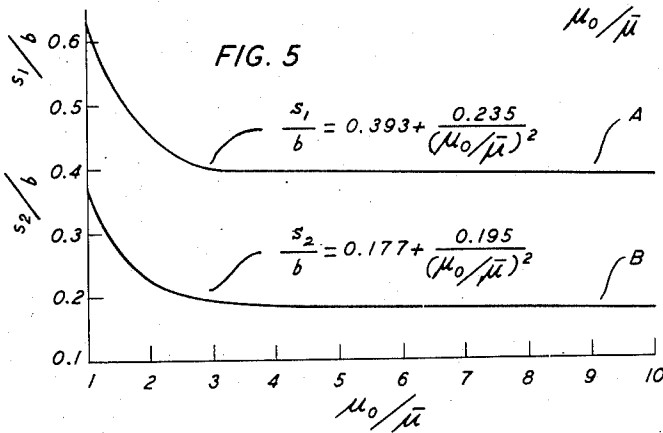
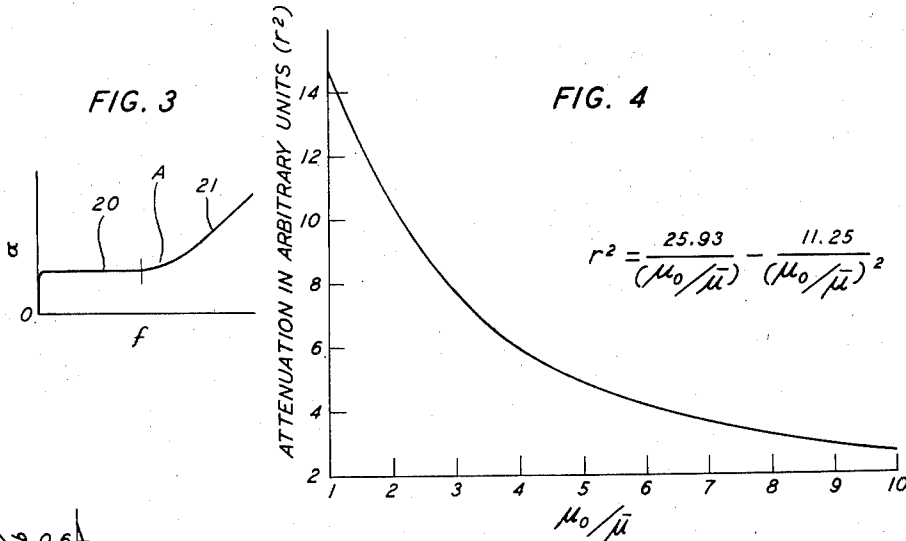
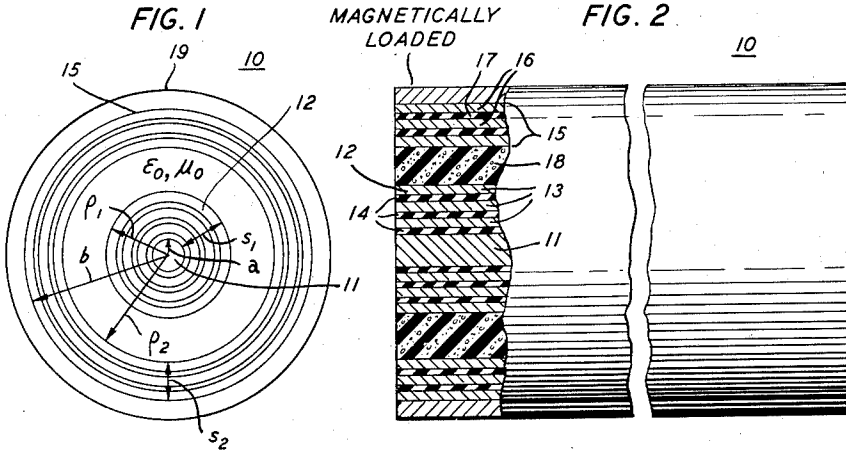


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S. P. MORGAN, JR
LOADED LAMINATED CONDUCTOR

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LOADED LAMINATED CONDUCTOR

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2 Claims. (Cl. 178-45)

This invention relates to electrical conductors and more particularly to magnetically loaded composite conductors formed of a multiplicity of insulated conducting portions and which are of the class of composite conductors which have come to be known as Clogston conductors.

