April 23, 1968 F. N. HANSEN 3,380,004

APERIODIC LOW-PASS FILTER

Filed Jan. 29, 1962 2 Sheets-Sheet 1

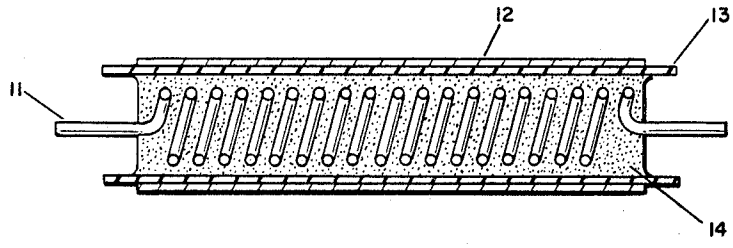


FIG. 1

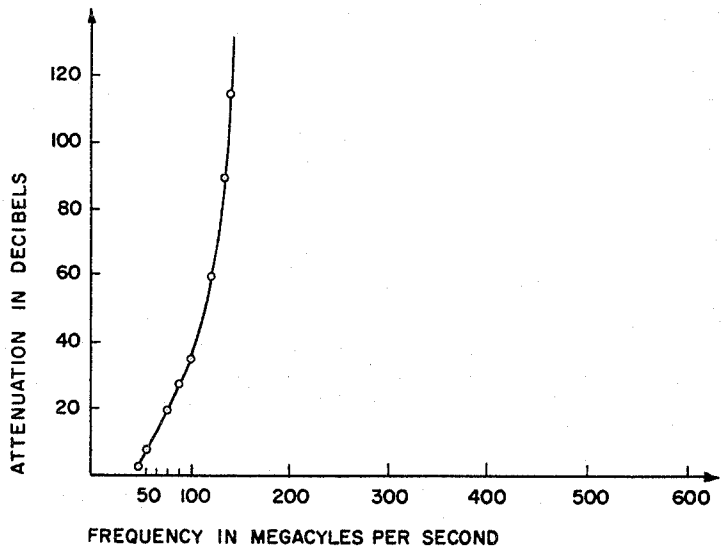


FIG. 2

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APERIODIC LOW-PASS FILTER

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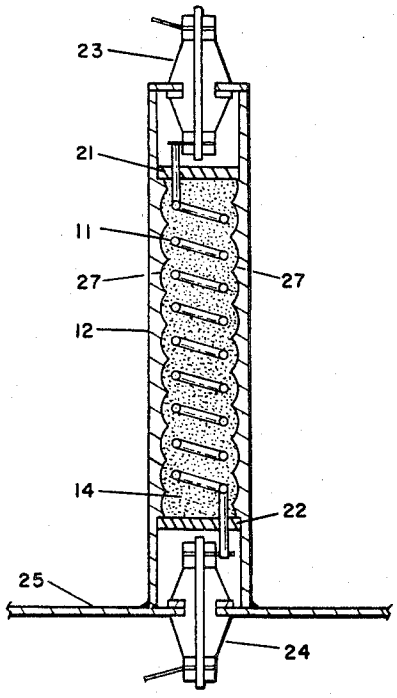


FIG. 3

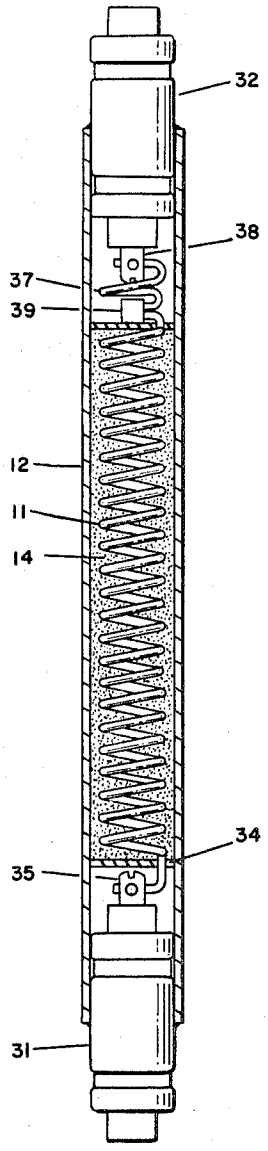


FIG. 4

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APERIODIC LOW-PASS FILTER

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Continuation-in-part of application Ser. No. 787,885, Jan. 20, 1959. This application Jan. 29, 1962, Ser. No. 177,131

13 Claims. (Cl. 333—79)

This invention relates to filters for permitting the transmission of electrical power of desired low frequencies while supporting the transmission of power of undesired high frequencies.

