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Suppresion of Corona in Stator Winding of Synchronous Machines

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Abstract: - The electric field on the surface of a semiconductive coating of high-voltage bushing is analysed, to determine the tangential component of electric field intensity. This component is cruicial for the existence of electric discharges. The problem is solved with help of a circuit model, using two-úport theory. The solution is applied to a bar of a stator winding of turboalternators, in the area of coil ends.

Key-Words: - Stator winding of synchronous machines, supressing of corona, high-voltage bushing.

1 Introduction

In order to suppress corona in the coil ends of the stator windings of synchronous machines of highest parameters, semiconductive anticorona coating of relatively low resistivity is applied to the bar of stator winding. The coating is supposed to be well grounded by the direct contact with stator core. We investigate the region of stator end winding, which – from the viewpoint of insulation – is an analogy of bushing. Electric discharges have to be handled usually at the terminal voltage of about 6 kV. In large machines of extreme outputs, where the terminal voltage are ranging from 18 up to 24 kV, it is necessary to pay attention to the designing the means for suppression of discharges. The occurrence of electric discharges in the region of stator end winding depends especially on the tangential component of electric field on the surface of bar insulation. This component can be briefly denoted as *the surface intensity*.

The aim of the anticorona protection is to reduce surface intensity to a value at which electric discharge does not occur. The frequently used anticorona protection consist in covering the surface of insulation with semiconductive coating that overhangs the stator slot by certain length [1], [2]. The resistance of the coating is gradually increasing in the direction from the iron. To this more general way of anticorona protection the given analysis is devoted. Another way of reducing the maximum value of surface intensity is based on inserting the metal or semiconductive foils into the insulation of stator winding bar, where the foils gradually overhang, similarly to capacitor bushing. Another way of anticorona protection use only one-step coating that is electrically non-linear, and whose conductivity falls with the intensity of electric field.

2 Analysis of electric field on the surface of stator winding bar

Let the semiconductive coating in stator slot overhanging by several centimetres stator core end be followed by a semiconductive coating, arranged in n-1 steps, whose lengths are $l_1,\dots, l_{n-1}$, Fig. 1. The distribution of voltage and surface intensity is investigated. The influence of neighbouring conductors of stator winding is neglected. Resistivity of coatings per length unit is denoted R_i, where

$$\begin{aligned} &i = 0 \ \text{ for } \ x_1 \le 0\,, \\ &i = 1 \ \text{ for } \ x_1 <0;\, l_1>, \\ &\ldots\ldots\ldots\ldots\ldots\ldots \\ &i = n-1 \ \text{ for } \ x_{n-1} <0;\, l_{n-1}>, \\ &i = n \ \text{ for } x_n <0;\, \infty>, \ \text{ where } \ R_n \to \infty\,. \end{aligned} \quad (1)$$

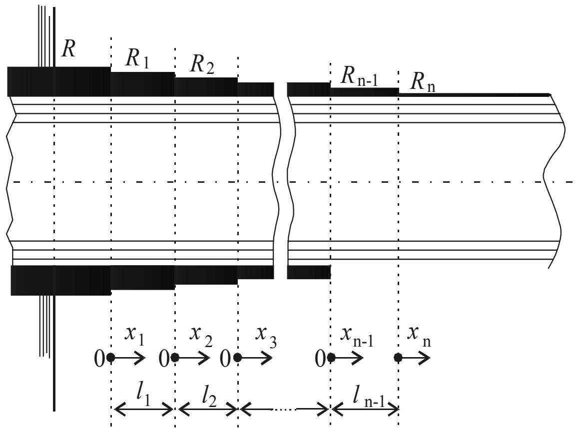

Fig. 1. Arrangement of semiconductive coatings.

The values R_i ($i = 0,\ldots, n$) must satisfy the following conditions:

$$R_0 << R_1 < \ldots.. R_{n-1} < R_n$$

The insulation of stator winding bar is characterized by the following parameters (related to a bar length unit):

R_n ….. surface resistance

K …… surface capacity

G …….conductivity between the surface of insulation and the conductor and

C …… capacity between the surface of insulation and the conductor.

The capacity between the surface of insulation and stator core end (the shielding plate) is negligible. The stator winding bar in the region of stator slot will be simulated by a circuit with distributed parameters, its length element is in Fig. 2.

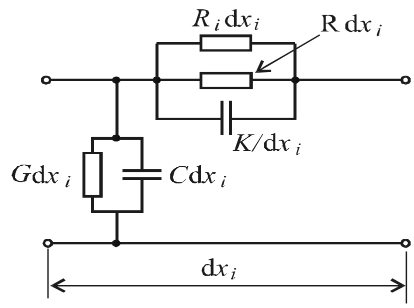

Fig. 2. Circuit model of length element of winding bar with semiconductive coating.

