Stray Capacitance Calculation of a Magneto Cumulative Generator Coil with Round Conductor

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***Abstract*—This paper presents a new method to calculate stray capacitance between conductor wire filaments. The new proposed method is called vespiary regular hexagonal (VRH) model. In this paper conductor of magneto cumulative generator (MCG) coil has a multilayer wire. So the proposed model is used to calculate stray capacitance between two adjacent wire filaments (WFs) and capacitance between the wire filaments and central cylindrical liner in one turn of coil (OTC). The presented method in this paper is based on an analytical method and geometrical structure. In one turn of coil, the wire filaments in VRH method are separated into many very small similar elementary cells. In this structure, an equilateral lozenge-shape basic cell (ELBC) with two trapezium-shape regions has been considered between two adjacent wire filaments. This method is applied to calculate the total stray capacitance of N-turns of coil (NTC) with multi WFs in round cross-section. Simulation results show that the proposed method is very useful for designing a geometrical structure of the MCG coil.**

***Index Terms*—Cylindrical liner, magneto cumulative generator, multi-filaments, multi-layers, stray capacitance.**

I. Introduction

Magnetic flux compression generators (MCG) have found widespread use as pulsed power sources for high magnetic field research or in commercial applications for oil and minerals and mine detection. A variety of basic magnetic flux compression generator designs have been developed and tested during the past five decades [1]-[2]. Fig. 1 shows a schematic of MCG. In the design of a MCG in order to well and correct performance of the generator, we need to obtain a geometrical model with sufficient accuracy and appropriate characteristics of geometrical components. In the past studies MCG coil was simulated only by resistance and inductance [3]-[4]. In our studies, we have never seen the effects of stray capacitance (SC) in MCG modeling by proposed model in this paper. However, the parasitic capacitances of the winding cannot be neglected at high frequencies [5]. Because of this important effect of the SC on electrical circuits, many literatures are related to it [5]-[11]. In [6] a method has been proposed for modeling the distributed SC of inductors by finite element method and a node-to-node lumped capacitance network. Reference [7] presented a method for predicting the SC of inductors. The method is based on an analytical approach and the physical structure of inductors. A practical technique is presented by [8] for determining SC in a two-winding high frequency transformer for circuit simulation. The approach is useful for the transformer circuit with the overall effects of SC, modeled as lumped stray-capacitance. A comprehensive procedure for calculating all contributions to the self-capacitance of high-voltage transformers is studied in [9]. In [10] a technique is proposed for extracting equivalent circuit parameters of an inductor such as series' resistance, inductance, and lumped shunt SC. In [5] a method for predicting SC is presented for solenoid HF inductors, which are made of one layer of turns with circular cross sections. Furthermore, there are many literatures in different subjects, which can be used to the design of MCG to obtain better performance like, transient response [12], over voltages [13], partial discharge [14], magnetic forces between coils[15], pulsed power magnification [16].

In this paper, for the first time, the effect of SC by a new method is extracted from [5] and [7] for MCG.

We need an accurate equivalent electrical circuit to predict the performance of the MCG before an explosion. The most important of MCG parameters are inductance, resistance and capacitance. In the literatures only equivalent electrical circuits for MCG with inductance and resistance are presented. So in this paper a new method to calculate SC is proposed.

During the progress of MCG, effects of electric field will be too much because of the voltage increase in each turn during explosion and decrease of the number of the coil turns. Electric field produced by operation of MCG process between turns of the coil and also between the turn and cylindrical liner placed at the coil center. In this paper, capacitances between adjacent turns and between a turn and liner are called C_{tt} and C_{tl} respectively. Because of high frequency performance of MCG, conductor of coil should be made of wire filaments and multi-layers. So, analysis presented in this paper applies for coils, which have a multi-layer cross-section with filamentary wires.

Because of the SC, resultant impedance of MCG will be affected by it. Therefore, to calculate total capacitance of MCG, we need to calculate the SC in the following cases:

- Capacitance between wire filaments in one turn (C_{ss}).
- Capacitance between wire filaments and liner (C_{sl}).
- Capacitance between coil turns (C_{tt}).
- Capacitance between turn and liner (C_{tl}).

In this paper, the effects of capacitance in MCG is discussed and analyzed.

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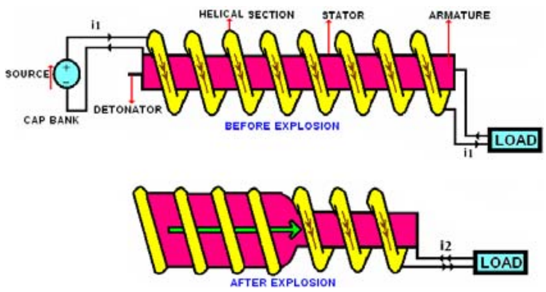


Figure 1. Helix MCG with explosive detonator, before explosion and during explosion

The SC of MCG coil may be has a significant effect on MCG performance. The purpose of this paper is to present a new method for predicting and calculating the SC of N-turns of MCG with circular cross-section, which have k-wire filaments (k-WFs) (k is the number of wire filaments, Figs. 3 and 4).

II. Algorithm and Method of Capacitance Calculation

The proposed algorithm to calculate the SC is as follows:

(a) Considering an overall model for equivalent circuit of N-turns of the generator coil.

(b) Calculation of filament-filament (C_{ss}) and filament-liner (C_{sl}) capacitance.

(c) Calculation of (filament-turn)-(filament-turn) capacitance (C_{stst}) between two wire filaments from two adjacent turns.

(d) Calculation of turn-turn capacitance (C_{tt}) between two adjacent turns, using results of the step (c).

