIVALENT CAPACITANCES IN LAYER WINDING

Figure 8 shows a layer winding. The advantage of this type of winding is simple to build. But series inherent capacitance in this type of winding is smaller than the parallel inherent capacitance. So this type of winding allows to lightning IVD along this winding being non-uniform and may be lead to burning. In the next step, the reduction of α and the amplitude of impulse voltage fluctuations will be achieved by increasing the series capacitance.

Capacitive network of the layer winding is shown in Figure 9. In this capacitive network there are two kinds of capacitors:

1. Turn-turn capacitor (C_{tt}), is as a series capacitor.
2. Turn-core capacitor (C_{tc}), is as a parallel capacitor.

According to capacitive network of a layer winding, there is a series capacitance between each conductor with next and previous conductors. If the number of conductors in this winding be n, so the number of series capacitances in capacitive network of the winding would be n-1. The total series capacitance of the winding (C_s) is calculated from Equation (12):

$$C_s = \frac{C_{tt}}{n-1} \quad (12)$$

where, C_{tt} is a turn-turn capacitance.

Also, there is a parallel capacitance (C_{tc}) between each conductor and core in layer winding. So, the total parallel capacitance of winding (C_p) is calculated from Equation (13):

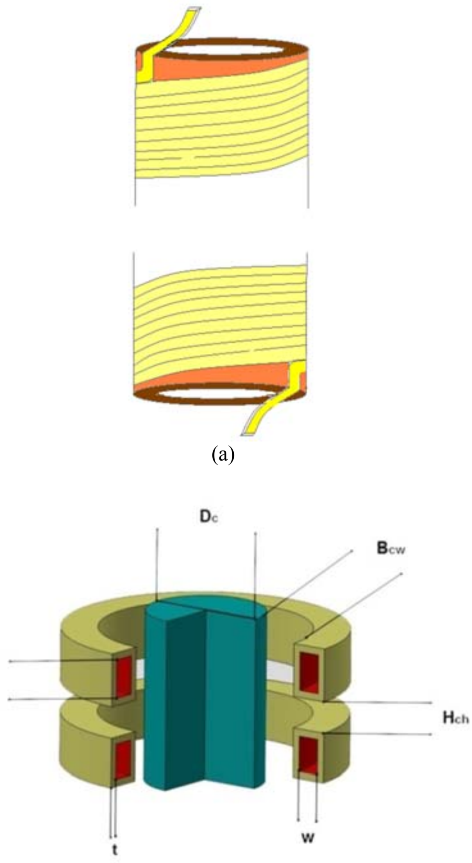
$$C_p = nC_{tc} \quad (13)$$

where, C_{tc} is a turn-core capacitance and n is the number of parallel conductors.

The number of turns (n) in a layer winding is assumed to be constant. So, the total series capacitance of winding is dependent on (C_{tt}) and the total parallel capacitance of winding is dependent on (C_{tc}). The series capacitors in the capacitive network of layer winding from Equation (7) and parallel capacitors can be calculated (Equation (11)).

IV. ANALYSES OF THE CAPACITIVE CHARACTERISTIC COEFFICIENT OF WINDING

In this section, a typical transformer with layer winding is considered for this study. The parameters of the transformer winding are introduced in Table 1. These parameters are shown in Figure 8.



(a)

(b)

Figure 8. (a) View of a complete layer winding, (b) View of a layer winding with 2 turns

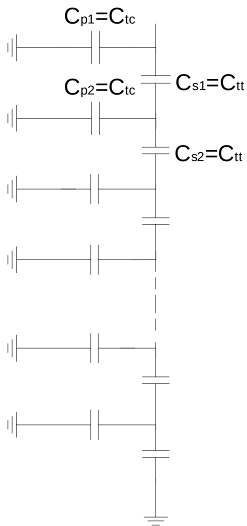


Figure 9. Capacitive network of the layer winding

The results of changing the winding parameters according to Matlab software are shown in the Figures 10-13. These figures show that how the total series and parallel capacitances of the winding will be changed due to the results of changing of the winding parameters. Also Figures 14-17, show the changes of the coefficient of α according to the changes of the winding parameters.