Let voltages and currents change with time according to sinus function. Using complex representation and length element dx of the winding bar, the following equations are valid

$$-\frac{\mathrm{d}\boldsymbol{U}}{\mathrm{d}t} = \frac{R\,R_i}{R + R_i + \mathrm{j}\omega R\,R_i\,K}\boldsymbol{I}$$
$$-\frac{\mathrm{d}\boldsymbol{I}}{\mathrm{d}t} = (G + \mathrm{j}\omega C)\boldsymbol{U} \quad (i=1,\ldots,n) \quad (2)$$

Their solution is

$$\boldsymbol{U} = a_{1i}\,\mathrm{e}^{\gamma_i x_i} + a_{2i}\,\mathrm{e}^{-\gamma_i x_i}$$
$$\boldsymbol{Z}_{0i}\boldsymbol{I} = -\ a_{1i}\,\mathrm{e}^{\gamma_i x_i} + a_{2i}\,\mathrm{e}^{-\gamma_i x_i} \quad (3)$$

where a_{1i} and a_{2i} are integration constants.

The constants γ_i and Z_{0i} are

$$\gamma_i = \sqrt{\frac{R\,R_i\,(G + \mathrm{j}\omega C)}{R + R_i + \mathrm{j}\omega R\,R_i\,K}}\,,$$
$$\boldsymbol{Z}_{0i} = \sqrt{\frac{R\,R_i}{(R + R_i + \mathrm{j}\omega R\,R_i\,K)(G + \mathrm{j}\omega C)}} \quad (4)$$

Equations (3), that describes the of voltage and current in each of n-1 regions of semiconductive coatings is similar to so-called telegraph equation for uniform transmission line.

Each of n-1 semiconductive steps is thus simulated by a linear passive two-port. The part of the road of winding that is not equipped with semiconductive coating, *i.e.* for $x_a \subseteq (0; \infty)$, is an analogy to unbounded uniform transmission line. Input voltage and current does not change, when the area <0; l_n> is given, where l_n is an arbitrary length, and this area is replaced by corresponding n-th two-port, that is on its output loaded with the characteristic impedance $\boldsymbol{Z}_{0n}$. The equivalent circuit model of the solved problem can be replaced with the cascade connection of n two-ports, where the last two-port is terminated by characteristic impedance $\boldsymbol{Z}_{0n}$, Fig. 3.

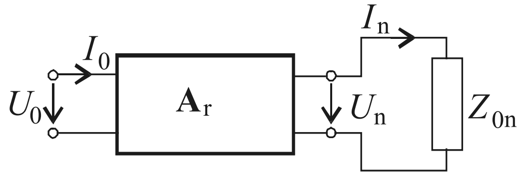

Fig. 4. Substitution of cascade connection of n two-port by one two-port.

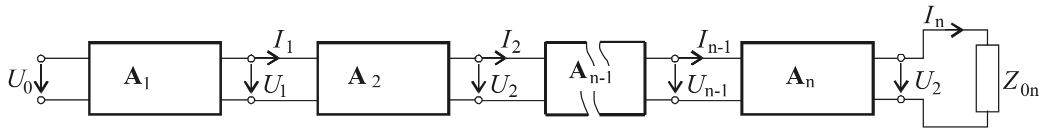

Fig. 3. Cascade connection of n two-ports.

Each of these n two-ports can be characterized by cascade matrix

$$\mathbf{A}_i = \begin{bmatrix} \cosh \boldsymbol{g}_i; & \boldsymbol{Z}_{0i} \sinh \boldsymbol{g}_i \\ \frac{1}{\boldsymbol{Z}_{0i}} \sinh \boldsymbol{g}_i; & \cosh \boldsymbol{g}_i \end{bmatrix} \tag{5}$$

where $\boldsymbol{g}_i = \gamma_i \, l_i$.

Input and output voltages and currents of i-th two-port are $\boldsymbol{U}_{i-1}$, $\boldsymbol{U}_i$, and $\boldsymbol{I}_{i-1}$, $\boldsymbol{I}_i$ ($i = 1,\ldots, n$). The are voltages and currents relate to the boundary of particular semiconductive coatings, except the values $\boldsymbol{U}_n$, $\boldsymbol{I}_n$ that tefer to the distance l_n from the end of the last semiconductive coating. Evidently the following inequalities are valid:

$$|\boldsymbol{U}_0| > |\boldsymbol{U}_1| > \ldots > |\boldsymbol{U}_{n-1}| > |\boldsymbol{U}_n|$$

and $|\boldsymbol{I}_0| > |\boldsymbol{I}_1| > \ldots > |\boldsymbol{I}_{n-1}| > |\boldsymbol{I}_n|$.