(e) Calculation of turn-liner capacitance (C_{tl}) between a turn and liner using results of the step (b).

(f) Calculation of total parasitic capacitance (C(N)) for N-turns, using step (d) & (e).

(g) Simulation of the total SC, i.e. C(N) for N turns of the coil (NTC) using results of step (f).

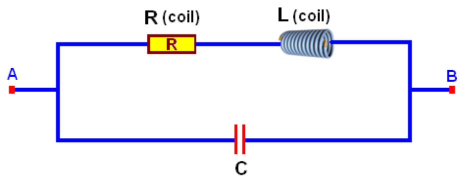


Figure 2. Equivalent circuit of the MCG coil

The total SC of the coil can be modeled by a lumped capacitance (C) which is connected between two coil's terminals, as shown in Fig. 2.

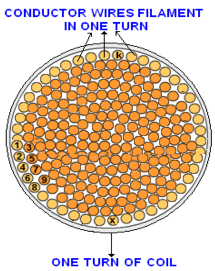


Figure 3. Cross-section of one turn of the MCG coil which have multi-layer and k-CWF

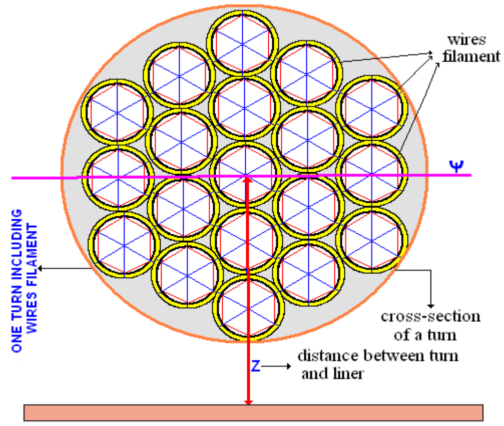


Figure 4. Cross-section of VHR of OTC with multi-layer and k-WFs

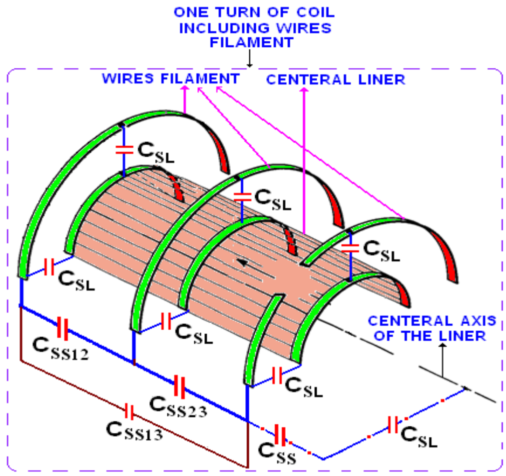


Figure 5. View of the total SC of OTC having multi-layer k-WFs of the MCG in non-real scale

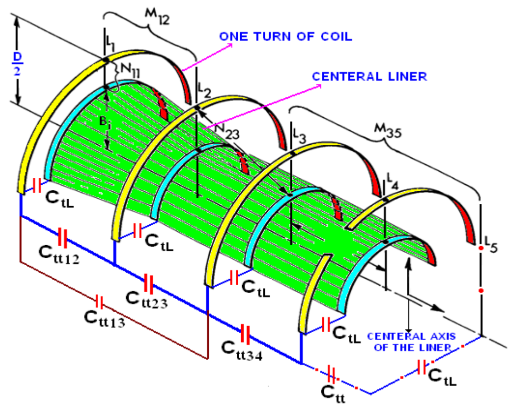


Figure 6. View of the SC of N turns of the MCG coil

In each turn of MCG coil, there is filament-filament capacitance(C_{ss}), filament-liner capacitance(C_{sl}), and turn-liner capacitance (C_{tl}). Fig. 5 shows the SC between WFs of only one turn with liner that includes the following:

1. Filament-filament capacitance between non-adjacent wire filaments in OTC is assumed to be negligible.

$$C_{ssij} = 0 \text{ for } i = 1,2,...,N-2, j = i+2,...,N$$

2. Filament-filament capacitance between adjacent wire filaments in one turn of the coil.

$$C_{ssij} = 0 \text{ for } i = 1,2,...,N-1, j = i+1$$

3. Filament-liner capacitance (C_{sl}).

$$C_{sil} \neq 0 \text{ for } i = 1,2,...,N$$

Fig. 6 shows the capacitances produced by N-turns of the coil (NTC), which includes the following:

1. Turn-turn capacitance between non-adjacent turns.
$$C_{ttij}=0 \text{ for } i=1,2,...,N-2,\ j=i+2,...,N$$
2. Turn-turn capacitance between adjacent turns.
$$C_{ttij}=0 \text{ for } i=1,2,...,N-1,\ j=i+1$$
3. Turn- liner capacitance (C_{tl}).
$$C_{til}\neq 0 \text{ for } i=1,2,...,N$$

Assumptions:

In order to draw details of Fig. 2, we suppose following assumptions:

- *Assumptions for NTC:*
  A. We neglect the capacitance effects between non-adjacent turns of the MCG coil.
- *Assumptions for OTC including k-CWF:*
  A. We neglect the capacitance between non-adjacent turns of the MCG.
  B. Space between all WFs in one turn of the MCG coil and central cylindrical liner are equal and considered to be Z.