Table 1. Parameters of simulated layer winding

Number of turns (n)	20
Relative permittivity of insulation	Paper = 4.2, Oil = 2.25
Height of turn’s cross-section without insulating coating (h)	9.5 mm
Width of turn’s cross-section without insulating coating (w)	6.5 mm
Thickness of paper insulation of the conductor in one side(t)	0.5 mm
Diameter of core (D_c)	500 mm
Distance of the outer surface of the core to winding (B_{cw})	30 mm
Length of the channel between winding’s turns (H_{ch})	4.5 mm

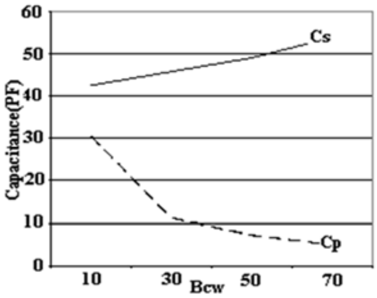


Figure 10. Changes of total series and parallel capacitances due to the changes of B_{cw}

According to Figure 10, by increasing the distance of the outer surface of the core to the winding (B_{cw}), the total series capacitance of the winding (C_s) will be increased and the total parallel capacitance of winding (C_p) will be decreased. Also according to Figure 14, the increase of B_{cw} will cause the coefficient of α to be decreased and as a result the IVD along the winding will be uniform. This is because, by increasing $B_{cw,}$ the parameter of D_T in Equations (7) and (11) and also the parameter of Z in Equation (11) will be increased and these variations will be caused the proportion of total series to parallel capacitance will be increased.

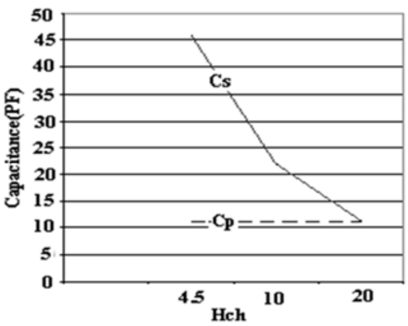


Figure 11. Changes of total series and parallel capacitances due to the changes of H_{ch}

From Figure 11, it is observed that the changes in the length of the channel between winding’s turns (H_{ch}), hasn’t any effect on the capacitance of C_p, but by decreasing H_{ch}, the parameter of P in Equation (7) was reduced and it was caused that the capacitance of C_s to be increased. From Figure 15 it was clearly seen that, by increasing the capacitance of C_s, the coefficient of α was decreased. So the decrease of H_{ch} will be caused the IVD along the winding to be more uniform.

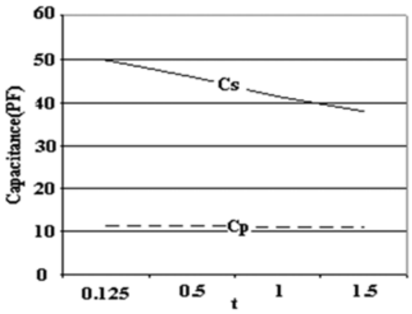


Figure 12. The variations of the total series and parallel capacitances duo to the changes of t

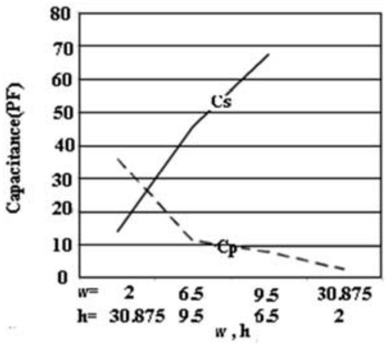


Figure 13. The variations of the total series and parallel capacitances duo to different value of w, h