The moment is chosen, in which $\boldsymbol{U}_0$ is a real number. The above input and output quantities will be investigated. By determining current $\boldsymbol{I}_0$, the cascade connections of n two-ports are replaced by one two-port only (see Fig. 4), whose cascade matrix is

$$\mathbf{A}_\mathrm{r} = \prod_{i=1}^{n} \mathbf{A}_i \tag{6}$$

From its cascade equation

$$\begin{bmatrix} \boldsymbol{U}_0 \\ \boldsymbol{I}_0 \end{bmatrix} = \begin{bmatrix} \boldsymbol{A}_{\mathrm{r}11} & \boldsymbol{A}_{\mathrm{r}12} \\ \boldsymbol{A}_{\mathrm{r}21} & \boldsymbol{A}_{\mathrm{r}22} \end{bmatrix} \begin{bmatrix} \boldsymbol{U}_0 \\ \boldsymbol{I}_0 \end{bmatrix}$$

and relation

$$\boldsymbol{U}_n = \boldsymbol{Z}_{0n} \boldsymbol{I}_n$$

we can eliminate $\boldsymbol{U}_n$, obtaining

$$\boldsymbol{I}_0 = \frac{\boldsymbol{Z}_{0n} \boldsymbol{A}_{\mathrm{r}21} + \boldsymbol{A}_{\mathrm{r}22}}{\boldsymbol{Z}_{0n} \boldsymbol{A}_{\mathrm{r}11} + \boldsymbol{A}_{\mathrm{r}12}} \boldsymbol{U}_0 \tag{7}$$

Supposing that $\boldsymbol{U}_0$ and $\boldsymbol{I}_0$ are known (as well as the parameters $\boldsymbol{g}_i$, $\boldsymbol{Z}_{0i}$), it is possible to determine all the voltages and currents on the boundary by solving the equations

$$\begin{bmatrix} \boldsymbol{U}_1 \\ \boldsymbol{I}_1 \end{bmatrix} = \mathbf{A}_1^{-1} \begin{bmatrix} \boldsymbol{U}_0 \\ \boldsymbol{I}_0 \end{bmatrix}$$
$$\ldots\ldots\ldots\ldots\ldots\ldots \tag{8}$$
$$\begin{bmatrix} \boldsymbol{U}_n \\ \boldsymbol{I}_n \end{bmatrix} = \mathbf{A}_n^{-1} \begin{bmatrix} \boldsymbol{U}_{n-1} \\ \boldsymbol{I}_{n-1} \end{bmatrix}$$

To verify the values of $\boldsymbol{U}_n$, $\boldsymbol{I}_n$ we can use the relation

$$\frac{\boldsymbol{U}_n}{\boldsymbol{I}_n} = \boldsymbol{Z}_{0n} \tag{9}$$

The inverse matrix $\mathbf{A}_i^{-1}$ follows from the condition that $\det \mathbf{A} = 1$. It is easily found that

$$\mathbf{A}_i^{-1} = \begin{bmatrix} \cosh \boldsymbol{g}_i; & -Z_0 \sinh \boldsymbol{g}_i \\ -\dfrac{1}{\boldsymbol{Z}_{0i}} \sinh \boldsymbol{g}_i; & \cosh \boldsymbol{g}_i \end{bmatrix} \quad (10)$$

The surface voltage between the stator core and the surface of insulation at the point $x_i < 0; l_i >$ inside the i-th two-port is

$$\boldsymbol{U}_{ai}(x_i) = \boldsymbol{U}_0 - \boldsymbol{U}_i(x_i) \quad (11)$$

where $\boldsymbol{U}_0$ is the input voltage of the first two-ports and $\boldsymbol{U}_i(x_i)$ is the voltage between the insulation surface and a conductor of i-th two-port at point x_i . It is known, that

$$\begin{bmatrix} \boldsymbol{U}_i(x_i) \\ \boldsymbol{I}_i(x_i) \end{bmatrix} = \begin{bmatrix} \cosh \gamma_i x_i; & -\boldsymbol{Z}_{0i} \sinh \gamma_i x_i \\ -\dfrac{1}{\boldsymbol{Z}_0} \sinh \gamma_i x_i; & \cosh \gamma_i x_i \end{bmatrix} \begin{bmatrix} \boldsymbol{U}_{i-1} \\ \boldsymbol{I}_{i-1} \end{bmatrix} \quad (12)$$