Fig. 4 shows the cross-section of one turn of the MCG coil with the multi-layer of WFs which has been wounded uniformly. To calculate the capacitance between two WFs of one turn of the coil (OTC), first we consider a regular hexagon with perfectly equal angles of 2π/3 radian and perfectly equal sides that each side is equal to y in circular cross-section of each WF, so that the center of each hexagon is the center of circular cross-section of each WF. Arcs opposite to sides of this hexagon are perfectly equal because of geometric equality of sides. Then, we consider an equilateral lozenge-shape basic cell (ELBC) composed of two trapezoid-shape regions (regions 1 and 2 in Fig.8). Extension of the sides of this equilateral lozenge will pass from two adjacent apex of the hexagon and will be tangent to the external surfaces of adjacent CWF.

In this paper, the hexagon region is called vespiary regular hexagonal (VHR) region because of the similarity to a regular hexagon network and also to vespiary.

Fig.7 shows lozenge basic cell 'abcd' related to filament-filament capacitance (C_{ss}). From Figs. 4 and 7, we can find geometric symmetry of the CWF of OTC. By considering this geometric symmetry of CWF, that part of electric field lines which exits from a CWF are completely surrounded by other CWF around this CWF. By considering the geometric symmetry of the coil, the electric field lines should be divided equally among adjacent CWF. If we consider two close adjacent CWF in one turn of the MCG coil, then elementary capacitance of *dC* between two elementary surfaces of these two CWF with area of *dS,* which are opposite to each other will be [7]:

$$dC=\varepsilon_0 * \varepsilon_r \frac{ds}{g(\beta)} \qquad (1)$$

Where, ε_r is the relative permittivity and ε_0 is the vacuum permittivity and $g(\beta)$ is the length of electric field lines between two elementary conductor surfaces, which are opposite to each other. Here, $g(\beta)$ is a function of two CWF elementary surface positions of one turn of the MCG coil with angle of β. The β is not constant. Thus, position of each elementary surface of each circular CWF in a turn of the MCG coil could be stated by β coordinates (Fig. 8).

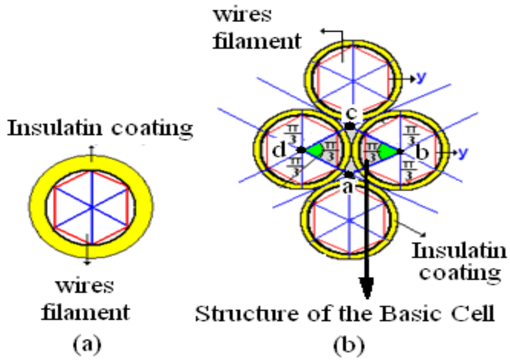
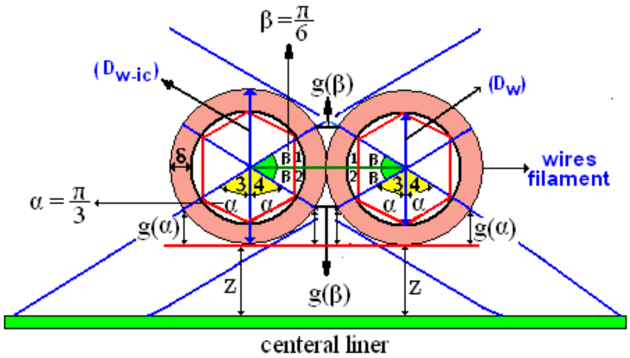
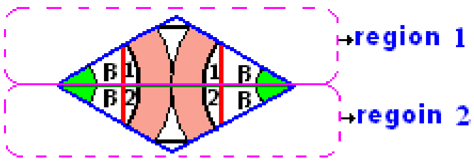


Figure 7. (a) Vespiary regular hexagon (VHR) region, (b) An 'abcd' equilateral lozenge-shape basic cell for calculating filament-filament capacitance



(a) View of g(β), the path of electrical field lines under β angle.



(b) Two trapezium-shape regions 1 and 2 in ELBC.

Figure 8. View of path g(β) of electrical field lines E under angel β between two adjacent CWF in OTC of the MCG

III. Filament-Filament Capacitance Between Two CWF in OTC

A. *Structure of ELBC of Vespiary Model.*

Fig. 7 shows an equilateral lozenge basic cell 'abcd' which forms filament-filament capacitance(C_{ss}). It was clearly seen that the geometric structure of the basic cell is the same for two adjacent CWF of the same layer and two adjacent CWF of different layers. So internal region of the cross-section of one turn of the coil could be divided into similar basic cells and only cells, which are adjacent to the central cylindrical liner, will be different from filament- filament cell.

An approximation and simple preliminary assumptions indicate that we can suppose all the basic cells to be similar and identical. These basic cells include a region of the periphery of CWF which correspond to angle of π/3 radian, because of geometric symmetry as shown in Figs. 4, 7 and 8. The above expression can be accepted for CWF which are completely surrounded by other CWF, if we neglect the edge capacitance and fringing. We can use the same angle of π/3 radian, which is considered previously, for CWF that are not perfectly surrounded. For ELBC shown in Fig. 7, three different regions which are crossed by electric field lines are as follows:

(a) Insulating coating region of the first CWF.
(b) Insulating coating region of the second CWF.
(c) Air gap region between two above CWF in OTC which are adjacent.

Therefore, elementary capacitance of dC between adjacent CWF in OTC of the generator is equivalent to a series' combination of three elementary capacitors in three above regions. In other words, first capacitor is related to insulating coating of the first CWF, second capacitor is related to the air gap between two adjacent CWF and third capacitor is related to insulating coating of the second CWF. Surfaces of CWF are considered co-potential with a relatively good approximation.

It is clearly seen that the direction of electric field lines between two adjacent CWF in OTC is in a radial form. A good approximation will give us the shortest possible path, which is parallel to the line connecting two centers of two adjacent circular CWF. This approximation applies for small amounts of β angle, which has a main role in filament-filament capacitance(C_{ss}). For big amounts of β, error of this approximation will increase. So, big amounts of β lead to increase the capacitance from actual capacitance. Anyway, the filament-filament capacitance of surfaces will decrease and the error amount produced in capacitance will be negligible when amounts of β increase.