It is an object of this invention to improve the current distribution in magnetically loaded composite conductors of the type comprising one or more stacks each including a large number of insulated conducting portions, and particularly to effect such improvement by the proportioning of the stacks.

In a copending application of A. M. Clogston, Serial No. 214,393, filed March 7, 1951, now Patent No. 2,769,148, there are disclosed a number of composite conductors, each of which comprises a multiplicity of insulated conducting elements of such number, dimensions, and disposition relative to each other and to the orientation of the electromagnetic wave being propagated therein as to achieve a more favorable distribution of current and field within the conducting material. In one specific embodiment disclosed in Figs. 7A and 7B of the Clogston application, two coaxially arranged composite conductors (stacks) are separated by dielectric material, each of the composite conductors comprising a multiplicity of thin metal laminations insulated from one another by layers of insulating material, the smallest dimensions of the laminations being in the direction perpendicular to both the direction of wave propagation and the magnetic vector. Each metal lamination is many times (for example 10, 100, or even 1000 times) smaller than the factor δ which is called one skin thickness or one skin depth. The distance δ is given by the expression

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \quad (1)$$

where δ is expressed in meters, f is the frequency in cycles per second, μ is the permeability of the metal in henries per meter, and σ is the conductivity in mhos per meter. The factor δ measures the distance in which the current and field penetrating into a slab of the material many times δ in thickness will decrease by one neper; i. e. their amplitude will become equal to $1/e=0.3679$. . . times their amplitude at the surface of the slab.

It is pointed out in the above-mentioned Clogston application that when a conductor has such a laminated structure, a wave propagated along the conductor at a velocity in the neighborhood of a certain critical value will penetrate further into the conductor (or completely through it) than it would penetrate into a solid conductor of the same material, resulting in a more uniform current distribution in the laminated conductor and consequently lower losses. In an application of J. G. Kreer, Jr., Serial No. 234,358, filed June 29, 1951, there is disclosed a conductor of the Clogston type which is magnetically loaded. The critical velocity for a magnetically loaded Clogston cable is determined by the thicknesses

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of the metal and insulating laminae, the dielectric constant of the insulating laminae, and by the permeabilities of both the metal and the insulating laminae. The relationship of the various factors determining the critical velocity in a cable loaded by making the relative permeability of the main dielectric member between the two composite conductors or stacks greater than one is as follows:

$$\mu_0 \epsilon_0 = \bar{\mu} \bar{\epsilon} \quad (2)$$

where μ_0 is the permeability of the main dielectric element between the two stacks in henries per meter, ϵ_0 is the dielectric constant of the main dielectric element in farads per meter, $\bar{\mu}$ is the average permeability of the stack in henries per meter and $\bar{\epsilon}$ is the average dielectric constant of the stack in farads per meter. The insulating laminae are also made very thin.

It has been discovered that in magnetically loaded Clogston conductors of the type just described, the attenuation constant is substantially uniform from a very low frequency, in practice a few kilocycles up to a certain frequency, which may in practice be many megacycles, the value of which is dependent on various factors among which are the composition, thickness and proportioning of the various laminae in the composite conductors. Above this certain frequency the attenuation constant rises. In the description which follows, the attenuation constant in this uniform or flat portion of the curve of attenuation constant vs. frequency will be known as the low frequency attenuation constant although, as mentioned above, in practice this region may extend up to many megacycles.

The present invention is based on the discovery that this low frequency attenuation constant can be minimized for various optimum conditions. There is a definite minimum (optimum) value of low frequency attenuation constant for each ratio of

$$\frac{\mu_0}{\bar{\mu}}$$

that is the ratio of the permeability of the main dielectric member to the average permeability of the stack. Moreover, for each value of

$$\frac{\mu_0}{\bar{\mu}}$$

there are optimum values of

$$\frac{s_1}{b}$$

and

$$\frac{s_2}{b}$$

where s_1 is the thickness of the inner stack, s_2 is the thickness of the outer stack and b is the inner radius of the outer shield.