More particularly, the invention relates to an aperiodic low-pass filter with uniformly distributed inductance and capacitance.

This application is a continuation-in-part of my copending application Ser. No. 787,885 filed on Jan. 20, 1959.

Briefly, the invention consists of a power conductor, a conductive shield surrounding the power conductor and insulated therefrom, and a core of finely divided magnetic material mixed with an epoxy resin binder interposed between the conductor and the shield.

The invention will be more fully understood upon reading the following specification, reference being had to the accompanying drawing forming a part thereof.

Referring to the drawing:

FIGURE 1 is a view in longitudinal section of a low-pass filter embodying the invention.

FIGURE 2 is a graph showing the frequency-attenuation performance of the filter of FIG. 1.

FIGURE 3 is similar to FIG. 1 showing a filter equipped with insulating terminals and mounted on a metal wall.

FIGURE 4 shows a filter similar to the filter of FIG. 1 equipped with shunt capacitors which also serve as its terminals.

Referring to FIG. 1, a power conductor **11** is shown as having a helical configuration intermediate its ends. The power conductor **11** is laterally surrounded by a length of conductive tubing **12** which also serves as a case for the filter. Both the conductor **11** and the tubing **12** should be of material having a relatively high conductivity, such as copper. Just inside conductive tubing **12** in FIG. 1, is shown an insulating sleeve **13** which may be a distinct component or may simply be an insulating coating applied to the interior surface of conductive tubing **12**. In the filter shown in FIG. 1, I employed mica-coated Fiberglas in the construction of insulating sleeve **13**. The interior of sleeve **13** including the space between the turns of the helix of conductor **11** and between conductor **11** and insulating sleeve **13** is filled with a magnetic material **14** which serves as a core for the helix and also as a lossy dielectric material for the capacitor formed by filamentary conductor **11** and conductive tubing **12**. To some extent, magnetic material **14** itself is sufficiently conductive so that it serves as a "plate" of a capacitor the other "plate" of which is conductive tubing **12**.

Magnetic material **14** comprises iron which has been powdered to such an extent that the particles are rather fine. Of the iron particles in the filter core shown in FIG. 1, 23 percent are smaller than 250 mesh, while the remainder are larger than 250 mesh. The power conductor **11** may be supported by a jig within conductive tubing **12** and insulating sleeve **13** while magnetic material **14** is introduced to fill all the void spaces. If desired, the magnetic material may be introduced under vacuum in order

that the amount of trapped air may be reduced to a minimum.

A point of interest in the construction of my filter is that filamentary conductor **11** should be in electrical contact with magnetic material **14**. While it is possible, by means of an insulating coating on filamentary conductor **11**, to permit magnetic material **14** to be in conductive contact with conductive tubing **12**, it is preferable from an electrical standpoint to use insulating sleeve **13** between conductive tubing **12** and magnetic material **14** while permitting magnetic material **14** to be in intimate electrical contact with filamentary conductor **11**. In other words, since it is necessary only that either filamentary conductor **11** or conductive tubing **12** to be insulated from magnetic material **14**, electrical considerations render it desirable for the insulation to be applied to conductive tubing **12** rather than to filamentary conductor **11**. In this way, skin effect currents of high frequency flow in the closest possible proximity to the magnetic material **14**.

A further point of interest in regard to magnetic material **14** is the fact that its conductivity must be finite rather than zero, and yet its conductivity must be much less than that of filamentary conductor **11**. It is clear that, while it must be possible for electrical loss to take place in magnetic material **14**, the greater part of the power current should still flow through conductor **11** rather than through magnetic material **14**. I have found that a good operational relationship between the conductivity of filamentary conductor **11** and that of magnetic material **14** in bulk is the ratio 100 to 1. Of course, I do not intend to limit myself to conductivities having that ratio.

Although power conductor **11** has been shown and described as being helical in configuration within conductive tubing **12**, it will be apparent that the pitch of the helix could become so large that filamentary conductor **11** would approach the configuration of a straight wire. In fact, a filter may be constructed in which power conductor **11** is a straight wire throughout its entire length. However, it is clear that, by employing the helical configuration for conductor **11**, I am able to increase its distributed series inductance per unit length.