B. Capacitance of Insulating Coating(C_{ic}) Between Two Adjacent CWF in OTC of the MCG.

In this section, a method of calculating capacitance of insulating coating among two turns of adjacent CWF in one turn of the MCG coil is presented. Fig. 9 shows a cylindrical elementary surface placed between the surface of CWF and the surface of insulating coating. Elementary capacitance related to this cylindrical insulating will be:

$$dC_{ic} = \varepsilon \frac{ds}{g(\beta)} = \varepsilon_0 * \varepsilon_r * \frac{r_{ic} * d\beta * dh}{dr_{ic}} \qquad (2)$$

Integrating of this equation for the range of radius (r) from the radius of CWF without insulating coating (r_w) to the outer radius of CWF with insulating coating ($r_{w\text{-}ic}$) and for h (turn length of CWF) from zero to turn length of CWF (l_{ts}), shows the capacitance of insulating coating limited to elementary angle of $d\beta$ as:

$$dC_{ic} = \varepsilon_0 * \varepsilon_r * d\beta * \int_0^{l_{ts}} dh \int_{r_w}^{r_{w-ic}} \frac{r_{ic}}{dr_{ic}} \qquad (3)$$

So we have:

$$dC_{ic} = \varepsilon_0 * \varepsilon_r * \frac{l_{ts}}{\ln\left(\frac{r_{w-ic}}{r_w}\right)} d\beta \qquad (4)$$

Since two insulating coating of two CWF in one turn of MCG coil are combined to series' form, insulating coating elementary capacitance of a basic cell of the two adjacent CWF with β angle will be:

$$\frac{1}{dC_{ic-ss}} = \frac{1}{dC_{ic}} + \frac{1}{dC_{ic}} = \frac{2}{dC_{ic}} \qquad (5)$$

Therefore, elementary capacitance of insulating coating of a basic cell is:

$$dC_{ic \to ss} = \varepsilon_0 * \varepsilon_r * \frac{l_{ts}}{2 * \ln\left(\frac{r_{w-ic}}{r_w}\right)} d\beta \qquad (6)$$

So, by integration of (6) on β, capacitance of insulating coating of two adjacent CWF in one turn of the generator coil is obtained by:

$$dC_{ic \to ss} = \varepsilon_0 * \varepsilon_r * \frac{l_{ts}}{2 * \ln\left(\frac{r_{w-ic}}{r_w}\right)} d\beta \qquad (7)$$

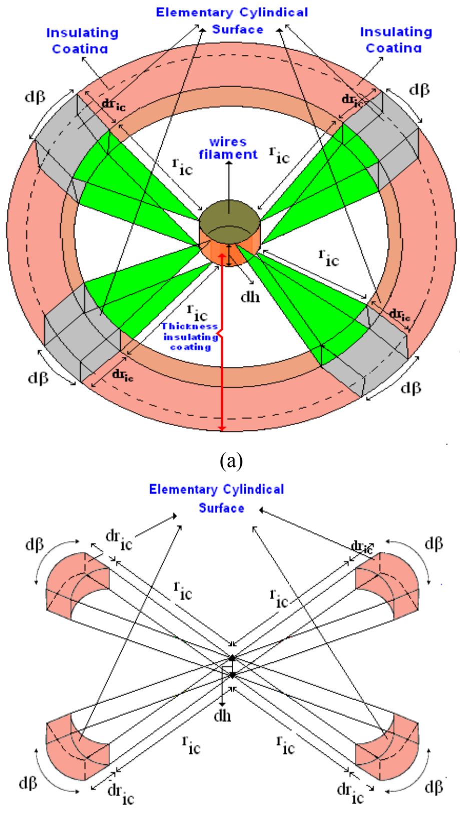


Figure 9. View of cylindrical elementary cross-section placed in insulating coating in non-real scale

C. Air Gap Capacitance (C_{ag}) Between Two Adjacent CWF in OTC of the Generator

Considering Figs. 7 & 8 cos(β) is:

$$\cos(\beta) = 1 - \frac{g(\beta)}{D_{w-ic}} \qquad (8)$$

Thus the path length of the electric field, which is a function of β, will be:

$$g(\beta) = D_{w-ic} * (1 - \cos(\beta)) \qquad (9)$$

The area of elementary surface of the CWF with insulating coating is obtained from (10).

$$ds = \frac{1}{2} * l_{ts} * D_{w-ic} d\beta \qquad (10)$$

Total capacitance of $dC_{ag\rightarrow ss}$ related to the air gap between two adjacent CWF will be:

$$dC_{ag\rightarrow ss}(\beta)=\varepsilon_0 * \frac{l_{ts} * D_{w-ic}}{2 * g(\beta)} d\beta = \varepsilon_0 * \frac{l_{ts}}{2*(1-\cos(\beta))} d\beta \qquad (11)$$

