THE PERSPECTIVE OF HIGH-TEMPERATURE SUPERCONDUCTIVITY ELTCTRICAL EQUIPMENT APPLICATION FOR TRACTION POWER SUPPLY AND THE PROBLEMS OF ELECTROMAGNETIC COMPATIBILITY

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ANNOTATION

EMC analysis of superconducting and traditional electrical equipment, study of the laws of the electromagnetic interaction, the nature of the mutual influence of the parameters and operation of electrical equipment, as well as search of protection and types of arrangement of electrical equipment, in which interference will not cause disruption to the interacting elements.

The analysis of the world tendencies in the development of the electrical engineering and power engineering, including the ones for the electrified transport, shows that one of the important tendencies in the nearest future will be the employment of the high-current applied superconductivity. It is well-known, that the new opportunities are opened by the ready for the mass production high-temperature superconductors of the second generation, capable of operating at temperatures up to the temperature of the liquid nitrogen, which is a hundred times more economical than the helium temperatures. As it is estimated, after the introduction of the high-temperature superconductors of the second generation the cost of the high-temperature superconducting wires will be comparable to the cost of the resistance wires. This means that in the nearest future the development of the new superconducting electrical equipment will be started, which will excel the conventional electrical equipment at physical, technical and commercial characteristics. Consequently, nowadays it is becoming more and more challenging the scientific research of the development, testing of models and production prototypes of various electrical equipment on the basis of the high-temperature superconducting materials, including cable power lines, transformers, electric motors, reactors and energy storage units.

The introduction and employment of the superconducting technologies and new high-temperature superconducting electrical equipment in locomotive and stationary energetic will enable to improve the traction electrical equipment safety and efficiency, to reduce the capital and maintenance costs, to provide the energy saving.

The problem of the superconducting electrical equipment employment on the transport objects is closely connected with the necessary solution of the parallel scientific, technological and design problems. One of them is the problem of the analysis of the electromagnetic interaction of the superconducting electrical equipment external fields with other types of equipment and with the conventional equipment as well. This problem is of special importance for the perspective transport vehicles, which size is more or less limited and where it is difficult to apply the easiest protection means from the external magnetic fields (EMF) – distance protection.

The advantages of the superconducting electrical equipment can be clearly seen at the increased capacity, that's why it is more reasonable to produce power (traction) equipment as superconducting and auxiliary equipment for providing transport vehicle needs (electric motors for compressors, ventilators, pumps and the electric drive control units & etc.) can be produced non- superconducting but conventional.

The problem of the electromagnetic compatibility, including the transport systems, was investigated in the terms of the conventional sources (static semiconducting converters, electrical machines, switchgear & etc.) and interference receptors (means of communication and information). The perspective of the improvement of transport means energy and technical-economic properties due to the application of the superconducting electrical equipment brings about a new aspect of the electromagnetic compatibility – the problem of the electromagnetic compatibility of superconducting and conventional electrical equipment. One of the basic questions to be investigated in the framework of the electromagnetic compatibility of superconducting and conventional electrical equipment is the study of the laws of the electromagnetic interaction, the nature of the mutual influence of the parameters and operation of electrical equipment, as well as the search of protection and types of arrangement of electrical equipment, in which interference will not cause disruption to the interacting elements.

At DC railway substations in the years to come a wide variety of superconducting electrical equipment will be applied, including non-resistance smoothing inductors, produced on the basis of high-temperature superconductivity, which will considerably increase the energy and technical properties of the substation smoothing equipment.

For the analysis and improvement of the electromagnetic and ecological conditions the methods of electromagnetic compatibility of superconducting and conventional electrical equipment in the linear focus has been worked out, which allows to analyse in general the impact of the conventional electrical equipment electromagnetic fields on the differential and integral properties of the superconducting electrical equipment.

The biggest part of the auxiliary conventional electrical equipment consists of the electrical machines and electromagnetic devices with a close air gap ferromagnetic wire, which considerably complicates the theoretical investigation of the impact of the superconducting electrical equipment external magnetic fields on the technical characteristics of the auxiliary generators and electric drive motors with an electric drive control system. The superconducting coil is supposed to be the source of the external electric fields; it is also the main element of the superconducting electrical equipment.