The invention will be more readily understood by referring to the following description taken in connection with the accompanying drawing forming a part thereof in which:

Fig. 1 is an end view of a magnetically loaded coaxial composite conductor in accordance with the invention, the outer conductor or stack comprising a multiplicity of metal laminations separated by insulating material and the inner conductor or stack being similar in this respect to the outer conductor, the space between these two stacks being filled with an intermediate or main dielectric member which contains magnetic material;

Fig. 2 is a longitudinal view, with portions broken away, of the composite conductor of Fig. 1;

Fig. 3 is a graph of attenuation constant vs. frequency for a composite conductor of the type shown in Figs. 1 and 2;

Fig. 4 is a graph of r^2 (a constant proportional to attenuation) vs.

$$\frac{\mu_0}{\mu}$$

Fig. 5 shows graphs of optimum values of

$$\frac{s_1}{b}$$

and

$$\frac{s_2}{b}$$

vs.

$$\frac{\mu_0}{\mu}$$

Referring more particularly to the drawing, Figs. 1 and 2 show, by way of example, a conductor 10 in accordance with the invention, Fig. 1 being an end view and Fig. 2 being a longitudinal view. The conductor 10 comprises a central core 11 (which may be either of metal or dielectric material), an inner composite conductor or stack 12 formed of many laminations of metal 13 spaced by insulating material 14, an outer composite conductor or stack 15 formed of a multiplicity of thin layers of metal 16 spaced by insulating material 17 and separated from the inner conductor 12 by a magnetically loaded intermediate or main dielectric member 18, and an outer sheath 19 of metal or other suitable shielding material. As disclosed in the above-mentioned Clogston application, each of the metal layers 13 and 16 is made very thin compared to the skin depth of the conductors used, which for example, can be copper, silver or aluminum. The insulating layers 14 and 17 are also made very thin and may be of any suitable material. Examples of satisfactory materials are: polyethylene, polystyrene, quartz and polyfoam. The inner conductor of stack 12 has 10 or 100 or more metal layers 13 and the outer conductor or stack 15 may have a somewhat similar number of metallic layers 16 as the number of metal layers 13 but, as will be pointed out below, there are not necessarily the same number of conductors in the two stacks. Since there are a large number of insulating and metallic layers, it makes no difference whether the first or the last layer in each stack (12 or 15) is of metal or of insulation.

The intermediate dielectric member 18, by way of example, may be magnetically loaded by any suitable means. A number of ways to magnetically load a Clogston conductor (some of them by loading the intermediate dielectric member and some by loading the stacks) are described in the above-mentioned Kreer application and in an application of A. M. Clogston, Serial No. 234,349, filed June 29, 1951, an application of H. S. Black, Serial No. 234,293, filed June 29, 1951, now Patent No. 2,777,896, and an application of J. G. Kreer, Serial No. 234,360, filed June 29, 1951. By way of example, a method illustrated by Fig. 7 of J. G. Kreer application Serial No. 234,358 is shown in Figs. 1 and 2 of the present application. In this specific arrangement the composite conductor is magnetically loaded by providing a composite dielectric member 18 formed by mixing magnetic ferrite in the form of a finely divided powder with a plastic dielectric material such as polyethylene foam. By choosing different ferrites or by varying the quantity used the ratio of

$$\frac{\mu_0}{\mu}$$

can be varied.

As pointed out above, the present invention is based on the discovery that certain optimum relationships exist in unloaded Clogston conductors or cables of the general

type just described. These optimum relationships make it possible to select various ratios and proportions of elements within the stack which will give the minimum low frequency attenuation constant. These relationships are optimum only in the low frequency portion of the graph of attenuation constant α vs. frequency f . As shown in Fig. 3 which presents a typical curve of attenuation constant α vs. frequency f , there is a low frequency portion 20 (which may extend in practice from a frequency of a few kilocycles to many megacycles) which is substantially flat and parallel to the horizontal axis and a high frequency portion 21 which curves upward. It should be understood that for each particular configuration of cable 10 there is a different curve of low frequency attenuation constant vs. frequency, the curve designated A in Fig. 3 being only one of a family of curves each one of which has the same general shape but which vary in the height of the low frequency portion 20 above the horizontal axis and the extent of this horizontal portion. This invention is based on the discovery that in loaded Clogston cables, such as for example, of the general type shown in Figs. 1 and 2, there are optimum conditions which give a minimum height for the portion 20 of the curve A above the horizontal axis, or, in other words, which give a minimum low frequency attenuation constant.