IV. Calculation of Filament-Filament Capacitance Between Two Adjacent CWF in OTC of the MCG

Since capacitances of regions 1 and 2 between two adjacent CWF will be combined to parallel form, so we have:

$$dC_{ss}(\beta) = dC_{ss1}(\beta) + dC_{ss2}(\beta) = 2 * dC_{ss1}(\beta) \qquad (12)$$

where, $dC_{ss1}(\beta)$ is total capacitance of region 1 and $dC_{ss2}(\beta)$ is total capacitance of region 2 between two CWF. Considering the geometrical symmetry of regions 1and 2 as shown in Fig. 8, the capacitances of these two regions are equal. Elementary capacitance of insulating coating and elementary capacitance of the air gap between two adjacent CWF of every two trapezoid-shape regions 1 and 2 are combined in series' form. So by considering (12), total capacitance between two adjacent CWF will be:

$$dC_{ss}(\beta) = 2 * dC_{ss1}(\beta) = \frac{dC_{ic\rightarrow ss} * dC_{ag\rightarrow ss}(\beta)}{dC_{ic\rightarrow ss} + 2dC_{ag\rightarrow ss}(\beta)} \qquad (13)$$

Consequently by considering the effect of insulating coating, total filament-filament capacitances (C_{ss}) of two adjacent CWF in OTC of the MCG is:

$$dC_{ss}(\beta) = \frac{\varepsilon_0 * l_{ts}}{1-\cos(\beta) + 2*\ln\left(\frac{D_{w-ic}}{D_w}\right)\varepsilon_r^{-1}} d\beta \qquad (14)$$

V. Filament-Liner Capacitance Between one CWF in OTC and Liner

To calculate filament-liner capacitance (C_{sl}), at first we use (4) to calculate the capacitance of insulating coating, which is placed between CWF and liner. It should be noted that we have only one insulating coating for calculating filament-liner capacitance.

So we have:

$$dC_{ic\rightarrow sl} = dC_{ic} = \frac{\varepsilon_0 * \varepsilon_r * l_{ts}}{\ln\left(\frac{r_{w-ic}}{r_w}\right)} d\alpha \qquad (15)$$

Length of electric field lines in the air gap between the CWF and imaginary line of ψ is equal to Z. The basic cell of filament-liner capacitance is bigger and wider than the basic cell of filament-filament capacitance. A part of the perimeter of the CWF with the angle of 2π/3 radian has the basic cell of the filament-liner (Fig. 8).

From Figs. 7 and 8, cos(α) is:

$$\cos(\alpha) = 1 - \frac{2g(\alpha)}{D_{w-ic}} \qquad (16)$$

The area of elementary surface of the CWF, which has insulating coating and is in a form of an elementary ring and as long as (l_{ts}) the turn of CWF, will be:

$$ds = \frac{1}{2} * l_{ts} * D_{w-ic} d\alpha \qquad (17)$$

Also, capacitance between the CWF and central cylindrical liner related to air gap is:

$$dC_{ag\rightarrow sl} = \varepsilon_0 * \frac{ds}{g(\alpha)+Z} \qquad (18)$$

where, $dC_{ag\rightarrow sl}$ is total capacitance related to region 3 of the air gap between the CWF and central cylindrical liner. So, by considering above explanations and relations (16), (17) and (18), the air gap capacitance of the filament-liner of region 3 is:

$$dC_{ag\rightarrow sl}(\alpha) = \frac{\varepsilon_0 * l_{ts} * D_{w-ic}}{2(g(\alpha)+Z)} d\alpha \qquad (19)$$

Since capacitance between the CWF and central cylindrical liner of two regions 3 and 4 are combined in parallel, we have:

$$C_{sl}(\alpha) = dC_{sl3}(\alpha) + dC_{sl4}(\alpha) = 2 * dC_{sl3}(\alpha) \qquad (20)$$

where $dC_{sl3}(\alpha)$ is total capacitance of region 3 and $dC_{sl4}(\alpha)$ is total capacitance of region 4 between the CWF and central cylindrical liner and considering the geometrical symmetry of two regions 3 and 4 in Fig. 8, capacitances of these regions are equal.

Considering the series' combination of the air gap elementary capacitance and insulating coating of every trapezoid-shape (region 3 and 4), the total equivalent capacitance between CWF in an OTC and central cylindrical liner, with considering (20), is:

$$dC_{sl}(\alpha) = 2 * dC_{sl3}(\alpha) = \frac{dC_{ag\rightarrow sl} * dC_{ic\rightarrow sl}}{dC_{ic\rightarrow sl} + 2dC_{ag\rightarrow sl}} \qquad (21)$$

Therefore we have:

$$dC_{sl}(\alpha) = 2 * \varepsilon_0^2 \varepsilon_r * \frac{l_{ts}^2 * D_{w-ic}}{K4 + (K5 * [\varepsilon_0 \varepsilon_r l_{ts}])} d\alpha \qquad (22)$$

$$K4 = (2\varepsilon_0 * D_{w-ic} * l_{ts}) * \ln(K1),$$

$$K5 = 2Z + D_{w-ic}(1-\cos(\alpha))$$

VI. Calculation of Turn-Turn Capacitance of the MCG

Cross-section of CWF existing in each turn can be considered as a circle, Fig. 10. In order to analyze the capacitance between two turns of the MCG coil, at first we should obtain (filament-turn)-(filament-turn) (C_{stst}) capacitance between two CWF of two adjacent turns. We can equalize the capacitance between two CWF of two adjacent turns and capacitance of per unit length of two straight parallel conductors with infinite length placed in a homogenous medium where neglecting the bend and curvature of turns. If the thickness (t) of insulating coating of CWF in OTC be smaller than the air gap (distance between centers of two CWF of two adjacent turns) ($p-2r_{w-ic}$) and considering previous assumptions, we can present analytical method to calculate (filament-turn)-(filament-turn) capacitance (C_{stst}) of CWF with circular cross-section.