The investigation of the electromagnetic coupling of superconducting and conventional electrical equipment requires the development of the mathematical apparatus of analysis. At the initial stage of investigation it is worth while applying the analytical image of coupling, based on the range of assumptions allowing analysing in general the impact of each parameter of the coupling elements. The apparatus of numerical procedures of magnetic field calculations can be applied for such type of analysis.

The theoretical investigations of the dependencies of the electromagnetic coupling of the superconducting and conventional electrical equipment for the defining the conditions of their joint usage includes mathematical physics methods for the solution of the boundary problems, numerical procedures of magnetic field calculations on the basis of the secondary source concept, applied with the help of the iteration methods, numerical procedures of extremal problems solution.

The produced analysis of the transient operation mode of the superconducting electrical equipment as a part of the traction power supply and a perspective transport vehicle demonstrates that the process time is long enough independently of the type of the transport vehicle, its application, capacity, running conditions & etc. It gives the opportunity to employ the approximation for the analysis of the impact of the superconducting electrical equipment external magnetic fields on the conventional electrical equipment. The given approximation is based on the assumption of the superconducting electrical equipment external magnetic fields, as the field of constant current.

The three-dimensional non-linear numerical model of the electromagnetic coupling of the superconducting and conventional electrical equipment is worked out. It is based on the assumption of the ferromagnetic wire magnetization field as the field of the equivalent secondary sources of the surface and volume fictitious magnetic charges. The model enables to calculate the induction of the resultant magnetic field (the field of primary sources – current in the coils – and ferromagnetic wire magnetization fields) in the arbitrary point of the unlimited computational domain. This is very comfortable while analysing the coupling of several sources of the external magnetic fields and several sources under their influence. The model enables to calculate the induction in the air gap of the conventional electric equipment and its integral parameters at the non-linear characteristics of ferromagnetic wire, the longitudinal size limits and arbitrary space orientation of the conventional electric equipment.

According to [2], the standing wave of the transmitting antenna (waveguide) presents to be a complex of the continuously changing positive and negative charges with a wave length l. These charges polarize the environment causing the appearance of volume positive and negative charges, which follow each other along the waveguide from the source to the receiver.

In the system of ETL the complex of the continuously changing positive and negative charges spaciously remind the eddy-current toroids and move along the waveguide. The figure 1 represents this process. The toroid inner diameter is close to the wire diameter and the outer diameter is defined by the frequency, voltage magnitude and charge density inside the eddy, or, in other words, the amperage of the electric induction current.

Each of the moving volume charges possesses its own magnetic field as shown on the figure 1a and the polar extensions of these dynamic magnets in the current nodes are similar. The figure 1b illustrates the toroids 1, 2 and 3, which represent the increase of volume charges (the increase of current antinode) and corresponding magnetic fields as the blind current and the transmitted power grow.

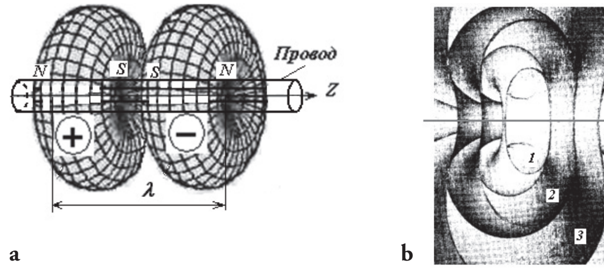

Figure 1. The models of charge and magnetic fields movement along the conductor resonance single-conductor ETL

The toroids surface 1, 2, 3 &etc. may be presented as the complex of “equipotential” magnetic power lines.

These magnetic fields pack each volume charge but, on the other hand, provide the movement along the wire due to mutual repulsion of the magnetic poles and the repulsion of the whole pack from the energy source.

The generating of such toroid eddies of opposite charges with inherent magnetic fields provides according to Tesla [3], *permanent energy transmission* from the source to the receiver.

Consequently, in the case of ETL we deal with dilatational waves which move not across the wire section but along it without entering it. It can be concluded, that wire resistance and its section are not important for ETL, and as its conductor it may serve thin steel wire or cable in insulation sleeve or fixed on the high-voltage insulators, as Tesla did [3].

The principle of local variable degree of unknown search field quantization is suggested for the improvement of the process of the iterative search of secondary field sources density distribution, which allows reducing the calculation time and the necessary ECM memory while preserving the accuracy of calculations. This principle is employed to construct the computer procedures for the systems with a great volume of ferromagnetic material and a close air gap.

The efficient protection measure of the conventional electric equipment from the electromagnetic coupling with superconducting electric equipment is electromagnetic screens [1].