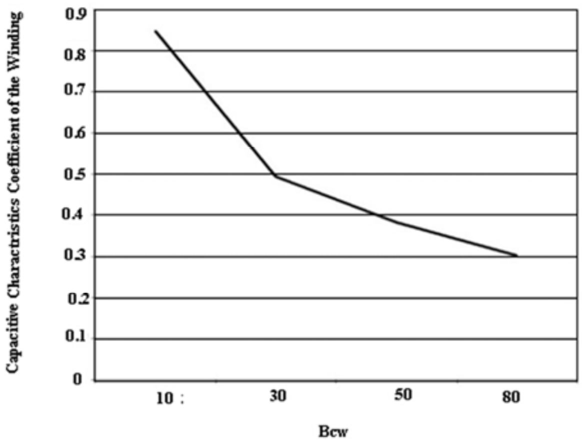


Figure 14. The variations of α duo to the changes of B_{cw}

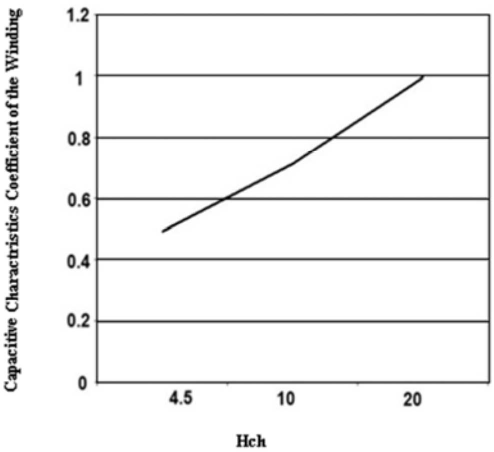


Figure 15. The variations of α duo to the changes of H_{ch}

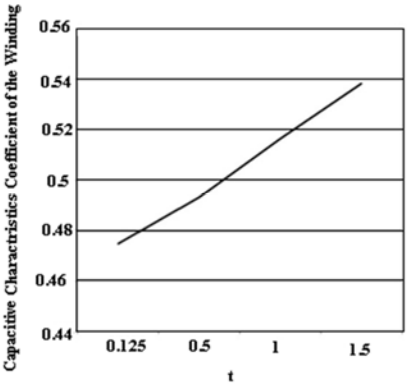


Figure 16. The variations of α duo to the changes of t

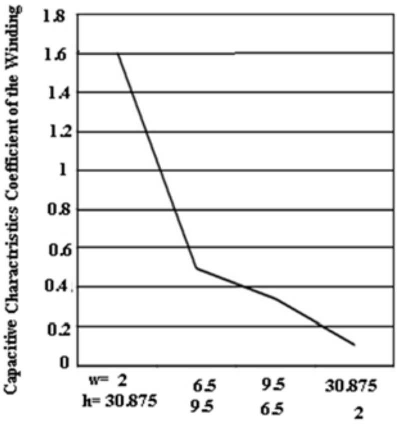


Figure 17. The variations of α duo to the changes of w, h

According to Figure 12, the changes in the thickness of paper insulation of the conductor (t) has no significant effect on the capacitance of C_p, but by decreasing t, the total series capacitance of the winding (C_s) has a little increase and as a result, the proportion of total series to total parallel capacitances will be increased a little. Also from Figure 16, it is clearly seen that by decreasing t, a little decrease in the coefficient of α is observed. The reason of this little effect by changing t in Equations (7) and (11) is that the proportion of total series to parallel capacitance will have a little change. Therefore, there are not significant changes in the IVD along the winding by the change of t.

To analyze the effect of changing the cross-section dimensions of the conductor winding on the coefficient of α, it was assumed that the area of conductor cross-section to be constant. So, the height (h) and width (w) of cross-section can be changed without any change in conductor cross-section. According to Figure 13, by reducing h and increasing w, the capacitance of C_s was increased, the capacitance of C_p was decreased, and also according to Figure 17, the coefficient of α was decreased. In the case of turn's cross-section which has its maximum w and its lowest h, the smallest amount of α and the most uniform IVD along the winding can be obtained.