To obtain a proper relation for equivalent SC of the coil network of the MCG, first we consider capacitance related to insulating coating and capacitance related to the air gap between CWF as a series' combination in the equivalent circuit and then using the formula of cylindrical model capacitance. We can get capacitance (C_{ic}) between two CWF related to insulating coating as below:

$$C_{ic}=\frac{2\pi\varepsilon_r}{\ln\left(1+\frac{2t}{D_w}\right)} \tag{23}$$

For capacitance C_{ag} related to air gap we have:

$$C_{ag}=\frac{\pi\varepsilon_0}{\ln\left[\left(\frac{p}{D_{w-ic}}+\sqrt{\left(\frac{p}{D_{w-ic}}\right)^2-1}\right)\right]} \tag{24}$$

where $D_{w\text{-}ic}$ is the sum of CWF diameter and insulating coating and D_w is the circular cross-section diameter of CWF and p is the winding pitch (i.e, the distance between centerlines of two adjacent turns) of turns of the MCG coil. Also, because of two insulating coating related to two CWF of two adjacent turns, which are combined in series' form, we have:

$$dC_{ic\rightarrow stst}=\frac{C_{ic}}{2}=\frac{\pi\varepsilon_r}{\ln\left(1+\frac{2t}{D_w}\right)} \tag{25}$$

where $C_{ic\rightarrow stst}$ is the sum of capacitances related to two insulating coating of two CWF of two adjacent turns of the MCG coil. Thus, the capacitance which is equal to the sum of series' combination of the air gap and the insulating coating of these two CWF of two adjacent turns of the MCG coil will be:

$$C_{ic\rightarrow ag}=\frac{C_{ic\rightarrow stst}*C_{ag}}{C_{ic\rightarrow stst}+C_{ag}}=\frac{C_{ic}*C_{ag}}{C_{ic}+2C_{ag}} \tag{26}$$

Hence with replacing (23) and (24) in (26) for calculating the capacitance between two CWF of two adjacent turns and with these assumptions that thickness of an insulating coating (t) has relative permittivity ε_r and the direction of electric field in insulating coating (t) is in the form of radial, so we have:

$$C_{stst}=\frac{\pi^2\times\varepsilon_0\times D}{\ln\left[A+\sqrt{[A]^2-\left(\frac{D_{w-ic}}{D_w}\right)^{\left(2\varepsilon_r^{-1}\right)}}\right]} \tag{27}$$

where $A=\dfrac{p}{D_w*\left(1-\frac{2t}{D_w}\right)^{\left(1-\varepsilon_r^{-1}\right)}}$

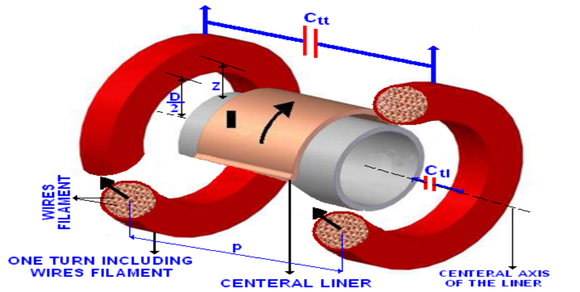
Since each turn has k-CWF in itself and with supposing that a CWF in the first turn is in the same distance from all CWF in the second turn and equal to p (winding pitch), so according to the superposition principle, there is k^2 (filament-turn)-(filament-turn) capacitances (C_{stst}) between two adjacent turns. Considering the series' combination of (filament-turn)-(filament-turn) capacitances (C_{stst}) related to k-CWF of two adjacent turns, total capacitance between two adjacent turns resulted from k-CWF will be:

$$\frac{1}{C_{tt}}=\frac{1}{C_{stst}}+\frac{1}{C_{stst}}+...+\frac{1}{C_{stst}}=\frac{K^2}{C_{stst}} \tag{28}$$

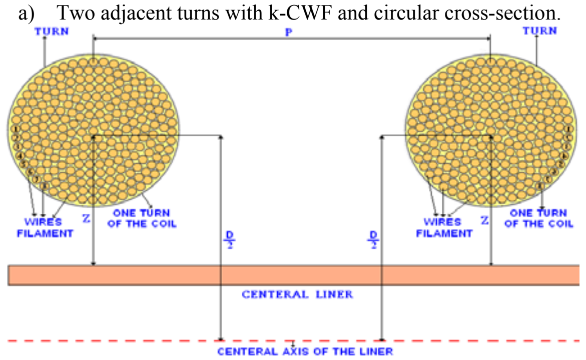
Therefore, we have:

$$C_{tt}=\frac{C_{stst}}{K^2}=\frac{\pi^2\times\varepsilon_0\times D}{K^2*\ln\left[\left[\frac{p}{Q}\right]+\sqrt{\left[\frac{p}{Q}\right]^2-\left(\frac{D_{w-ic}}{D_w}\right)^{\left(2\varepsilon_r^{-1}\right)}}\right]} \tag{29}$$

where $Q=D_w*\left(1-\frac{2t}{D_w}\right)^{\left(1-\varepsilon_r^{-1}\right)}$



a) Two adjacent turns with k-CWF and circular cross-section.



b) Cross-section of two adjacent turns with K- CWF and circular cross-section.