The screening effect of the electromagnetic screen is that the electromagnetic field penetrates the screen wall and generates charges there or induces currents, which fields overlap the primary field and fully or partially compensate it.

The value of the screening effect is the screening coefficient, which is defined by the ratio of inside the screen field strength to outer field strength when the screen is absent. For magnetic field

$$\underline{Q} = \underline{H}_{IN} / \underline{H}_{OT} \qquad (1)$$

In practice it is often used for calculations the term "attenuation coefficient", which is defined as logarithm of the ratio of inner and outer field strengths

$$a_э = \ln\left(1/\left|\underline{Q}\right|\right), \text{ Нп} \quad \text{or} \quad a_э = 20\lg\left(1/\left|\underline{Q}\right|\right), \text{ dB} \qquad (2)$$

The permanent and variable fields are differentiated, the variable fields are divided into quasi-static (slowly changing) and electromagnetic (quickly changing).

Any quasi-static field change reveals simultaneously everywhere that is why the instantly perceived field picture corresponding to a definite instant value of voltage or current always coincides with the static field picture created by the direct current or voltage of the similar value. A quasi-static field may be presented as a time superposition of static fields with a similar space distribution $E_v(x, y, z)$ или $H_v(x, y, z)$, which in each case differ in strength only by a definite constant multiplier. If the receiver is located in the immediate presence from the radiation source in the so called near zone, it receives the constant (space fixed) quasi-static field. In the near zone the field changes, grows or diminishes in time simultaneously in all the points. In the far distance from the radiation source the re4ceiver is located in the so called far zone. Independently from the radiation source design the non-constant electromagnetic wave field prevails in the far zone.

The near zone is defined not only by the distance between the source and the receiver but by the field change speed. In the time domain near or quasi-static zone is the space, which length l is so, that the field rise time T_H exceeds the time of the electromagnetic wave crossing the length l. In the frequency domain the near zone is the space, which length is shorter the wave length ($l < \lambda$).

The difference between the near and far zones may be formalized mathematically by employing the Hertz dipole field in the spherical coordinate system (Fig. 2).

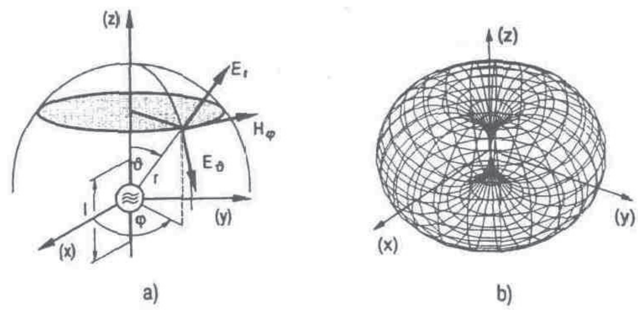

Figure 2. Hertz dipole in the spherical coordinate system (*a*) and the corresponding power lines of the electric and magnetic fields in the near zone *(b)*

The calculation of the Maxwell's equations in the frequency domain gives the following expressions for the electric-field vectors illustrated in Fig. 2 [1]:

$$\underline{E}_{\vartheta} = \frac{I_m l Z_0 \lambda \sin\vartheta}{j \cdot 8\pi^2 r^3}\left[1 + j\frac{2\pi}{\lambda}r + \left(j\frac{2\pi}{\lambda}r\right)^2\right]e^{-j\frac{2\pi}{\lambda}r} \qquad (3)$$

$$\underline{E}_r = \frac{I_m l Z_0 \lambda \cos\vartheta}{j \cdot 4\pi^2 r^3}\left[1 + j\frac{2\pi}{\lambda}r\right]e^{-j\frac{2\pi}{\lambda}r} \qquad (4)$$

$$\underline{E}_{\varphi} = \frac{I_m l \sin\vartheta}{4\pi r^2}\left[1 + j\frac{2\pi}{\lambda}r\right]e^{-j\frac{2\pi}{\lambda}r} \qquad (5)$$

where I_m, - AC amplitude value; I – maximum distance between dipole charges; Z_0 – vacuum wave impedance (further $w/c = 2\pi/\lambda$, where c - light speed in vacuum). The factor $e^{-j\frac{2\pi}{\lambda}r}$ describes phase shift angle.

The equations given above are not representative, but they are easy to interpret, if we stick to two limiting cases – near and far zones.