In Figure 18, the maximum and minimum capacitive characteristic coefficient of the winding (α) for various parameters has been shown. These values have been taken from Figures 14-17.

From Figure 18, it is observed that the change of dimensions of turn's cross-section (without insulating coating) has the most impact on decreasing of the capacitive characteristic coefficient of winding (α). Also the changes of paper insulation thickness of the conductor, has the minimal impact on the coefficient of α.

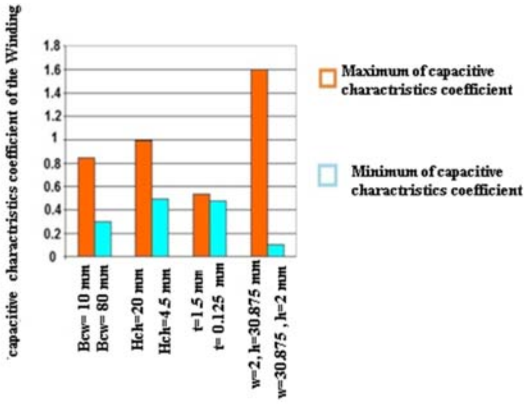


Figure 18. The max and min of the coefficient of α for the various parameters

V. CONCLUSIONS

By using the transformer winding simulations in this paper, the variations of total series and parallel capacitances of the transformer winding and also the variations of the winding capacitive characteristic coefficient duo to the changes of parameters of winding were analyzed. In this research, a layer winding with rectangular cross-section and with the desired parameters was considered. Then with changing the parameters of the winding, the desired results were extracted.

From the results which are obtained from the Matlab software, the increase of the proportion of total series to parallel capacitance means that to reduce the capacitive characteristic coefficient of the winding and finally these variations means a more uniform IVD along the winding. The results of simulations in this paper show that any change in each parameter of the winding, will be caused the capacitive network of the winding and the capacitive characteristic coefficient of the winding to be changed and this will be caused a change in IVD of the winding.

It was observed that the thickness of paper insulation of the conductor hasn't a significant effect on the capacitive characteristic coefficient of the winding, but by increasing the distance of the outer surface of the core from the winding and decreasing the length of the channel between winding's turns, the capacitive characteristic coefficient of the winding will be decreased and the result will be caused a more uniform IVD along the winding. The obtained results show that for decrease of the capacitive characteristic coefficient of winding, the height of turn's cross-section (without insulating coating) must to decrease and the width of the turn's cross-section (without insulating coating) must to increase.

NOMENCLATURES

U: The amplitude of the applied impulse voltage to the winding terminal

l : The total length of winding

x: The coordinates of point for calculating the voltage

C_s: The total series capacitance of the winding
C_p: The total parallel capacitance of the winding
A: The cross-section of parallel planes
d: The distance between two parallel planes
ε_0 : The permittivity of vacuum
K: A constant for winding leakage effects
D_T: The average diameter of the turn
w: Width of turn’s cross-section without insulating coating
t: The thickness of the insulating coating on one side
ε_r : Relative permittivity of insulating coating of each wire
P: Winding pitch or distance between centers of the cross-sections of the adjacent turns
h: Height of turn’s cross-section without insulating coating
$\varepsilon_{r(oil)}$: The relative permittivity of oil
Z: Distance between the center of turn’s cross-section and the outer surface of the core
C_{tt}: Turn-turn capacitance
n : The number of conductors
C_{tc}: Turn-core capacitance
D_c : Diameter of core
B_{cw}: Distance of the outer surface of the core to winding
H_{ch}: Length of the channel between winding’s turns

REFERENCES

[1] M. Nojavan, A. Gholami, “One Mathematic Equation for Assessment of Maximum Lightning Overvoltage along a Cable”, International Journal on Technical and Physical Problems of Engineering (IJTPE), Vol. 3, No. 1, pp. 57-60, March 2011.