Before pointing out these optimum conditions a general relationship will be set forth. In this relationship the notation is as follows:

a =radius of inner core 11.

b =inner radius of outer shield 19.

ρ_1 =inner radius of main dielectric 18.

ρ_2 =outer radius of main dielectric 18.

$s_1 = \rho_1 - a$ =thickness of inner stack 12.

$s_2 = b - \rho_2$ =thickness of outer stack 15.

t_1 =thickness of each conducting lamina 13 or 16 (called W by Clogston in the above mentioned Clogston application Serial No. 214,393).

t_2 =thickness of each insulating lamina 14 or 17 (called t by Clogston in his application Serial No. 214,393).

$\theta = t_1 / (t_1 + t_2)$ =fraction of stacks 12 and 15 filled with conducting material 13 or 16.

ϵ_0 =dielectric constant of main dielectric member 18.

ϵ_2 =dielectric constant of insulating laminae 14 and 17.

$\bar{\epsilon} = \epsilon_2 / (1 - \theta)$ =average dielectric constant of stacks 12 and 15.

μ_0 =the permeability of the main dielectric member 18.

μ_1 =permeability of conducting laminae 13 and 16.

μ_2 =permeability of insulating laminae 14 and 17.

$\bar{\mu} = \theta \mu_1 + (1 - \theta) \mu_2$ =average permeability of stacks 12 and 15.

σ_1 =conductivity of the conducting laminae 13 and 16.

$\bar{\sigma} = \theta \sigma_1$ =average conductivity of stacks 12 and 15.

For all configurations of the cables shown in Figs. 1 and 2 it is assumed that the relationship which has come to be known as "Clogston's condition," that is, Equation 2, is exactly satisfied. The conducting laminae are considered as being infinitesimally thin compared to the skin depth; the thinner the laminae, the greater the frequency range over which this assumption is valid. Furthermore, the impedances of both the inner core 11 and the outer shield 19 are made so high that the currents, if any, flowing in the core and shield are negligible compared to the currents in the stacks. No restrictions, however, are placed on the values of a , ρ_1 , ρ_2 , and b .

The low frequency attenuation constant of the principal mode in cables of the type shown in Figs. 1 and 2 is given by

$$\alpha \sqrt{\frac{\epsilon \mu}{2\pi b^2}} \quad (3)$$

where r is the lowest positive root of the equation:

$$\frac{b}{r\rho_2} \frac{J_1(r)N_0(r\rho_2/b) - N_1(r)J_0(r\rho_2/b)}{J_1(r\rho_2/b)N_1(r) - N_1(r\rho_2/b)J_1(r)} - \frac{b}{r\rho_1} \frac{J_1(ra/b)N_0(r\rho_1/b) - N_1(ra/b)J_0(r\rho_1/b)}{J_1(r\rho_1/b)N_1(ra/b) - N_1(r\rho_1/b)J_1(ra/b)} = \log \frac{\rho_2}{\rho_1} \quad (4)$$

In Equation 4, J and N are Bessel and Neumann functions of orders 0 and 1 as indicated. Given the values of a , b , ρ_1 , ρ_2 , μ_0 , and $\bar{\mu}$, the lowest value of r which satisfies Equation 4 can be obtained by graphical or numerical means.

By varying the ratios a/b , ρ_1/b , ρ_2/b , and $\mu_0/\bar{\mu}$, and solving for r in a number of different cases, it is possible to determine how r depends on the geometric proportions of the cable and the permeability ratio $\mu_0/\bar{\mu}$. For a fixed value of the ratio $\mu_0/\bar{\mu}$, it is found that the lowest value of r , corresponding to the lowest attenuation constant, is obtained when the core radius a is zero. (This is a mathematical limit; but the use of a small core in the manufacturing process will not have serious adverse effects.) To obtain the lowest value of r , the relative stack thicknesses s_1/b and s_2/b must also have definite values, which depend only on the loading ratio $\mu_0/\bar{\mu}$. These optimum stack thicknesses are found by repeated solution of Equation 4 for cables with a variety of different proportions.