Figure 10. Circular cross-section of turns along with cylindrical liner placed at the center of MCG coil

VII. SC Between a Turn With k-CWF and Liner

We can obtain capacitance between one turn with k-CWF and liner by neglecting bend and curvature of the CWF. If the thickness of insulating coating (t) of CWF is smaller than the air gap (z), and if we take the previous simplified assumptions and (22) into consideration, we will obtain capacitance between conductor wire filament and liner (C_{si}) for wire filaments with circular cross-section and insulating coating. Besides, considering that each turn has k-CWF in itself and also considering a parallel combination of filament-liner capacitances (C_{si}) of k-CWF, total capacitance of one turn resulted from filament-liner capacitance of k-CWF is:

$$C_{tl}(\alpha)=C_{sl}+C_{sl}+C_{sl}+...=KC_{sl} \tag{30}$$

Therefore, we have:

$$C_{tl} = (K)*\mathrm{K10}*K6*\frac{Arc\tan\left[\frac{K9}{\sqrt{K6+K7+K8}}*\frac{1}{\sqrt{3}}\right]}{\sqrt{K6+K7+K8}} \quad (31)$$

where ,

$\mathrm{K6} = \varepsilon_r{}^2*\mathrm{Z}\left(\mathrm{D}_{w-ic}+\mathrm{Z}\right)$,

$\mathrm{K7} = \mathrm{D}_{w-ic}\varepsilon_r\left(\mathrm{D}_{w-ic}+2\mathrm{Z}\right)\ln\left[\mathrm{K1}\right], \mathrm{K8} = \mathrm{D}_{w-ic}{}^2\ln^2\left[\mathrm{K1}\right]$,

$\mathrm{K9} = \varepsilon_r\left(\mathrm{D}_{w-ic}+\mathrm{Z}\right)+\left(\mathrm{D}_{w-ic}*\ln\left(\mathrm{K1}\right)\right)$,

$\mathrm{K10} = 2*\varepsilon_0*\varepsilon_r*l_{ts}*\mathrm{D}_{w-ic}$, $\quad \mathrm{K1} = \frac{D_{w-ic}}{D_w}$.

VIII. TOTAL SC OF THE MCG

In order to obtain the total SC of the MCG, as shown in Fig. 2, according to Fig. 11, we can calculate the total SC of *C(n)* for n adjacent turns, including multi-layer that each turn has k-CWF in itself by using turn-turn capacitance (C_{tt}) and filament-liner capacitance (C_{tl}). A network composed of lumped capacitors as shown in Fig. 13. So equivalent circuit can be modeled by the total stray capacitor network of C(n).

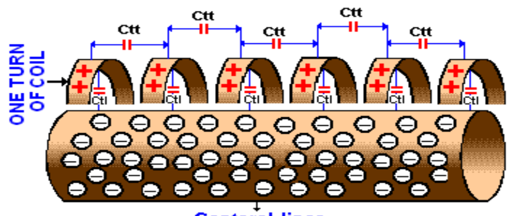


Figure 11. Geometrical space of n turns, including multi-layer with k-CWF and cylindrical liner placed at the center of coil turns and turn-turn stray capacitance (C_{tt}) and turn-liner stray capacitance (C_{tl}) in non-real scale

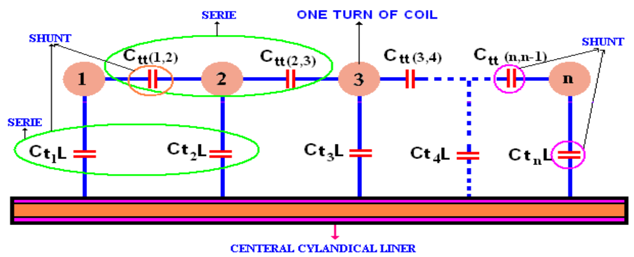


Figure 12. Lump capacitors of n multi-layer turn of the MCG coil in non-real scale

For NTC of the MCG that each turn is composed of many CWF in itself, first we consider two adjacent turns among turns of the MCG coil that for these two turns (n=2), network capacitance, consists of capacitance (C_{tt}) between two turns 1 and 2, which are parallel with the series' combination of turn-liner capacitances of ($C_{t(1)l}$) and ($C_{t(2)l}$), where $C_{t(2)l} = C_{t(1)l} = C_{tl}$, ($C_{t(1)l}$) and ($C_{t(2)l}$) are capacitances between turns 1 and 2 with central cylindrical liner of the generator respectively.

So, equivalent capacitance of these two adjacent turns is:

$$C(n=2) = C(1,2) = C_{tt} + \frac{C_{tl}}{2} \quad (32)$$

For more turns, we consider three adjacent turns of the MCG coil. Equivalent Capacitance of this capacitor network with three turns (n=3) can be obtained by splitting capacitance ($C_{t(2)l}$) into two halves and applying the Δ/Y transformations (Fig. 13).

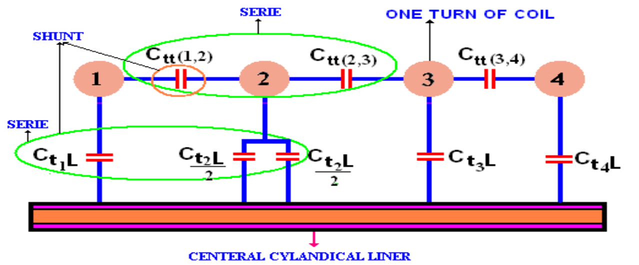


Figure 13. Capacitance between CWF in one turn wounded around the cylindrical liner placed at the center of coil

So, we have:

$$C(n=3) = C(1{,}2{,}3) = \frac{C_{tt}}{2} + \frac{C_{tl}}{2} \quad (33)$$

In order to obtain the total capacitance of four turns composed of k-CWF in turns, we can consider one more turn beside of three turns. So, total capacitance is equal to capacitance of previous arrangement (i.e. two turns), which is in series' form with turn-turn capacitance and parallel to the series' combination of turn-liner capacitance.