[2] K. Karsai, D. Kerenyi, “Large Power Transformer”, Elsevier, New York, 1987.

[3] A. Greenwood, “Electrical Transient in Power System”, John Wiley, 1991.

[4] S.V. Kulkarni, S.A. Khaparde, “Transformer Engineering Design and Practice”, Marcel Dekker, 2004.

[5] A. Mamizadeh, I. Iskender, “Winding Thermal Analyzing of Dry Type Transformers”, International Journal on Technical and Physical Problems of Engineering (IJTPE), Vol. 2, No. 4, pp. 80-84, Dec. 2010.

[6] M. Bagheri, M. Vakilian, A. Hekmati, R. Heidarzadeh, “Influence of Electrostatic Shielding of Disc Winding on Increasing the Series Capacitance in Transformer”, IEEE Lausnne Powertech, pp. 1780-1784, 2007.

[7] M. Bagheri, A. Hekmati, R. Heidarzadeh, M.S. Naderi, “Impulse Voltage Distribution in Intershield Disk Winding VS Interleaved and Continuous Disk Winding in Power Transformer”, IEEE International Conference on Power and Energy, pp. 387-392, 1-3 Dec. 2008.

[8] M. Bagheri, M. Vakilian, A. Hekmati, “Simulation and Comparison of Primary Surge Voltage Distribution in Simple Disk Winding, Disk Winding with Complete Shield and Interleaved Winding in Power Transformers”, 22th Power System Conference (PSC), Iran, 2007.

[9] M. Bagheri, M. Vakilian, A. Hekmati, “Using Electrostatic Shields Rather than Interleaving Windings in order to Increase Windings Series Capacitors in Power Transformers”, 21th Power System Conference (PSC), Iran, 2006.

[10] Y. Li, J. Du, X. Li, D. Li, “Calculation of Capacitance and Inductance Parameters Based on FEM in High Voltage Transformer Winding”, IEEE International Conference on Electrical Machines and Systems (ICEMS), 2011.

[11] L. Dalessandro, F.D.S. Cavalcante, J.W. Kolar, “Self Capacitance of High Voltage Transformers”, IEEE Transactions on Power Electronics, Vol. 22, No. 5, pp. 2081-2092, Sep. 2007.

[12] S. Pramanik, L. Satish, “Estimation of Series Capacitance of a Transformer Winding Based on Frequency Response Data: An Indirect Measurement Approach”, IEEE Transactions on Power Delivery, Vol. 26, No. 4, pp. 2870-2878, Oct. 2011.

[13] G. Grandi, M.K. Kazimierczuk, A. Massarini, U. Reggiani, “Stray Capacitances of Single Layer Solenoid Air-Core Inductors for High Frequency Applications”, IEEE Transactions on Industry Applications, pp. 1384-1388, Sep. 1996.

[14] G. Grandi, M.K. Kazimierczuk, A. Massarini, U. Reggiani, “Stray Capacitances of Single Layer Solenoid Air Core Inductors”, IEEE Trans. Industry Application, Vol. 35, No. 5, pp. 1162-1165, Sep./Oct. 1999.

[15] M.E. Mosleh, M.R. Besmi, “Sensitivity Analysis of Effective Parameters in Stray Capacitance of Magneto Cumulative Generator Having Integrated Rectangular Cross-Section Turns, with Insulating Coating”, International Review of Electrical Engineering (I.R.E.E), Vol. 6, No. 1, pp. 275-284, Jan.-Feb. 2011.

[16] M.E. Mosleh, M. R. Besmi, “Stray Capacitance of a Magneto Cumulative Generator Including N-Turn, Single-Layer, Solid, and Round Conductor With Insulating Coating”, IEEE Transactions on Plasma Science, Vol. 39, No. 10, pp. 1990-1997, Oct. 2011.

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