If to assume $r >> 2\pi/\lambda$ only the members with great exponents may be considered in (3 - 5), and the equations are simplified:

$$\underline{E}_{\vartheta} = \frac{I_m l Z_0 \lambda \sin\vartheta}{j \cdot 8\pi^2 r^3} \left(j \frac{2\pi}{\lambda} r \right)^2 e^{-j\frac{2\pi}{\lambda} r} \tag{6}$$

$$\underline{E}_{r} = \frac{I_m l Z_0 \lambda \cos\vartheta}{j \cdot 4\pi^2 r^3} \left[j \frac{2\pi}{\lambda} r \right] e^{-j\frac{2\pi}{\lambda} r} \tag{7}$$

$$\underline{H}_{\varphi} = \frac{I_m l \sin\vartheta}{4\pi r r^2} \left[j \frac{2\pi}{\lambda} r \right] e^{-j\frac{2\pi}{\lambda} r} \tag{8}$$

Due to different exponent *y*, the component *r* of $\underline{E_r}$ may be neglected in comparison to $\underline{E_\vartheta}$, so that finally only the vector $\underline{E_\vartheta}$ and $\underline{H_\varphi}$ are left. These vectors are perpendicular to each other and the direction of the wave propagation. They oscillate in-phase and their attitude in time and space is constant:

$$\underline{E_\vartheta} / \underline{H_\varphi} = Z_0 = \sqrt{\mu_0 / \varepsilon_0} \tag{9}$$

The active impedance Z_0 is called the wave impedance of vacuum.

In the immediate proximity of the antenna (*r* >> 2π/λ) (near zone) both the second and the third members of (3-5) are significantly less than one, and these equations are simplified:

$$\underline{E}_{\vartheta} = \frac{I_m l Z_0 \lambda \sin\vartheta}{j \cdot 8\pi^2 r^3} e^{-j\frac{2\pi}{\lambda} r} \tag{10}$$

$$\underline{E}_{r} = \frac{I_m l Z_0 \lambda \cos\vartheta}{j \cdot 4\pi^2 r^3} e^{-j\frac{2\pi}{\lambda} r} \tag{11}$$

$$\underline{H}_{\varphi} = \frac{I_m l \sin\vartheta}{4\pi r r^2} e^{-j\frac{2\pi}{\lambda} r} \tag{12}$$

According to [1] it may be deduced the ratio $\underline{E_\vartheta} / \underline{H_\varphi}$

$$\underline{E_\vartheta} / \underline{H_\varphi} = Z_0 \lambda / (j \cdot 2\pi r) = Z_{0E} \tag{13}$$

The impedance Z_{0E} is being capacitive

$\lfloor \underline{Z_c} = 1/(jwC) \rfloor$ at *r* >> 2π/λ or λ/2π>>1

$$|Z_{0E}| > \ Z_0 \tag{14}$$

The specific energy in the near zone of the high-impedance (electric) field has the prevailing electric nature, i.e.

$$w(r) = w_{эл}(r) = \frac{1}{2} \varepsilon E^2 \tag{15}$$

For the field in the proximity of a small circuit with current (FitzGerald dipole), structurally dual equations will be got in the coordinate system J and j, the calculation of which produces the active wave impedance for the far zone из Z_0 = 377 Ω, and for the near zone:

$$\underline{Z}_{0H} = jZ_0 \cdot 2\pi r / \lambda \tag{16}$$

The wave impedance $\underline{Z_{0H}}$ of the loop antenna near zone is of the inductive character (*r* >> λ/2π or λ/2π>>1), and

$$|\underline{Z}_{0H}| >> Z_0 \tag{17}$$

It is the characteristics of the low resistance field, i.e. the magnetic field in the proximity to the loop antenna. The specific energy in the near zone is of the magnetic nature:

$$w(r) = w_M(r) = \frac{1}{2} \mu H^2 \tag{18}$$

In the far zone the vectors of the electric and magnetic field strength are directed at the right angle to each other and to the propagation direction. While the electric field in the near zone remains transversal, then the magnetic field contains the additional $\underline{H}_r$.

If the condition *l*<<λ. is not satisfied, then it is necessary to use not the dipole equation but the equation of electric long lines.

Figure 3 illustrates the examples of quasi-static fields in the near zone.