Fig. 4 shows a curve obtained by assigning specific values to the ratio $\mu_0/\bar{\mu}$ and represents the lowest attenuation that can be obtained for a given value of this ratio. In this curve the attenuation in arbitrary units (r^2) is plotted against $\mu_0/\bar{\mu}$. The curve may be represented approximately by the following equation; which holds for all values of the ratio $\mu_0/\bar{\mu}$ greater than unity:

$$r^2 = \frac{25.93}{\mu_0/\bar{\mu}} - \frac{11.25}{(\mu_0/\bar{\mu})^2} \quad (5)$$

Fig. 5 shows the optimum stack thicknesses for various permeability ratios. In this figure, the upper curve A is a plot of s_1/b vs. the permeability ratio $\mu_0/\bar{\mu}$ while the lower curve B is a plot of s_2/b vs. the permeability ratio $\mu_0/\bar{\mu}$. The relation shown in both curves in Fig. 5 (as well as that shown in Fig. 4) exists throughout the region represented by the portion 20 of the curve in Fig. 3. For all values of $\mu_0/\bar{\mu}$ greater than unity, the upper curve A in Fig. 5 obeys substantially the equation:

$$s_1/b = 0.393 + \frac{0.235}{(\mu_0/\bar{\mu})^2} \quad (6)$$

and the lower curve B obeys approximately the relationship

$$s_2/b = 0.177 + \frac{0.195}{(\mu_0/\bar{\mu})^2} \quad (7)$$

It is seen from the curves that the ratios s_1/b and s_2/b decrease sharply for increasing $\mu_0/\bar{\mu}$ to a value for the latter ratio between two and three, and then approach constant asymptotic values for more heavily loaded cables.

The optimum relationships shown in Fig. 5 make it possible to design a cable for minimum low frequency attenuation. If there is no magnetic loading, or more generally if the stacks are loaded relative to the main dielectric so that $\mu_0/\bar{\mu} < 1$, then the cable should be completely filled with laminations (no main dielectric). If

on the other hand there is magnetic loading of the main dielectric so that $\mu_0/\bar{\mu} > 1$, then for any given value of $\mu_0/\bar{\mu}$ a particular set of proportions including a main dielectric gives lowest attenuation. Fig. 4 shows how much the low-frequency attenuation constant of a cable of given size can be decreased using various amounts of magnetic loading, other factors being equal.

What is claimed is:

1. A composite elongated electromagnetic wave conductor adapted for use with high frequency electromagnetic waves comprising an inner stack of insulated elongated conducting members, an outer stack of insulated elongated conducting members surrounding the inner stack, and means between the stacks for magnetically loading the cable, the relationship of relative inner stack thickness s_1/b and permeability ratio $\mu_0/\bar{\mu}$ being given substantially by the equation:

$$s_1/b = 0.393 + \frac{0.235}{(\mu_0/\bar{\mu})^2}$$

in which s_1 is the thickness of said inner stack, b is the outer radius of the outer stack, μ_0 is the effective permeability of said loading means between the stacks and $\bar{\mu}$ is the average permeability of the two stacks, and

$$\frac{\mu_0}{\bar{\mu}} > 1$$

each of the insulated conducting members in said inner and outer stacks being thinner than the skin depth of penetration of waves into the material of said conducting members at the highest frequency of operation of said conductor.

2. A composite elongated electromagnetic wave conductor adapted for use with high frequency electromagnetic waves comprising an inner stack of insulated elongated conducting members, an outer stack of insulated elongated conducting members surrounding the inner stack, and means between the stacks for magnetically loading the cable, the relationship of relative outer stack thickness s_2/b and permeability ratio of $\mu_0/\bar{\mu}$ being given substantially by the equation:

$$s_2/b = 0.177 + \frac{0.195}{(\mu_0/\bar{\mu})^2}$$

in which s_2 is the thickness of the outer stack, b is the outer radius of the outer stack, μ_0 is the effective permeability of said loading means between the stacks, and $\bar{\mu}$ is the average permeability of the two stacks, and

$$\frac{\mu_0}{\bar{\mu}} > 1$$

each of the insulated conducting members in said inner and outer stacks being thinner than the skin depth of penetration of waves into the material of said conducting members at the highest frequency of operation of said conductor.

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