Therefore, for n=4, we have:

$$(n=4) = C(1,2,3{,}4) = \frac{C_{tt}*C(2)}{C_{tt}+2*C(2)} + \frac{C_{tl}}{2} \quad (34)$$

In order to obtain the total capacitance of n turns, we can add one turn to previous turns in each time. Therefore, the total SC of the MCG with any number of turns can be calculated by the mentioned method. So, for coil of the MCG composed of n turns, which are placed in multi-layer and each turn has k-CWF in itself, we have:

$$C(n) = \frac{C_{tt}*C(n-2)}{C_{tt}+2*C(n-2)} + \frac{C_{tl}}{2} \quad (35)$$

where, C(n-2) is the SC of (n-2) the turns of the MCG coil composed of k-CWF and n is total number of turns existing in the generator coil.

IX. RESULTS OF SIMULATIONS

Considering Figs. 14, 15, and 16 resulted from simulation related to the total capacitance C(n) of the MCG, we see that by progress of explosion and extension of liner and decrease of the number of the MCG coil turns, total capacitance of the MCG will be increased. This incremental of capacitance will continue until the number of turns existing in circuit decrease to two turns. However, it was seen when only one turn remains in the circuit, there occurs a descending decrease in total capacitance of the MCG. Because, there is only one turn remained in the circuit, and we have only turn-liner capacitance.

According to Figs 14, 15 and 16, it was clearly seen that by increasing the CWF turn length(L_{ts}) in turns of the coil and by increasing the cross-section diameter of CWF in turns of the coil (D_w) and by decreasing of winding pitch of the coil turns (p) and also by increasing of the number of CWF existing in turns of the coil (k), the total SC of NTC will increase. So, to decrease the total SC of NTC, we should consider the following cases:

1. Decrease the number of CWF in turns as much as possible.
2. Decrease turns length of CWF in turns.
3. Increase winding pitch of coil turns.
4. Increase diameter of the cross-section of CWF in

turns of the MCG coil.

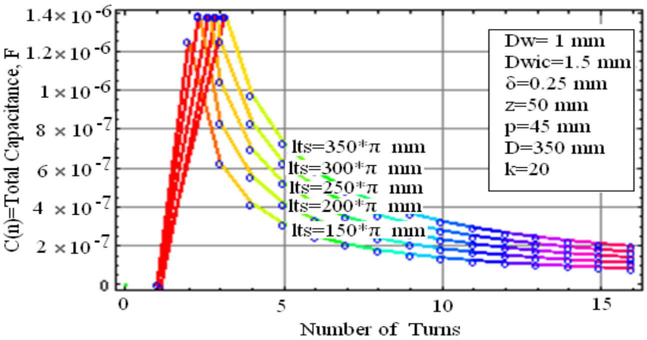


Figure 14. Total capacitance of the MCG for different length of CWF turn

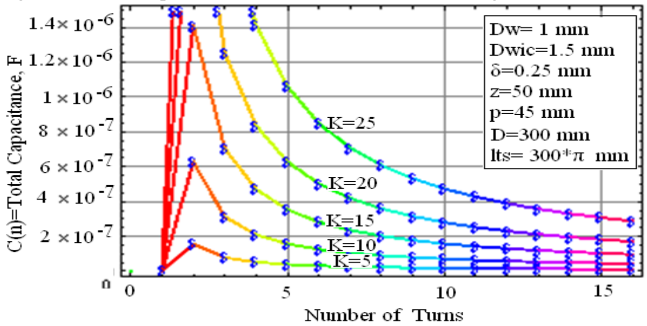


Figure 15. Total capacitance of the MCG for different numbers of CWF existing in turns

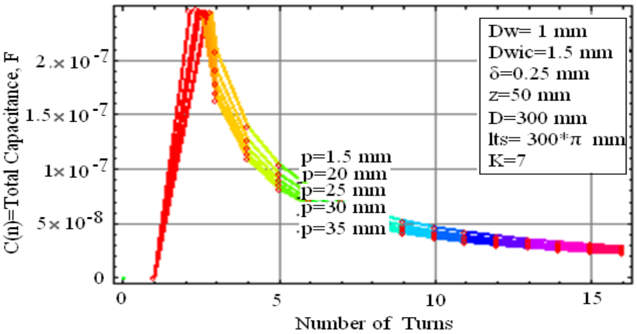


Figure 16. Total capacitance of the MCG for different winding pitches

X. Conclusions

This paper, presents a method that called vespiary regular hexagon(VRH) model in order to calculate the SC between multilayer CWF in OTC and finally between the turns of coil and also between turn and central cylindrical liner of the MCG. The presented method is appropriately used to calculate the SC of coils with the multi-layer of CWF.

It was seen that the number of CWF, diameter of CWF existing in one turn of the MCG coil, kind and thickness of insulating coating of CWF, turn length of CWF and winding pitch will be effective on the total SC of the MCG. In order to decrease the total SC of the MCG, we should decrease the radius of circular cross-section of the coil turns, diameter of the coil turns and the number of CWF in the coil turns and increase air gap between turns of the coil and central cylindrical liner, winding pitch and thickness of insulating coating of turns of coil. We saw that by progress of explosion and volume extension of liner and decrease of the number of turns of the MCG coil, total capacitance of the MCG increases.

It is clear from simulation, when only one turn remains in the circuit, a descending decrease occurs in total capacitance of the generator, and it is because of remaining only one turn in the circuit. So we have only turn-liner capacitance. On the other hand, capacitance resulted from turn-liner capacitance has more effects on results. Besides, in last turn, by progress of the explosion, turn length decreases hence effective cross-section between a turn and liner decreases and finally capacitance between turn and liner will decrease.

It was seen that the amount of reactance which is produced by the total SC of the MCG will be reduced by progress of explosion and reduction of coil turns. The reactance has its minimum amount in the second remaining end turn of the circuit, but in the last ring the amount of reactance will go to increase because of the reduction of the SC in it.

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