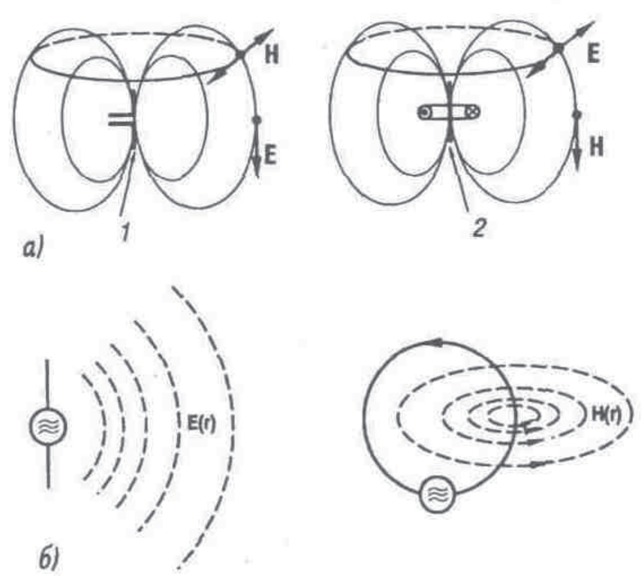

Figure 3. The ration of Hertz dipole and FitzGerald dipole (*a*) and schematic representation of the electric and magnetic fields in the near zone (*б*):
1 – electric field ; *2* – magnetic field

With the increasing distance from the whip antenna the value of the wave impedance decreases at the rate 20 dB/decade from great to small values and asymptotically approaches the value of the wave impedance of vacuum at a great distance. On the contrary, the wave impedance of the loop antenna at first increases at the rate 20 dB per decade and then also asymptotically approaches the value of the wave impedance of vacuum at a great distance (Fig. 4).

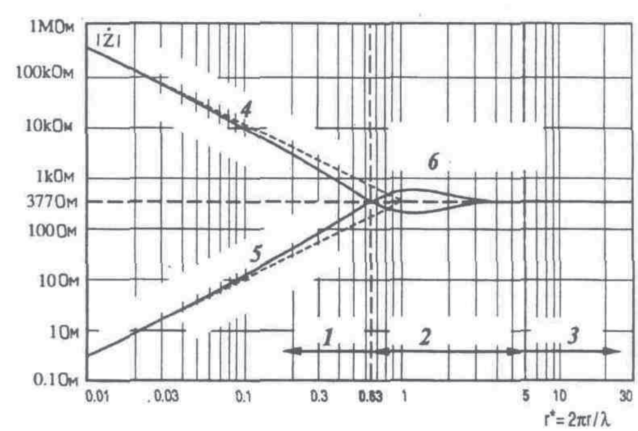

Figure 4. The device wave impedance depending on the normalized distance from the source *(r = 2r/λ): 1* – near zone; *2* – transition zone; *3* – far zone; *4* – high-impedance electric field; 5 – low-impedance magnetic field; 6 – electromagnetic wave field

These distance-based wave impedances are used at the attenuation coefficient calculations by the Schelkunov's method.

The electric field shielding by the closed conducting screen (without cracks) is infinitely large. Such screen is called Faraday cage. For the electric fields that change in time at a great rate the attenuation coefficient has a finite value. For the normal field components the following equations may be obtained by the Gauss's law:

$$E_{H.BH} = 0 \text{ and } E_{H.BШ} = \rho_S / \delta_0 \quad (19)$$

where ρ_s – surface density of the displaced charges.

For the tangential components it is followed from the said above that $E_{K.BH} = E_{H.BШ} = 0$. Finally, it should be mentioned, that the dielectric shells exert a certain shielding effect on the electrostatic fields. In the same way as the magnetic flux passes mainly through the circuit with high magnetic conductivity (relative magnetic permeability μ_r), the electric field flux *y* passes through the dielectric with high dielectric conductivity (dielectric permittivity ε_r).

With a large ration of the wall thickness *d* to the shell diameter *D* due to the refraction of the electric field lines on the boundary the electric flux mainly occurs in the screen wall. The attenuation coefficient is calculated by Kaden:

$$a_E = \ln(E_{BШ} / E_{BH}) = \ln(1 + 1{,}33\varepsilon_r d / D) \quad (20)$$

The noticeable shielding occurs only at thick-walled screens with high dielectric permittivity $\varepsilon_r d >> D$.