Since we are interested only in the course of the voltage, we can write

$$\boldsymbol{U}_i(x_i) = \boldsymbol{U}_{i\text{-}1} \cosh \gamma_i x_i - \boldsymbol{Z}_{0i} \boldsymbol{I}_{i\text{-}1} \sinh \gamma_i x_i$$

The course of the surface intensity on the stator winding bar is

$$\boldsymbol{E}_i(x_i) = -\frac{\mathrm{d}\boldsymbol{U}_{ai}}{\mathrm{d}x_i} = \gamma_i \left\{ \boldsymbol{U}_{i\text{-}1} \sinh \gamma_i x_i - \boldsymbol{Z}_{0i} \boldsymbol{I}_{i\text{-}1} \cosh \gamma_i x_i \right\} \quad (13)$$

The maximum value of surface intensity, occurring at the beginning of the i-th semiconductive coating at the point $x_i = 0$, is

$$\boldsymbol{E}_{i1} = -\boldsymbol{Z}_{0i} \gamma_i \boldsymbol{I}_{i\text{-}1} \quad (i = 1,...,n) \quad (14)$$

With increasing x_i, the surface intensity falls monotonously. Its minimum value, appearing at the end of the coating at point $x_i = l_i$, is

$$\boldsymbol{E}_{i2} = \gamma_i \left\{ \boldsymbol{U}_{i\text{-}1} \sinh \boldsymbol{g}_i - \boldsymbol{Z}_{0i} \boldsymbol{I}_{i\text{-}1} \cosh \boldsymbol{g}_i \right\} \quad (15)$$

In the set of matrix equations (8) the i-th equation can be expressed as a set of the two equations

$$\boldsymbol{U}_i = \boldsymbol{U}_{i\text{-}1} \cosh \boldsymbol{g}_i - \boldsymbol{Z}_{0i} \boldsymbol{I}_{i\text{-}1} \sinh \boldsymbol{g}_i$$

$$\boldsymbol{I}_{i\text{-}1} = -\frac{\boldsymbol{U}_{i\text{-}1}}{\boldsymbol{Z}_{0i}} \sinh \boldsymbol{g}_i + \boldsymbol{I}_{i\text{-}1} \cosh \boldsymbol{g}_i$$

On multiplying the second equation by $\boldsymbol{Z}_{0i}$, we have

$$\boldsymbol{Z}_{0i} \boldsymbol{I}_{i\text{-}1} \cosh \boldsymbol{g}_i - \boldsymbol{U}_{i\text{-}1} \sinh \boldsymbol{g}_i = \boldsymbol{Z}_{0i} \boldsymbol{I}_i \quad (16)$$

According to (15), it follows

$$\boldsymbol{E}_{i2} = -\boldsymbol{Z}_{0i} \gamma_i \boldsymbol{I}_i \quad (i = 1,...,n) \quad (17)$$

The course of the magnitude of phasors $\boldsymbol{U}_i$ and $\boldsymbol{E}_i$ is shown in the Fig. 5.

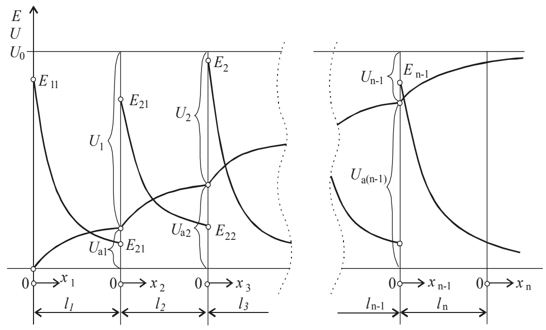

Fig. 5. Course of voltage and surface intensity on the surface of winding bar.

A special case: the stator winding bar is not equipped with a semiconductive coating *i.e.* $n = 1$. Maximum surface intensity is at $x_1 = 0$. From Eq. (7) and Eq.(15) we obtain

$$\boldsymbol{E}_{11} = -\gamma_1 \boldsymbol{Z}_{01} \frac{Z_{01} A_{r21} + A_{r22}}{Z_{01} A_{r11} + A_{r12}} \boldsymbol{U}_0 \quad (18)$$

On substituting for $\boldsymbol{A}_{r11}, \ldots \boldsymbol{A}_{r22}$ from matrix (5), we obtain

$$\boldsymbol{E}_{11} = -\gamma_1 \boldsymbol{U}_0 \quad (19)$$

The course of voltage and surface intensity as a function x_1 are shown in the Fig. 6.