The following ratio of tangential E_K and normal E_H components of the electric field strength can be obtained on the basis of the Gauss's law and induction laws:

$$E_{K1} = E_{K1} \; u \; E_{H1} = E_{H2} = \varepsilon_{r2} / \varepsilon_{r1}$$

The magneto-static fields can be shielded with the help of the ferromagnetic shells with high magnetic permeability in the same way as the electrostatic fields with the help of the dielectric screens with high dielectric permittivity. Due to the refraction of the magnetic field lines on the surface boundary of the thick-walled screens from the materials with high magnetic permeability the magnetic flux mainly passes in the screen wall.

The attenuation coefficient is calculated in the following way:

$$a_H = \ln\left(H_{ВШ}/H_{ВН}\right) \approx \ln\left(1 + 1{,}33\mu_r d/D\right)$$

In the absence of currents in the screen the following ratio of normal and tangential components of the magnetic field strength on the screen surface can be obtained due to the Gauss's law and flux continuity law

$$H_{K1} = H_{K2} \qquad \text{and} \qquad H_{H1}/H_{H2} = \mu_{r2}/\mu_{r1}$$

The shielding of the quasi-static electric alternating fields works in the same way as of the electrostatic fields due to the redistribution of charges. However, if in the electrostatic field the attenuation coefficient is infinitely large, then in the alternating field the frequency growth causes a phase shift, which defines the final value of the attenuation coefficient. This effect becomes noticeable at very high frequencies. Actually the attenuation coefficient is supposed to be infinitely large at the quasi-static fields. The same boundary conditions are used as for the electrostatic field. The actual screens, for example the device cases, have gaps, cracks. If the separate screen walls are not connected to each other electrically, then the difference of potential arises and the screen has almost no effect. The shielding elements should be connected together while shielding from electrostatic fields.

The electromagnetic impact is possible through the cracks between the screen elements. This impact can be reduced by using labyrinth seals. At high frequencies, the screen elements should have numerous galvanic contacts for the currents affecting the equipotential bonding could follow the shortest path. While the fully closed metal screen provides field absence inside it without screen grounding, the application of the shadow effect of three separate shielding sheets requires their grounding.

The harmful effects of gaps in the closed screens can reduce the role of the screen to the shielding effect of a single screen elements plate. The higher the screen material conductivity is, the more are the currents in the screen at the similar induction electric field strength, and the higher is the attenuation coefficient. As the static magnetic field cannot induct currents, the non-ferromagnetic shells for constant magnetic fields (f = 0) have no shielding effect. On the other hand, the attenuation coefficient of quasi-static magnetic field tends to infinity with the frequency increase. This tendency has a limit on the frequencies where, along with the quasi-static magnetic field the magnetic field of displaced currents (electromagnetic waves) must also be taken into account. With increasing frequency we can no longer ignore the effect of displacement currents. The impact of the displaced currents can't be ignored any longer due to the frequency increase.

To manufacture the screens it is used the materials, which have high conductivity for the existing fields fluxes and which are able to create an opposing magnetic field due to the induction. The screen from good conductive metals and ferromagnetic materials are used most frequently. The comparison of the characteristics of the two screens with the same thickness and made of iron and copper explains the features of their shielding action (Fig. 5).

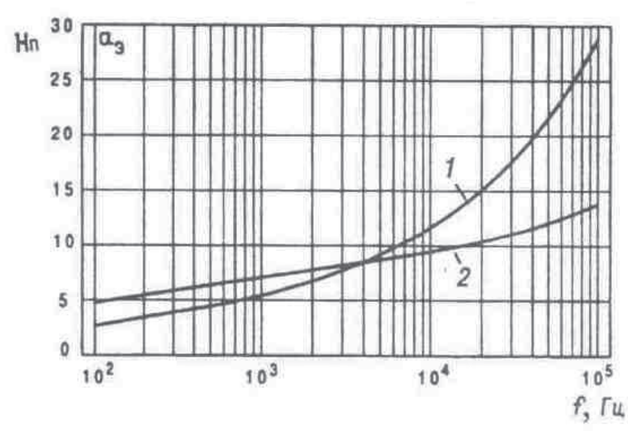

Figure 5. The ration of attenuation coefficient a_s of the magnetic field of the cylindrical screen from frequency f: *1* – for iron screen (r_0= 5 m, d_0= 0,1 mm, σ = 7 o 10^6 Cm/m, μ_r=200); *2* – for copper screen (r_0= 5 m, d_y= 0,1 mm, σ =58 o 10^6 Cm/m, μ_r =1)

In the range up to 100 kHz, the penetration depth of the electromagnetic field is greater than the thickness of the screen wall, and a material with high conductivity has a higher attenuation coefficient. The shielding effect here is based only on the screen attenuation, which acts as a shorted turn.

The analytical calculation of the shielding effect of electromagnetic screens requires the solution of Maxwell's equations for the areas inside and outside of the screen, and also in its wall. The result of the solution is the values of the shielding coefficient or attenuation coefficient. This method provides a deeper, beyond the known approximation formulae, understanding of the principle of electromagnetic screens and the screen operation becomes available for accurate quantitative assessment. However, this method is mathematically intensive, with approximate formulae the screens calculation is possible with the help of a grid method. The attenuation graphs for the cabin with an edge length2 m calculated by this method are presented in Fig.6.

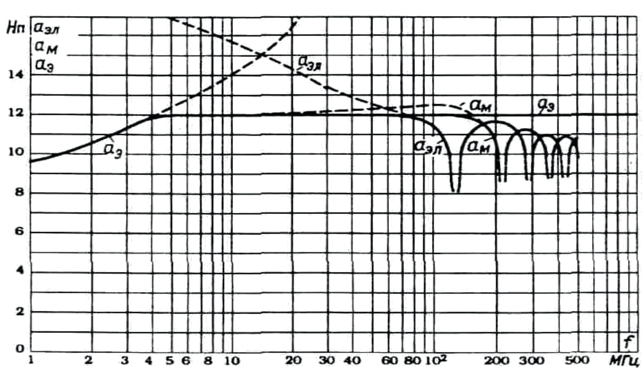

Figure 6. The attenuation coefficients of the measuring cabin with an edge length of 2m and copper foil screen thickness of 0.1 mm.

It should be noted that the spherical screens in practice are very rare; more often the question arises whether it is possible to calculate the shielding effect of the rectangular screening cabin. Taking into account the significant difficulties, it should not be tried to calculate the attenuation coefficient of the fields in the rectangular cabin accurately and analytically but it should be replaced with the sphere the radius r_0 of which equals to half of the length of the cabin edges. Due to the edge effect the shielding effect near the cabin corners is weaker as the current in the screen wall should pass the longer way, which results in a high active and inductive voltage drop along the wall. The edge effect can be smoothed by the rounding of corners and increasing the wall thickness near the corners.

The attenuation coefficient for the quasi-static magnetic fields theoretically reaches high values, however, in practice due to the door gaps, lattice ventilation widows, power supply input & etc. it is limited.

The method of calculation of the shielding effect of multilayer cylindrical and flat ferromagnetic (magneto static) screens in the linear approximation is based on the recurrence relations, which allows calculating the magnetic field induction in the field behind the screen for an arbitrary number of layers of the screen. Multilayer cylindrical screens provide a higher ratio of the shielding effect than single-layer screens of similar thickness with practically a very slight increase in the weight and dimensions. The cylindrical screens are more effective than the flat ones. Flat multilayer and single-layer screens of equal thickness provide almost the same shielding effect.

The principles of the numerical calculation of the ferromagnetic screen with a complex shape are based on the fact that the screen can be represented as a set of discrete elements. The size and position of each element are defined on the basis of the condition of minimization of the magnetic field energy in the given volume (shielded area), due to this there arises a possibility to synthesize a complex shape screen. The active screens synthesizing method is based on the gradient methods for solving extremal problems and allows to calculate the geometrical dimensions and the space position of axisymmetric shielding coils with rectangular cross section for superconducting coils of the similar geometry, while maintaining the predetermined intensity of the entire system.

The areas of numerical modelling are identified and the nonlinear numerical models are worked out, what allows analyzing the interaction of the conventional and superconducting electrical equipment electric field sources with the unlimited area of the magnetic field distribution and the lack of symmetry of the field distribution in space. The algorithm and software package are developed to determine the effect of electromagnetic fields on the integral parameters of conventional and superconducting electrical equipment. There have been conducted the research and the definition of the parameters and sizes of the superconducting inductive reactors of the smoothing filters for traction substations, which minimize the space occupied and ensure the best application of superconducting material at a given power intensity.

The obtained results can be considered as the basis of the research area related to electromagnetic compatibility of power superconducting and conventional electrical equipment for traction power supply and perspective vehicles.

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