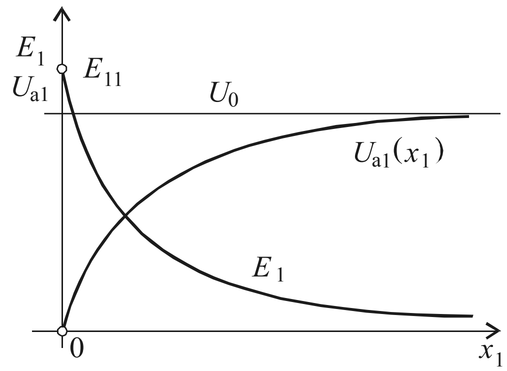

Fig. 6. Course of voltage and surface intensity on the surface of winding bar without semiconductive coating.

The anticorona protection under consideration is capable of suppressing electric discharges on satisfying the condition

$$\left|\boldsymbol{E}_{i1}\right| \leq \boldsymbol{g}_1 \qquad (20)$$

where g_1 is critical surface intensity. Its RMS value found by experiments is about 8 kV/cm [1].

The condition (20) is the criterion for judging the efficiency of the designed semiconductive coatings. Too high a value of surface intensity shows that the coating is too short and is not fully used for reaching sufficient distribution of voltage. On the other hand, a too low value of surface intensity shows a uselessly long semiconductive coating.

3 A numerical example

The maximum and minimum values of surface intensities are examined for a winding bar with one semiconductive coating. The parameters of the insulation are: $R = 1.10^{13}$ Ω/cm, $\omega K = 3.10^{-10}$ Ω/cm, $G = 1.10^{-14}$ Ω/cm, $\omega C = 3.10^{-9}$ Ω/cm. The parameters of the semiconductive coating are: $R_1 = 1{,}5.10^8$ Ω/cm ($R_0 = 0$) and the length $l_1 = 5$ cm; we propose $l_2 = 1$ cm.

The cascade matrix of both two-ports according to Eq. (5) are:

$$\mathbf{A}_1 = \begin{bmatrix} -3{,}857 + \mathrm{j}4{,}110; & (0{,}001 + \mathrm{j}12{,}584).10^8 \\ (2{,}525 + \mathrm{j}0{,}063).10^{-8}; & -3{,}858 + \mathrm{j}4{,}111 \end{bmatrix}$$

$$\mathbf{A}_2 = \begin{bmatrix} 11{,}833; & (86 - \mathrm{j}12429).10^6 \\ (-40 + \mathrm{j}11186).10^{-13}; & 11{,}8336 \end{bmatrix}$$

The resulting matrix according to Eq. (6) is:

$$\mathbf{A}_r = \mathbf{A}_1\,\mathbf{A}_2 = \begin{bmatrix} -59{,}69 - \mathrm{j}49{,}64; & (521{,}49 + \mathrm{j}\ 628{,}01).10^8 \\ (-34{,}47 - \mathrm{j}3{,}55).10^{-8}; & -37{,}70 + \mathrm{j}362{,}37 \end{bmatrix}$$

From Eq. (7) the current at the beginning of the coating is calculated:

$$\boldsymbol{I}_0 = (3{,}121 + \mathrm{j}\ 3{,}191).10^{-7}\ \boldsymbol{U}_0$$

From Eqs. (8), (10) voltages and currents at the ends of the coatings are:

$$\boldsymbol{U}_1 = (-0{,}11717 - \mathrm{j}\ 0{,}09729)\ \boldsymbol{U}_0\ ,$$
$$\boldsymbol{I}_1 = (0{,}9228 - \mathrm{j}\ 1{,}1117).10^{-10}\ \boldsymbol{U}_0$$

and behind the coating at place $x_2 = l_2$:

$$\boldsymbol{U}_2 = (-\,0{,}00496\ - \mathrm{j}\ 0{,}00412)\ \boldsymbol{U}_0\ ,$$
$$\boldsymbol{I}_2 = (3{,}902 - \mathrm{j}\ 4{,}708).10^{-10}\ \boldsymbol{U}_0$$

Checking:

$$\boldsymbol{Z}_{02} = \boldsymbol{U}_2/\boldsymbol{I}_2 = (0{,}0056 - \mathrm{j}\ 1{,}0543).10^9$$

This value agrees with the previously calculated value.

The maximum and minimum surface intensities according to Eq. (15) are:

$$|\boldsymbol{E}_{11}| = 0{,}66879\ U_0,$$
$$|\boldsymbol{E}_{21}| = 0{,}48160\ U_0,$$
$$|\boldsymbol{E}_{12}| = 0{,}021649\ U_0,$$
$$|\boldsymbol{E}_{22}| = 0{,}020384\ U_0$$

It is seen that for the terminal voltage 10kV the surface discharge protection is suitable.

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