Still another point of interest depends upon the fact that all of the convolutions of the helix of filamentary conductor **11** are equidistant from the internal surface of conductive tubing **12** and hence, each increment of a given length of filamentary conductor **11** has capacitance to conductive tubing **12** which is comparable with the capacitance of every other increment of the same length of filamentary conductor **11**. While it will be apparent that some increments of filamentary conductor **11** are closer than others to the ends of conductive tubing **12** and therefore have capacitances to the grounded tubing **12** which differ to some degree. Nevertheless, the capacitance along the helix is characterized by a smooth, uniform distribution. Consequently, and by reason of the lossy nature of magnetic material **14**, the filter is aperiodic and free from any sharp peaks in the frequency response characteristic. Such aperiodic performance is in sharp contrast to that of the prior art filters which display peaks and valleys in their frequency response characteristics. This aperiodic performance is largely attributable to the use of the core **14** of magnetic material of moderate conductivity.

In operation, the conductive sleeve **12** tends to simulate the outer conductor of a coaxial transmission line at higher frequencies. This wave transmission line action, however, is impeded by the moderately conductive magnetic material **14** which operates as a lossy obstructing plug. In order to enhance the obstructing effect of the

lossy magnetic material **14**, the thickness of the insulating sleeve **13** should be kept to a minimum.

It is clear that a number of variations can be made in the filter of FIG. 1 without departing from the essence of this invention. For instance, instead of a Fiberglas insulating sleeve **13**, one might employ a film of lacquer or high dielectric plastic material sprayed or brushed upon the internal surface of conductive tubing **12**. Alternatively, it would be possible to apply such an insulating coating to the outer surface of a subassembly consisting of the filamentary power conductor **11** and lossy magnetic material **14**, and then apply conductive tubing **12** by spraying or painting highly electrically conductive material over the insulative coating previously applied to the moderately conductive magnetic material **14**. Some method would have to be employed for maintaining the mechanical stability of the magnetic material until the insulated conductive tubing is in place around the magnetic material. One way to obtain such a construction is to form an inner core of magnetic material, such as powdered iron in cylindrical form, and sinter it so that it will hold its shape while the turns of the power conductor **11** are applied around it. If desired, this inner core may be formed and sintered in a container having helical depressions formed on its inner surface, whereby the inner core is produced with a "threaded" surface suitable for receiving the convolutions of the filamentary power conductor **11**. When these turns have been applied to the inner core, the subassembly may be supported within the insulated conductive tubing while the remainder of the magnetic material **14** is put in place, thereby completing the core and filling in the spaces between turns of the helix and the insulated inner surface of the conductive tubing.

With regard to the specific physical dimensions of the filter of FIG. 1, conductive tubing **12** is a 5 inch length of copper tubing having an outside diameter of 5/8 inch. Power conductor **11** is formed of No. 14 copper wire wound into a helix providing 24 turns within the 5 inch length of conductive tubing **12**. Magnetic material **14** comprises ordinary powdered iron designated No. 5–P38–5, which is inexpensive and easily obtained on the market. These dimensions give the filter a uniformly distributed inductance of approximately 4 microhenries and a uniformly distributed capacitance of approximately 800 micromicrofarads. It will be understood that these parameters, while appropriate for the performance characteristic of FIG. 2, are by no means to be taken in a limiting sense. The effective inductance of the filter may be increased by increasing the length of the power conductor **11**, as by increasing the number of turns in its helical configuration. The spacing between adjacent turns must, however, be kept sufficiently large to prevent efficient interturn coupling. The capacitance to ground is determined by the thickness of the insulation between the lossy magnetic material **14** and the conductive tubing **12** which is provided in FIG. 1 by insulating sleeve **13** and also, to a certain extent, by the proximity of the turns of the helix to the conductive tubing **12**.

While the filters described in this specification are straight in external over-all configuration, it is clear that filters according to my invention need not always be straight and in fact might necessarily be other than straight under some circumstances. A possible occasion for making a filter other than straight would occur if a very long filter were required and the space to accommodate it were limited. In that event, it might be advantageous to form the entire filter into a coil. The use of a flexible power conductor and flexible conductive tubing would facilitate the production of filters having other than rectilinear configurations.

Turning now to FIG. 2 of the drawing, there is shown a graph of the frequency-attenuation performance characteristics of the filter shown in FIG. 1. The plot shows, as a function of frequency, the attenuation of currents passing through the filter, where the input power is connected to conductor **11** with conductive tubing **12** grounded. It will be noted that the attenuation begins, with increasing frequency, at a rather low value and rises sharply with further increasing frequency to a value beyond which it can no longer effectively be measured. It is possible, however, to state with assurance that the attenuation for these higher frequencies is in excess of 120 decibels and that there are no points of resonance where the attenuation reverts below that level in the upper frequency ranges. This is an important feature in view of the requirements which have been established for filters for use in connection with shielded rooms, for example, and which require that they attenuate all energy components having frequencies of 200 megacycles per second or higher by at least 120 decibels. While the performance of the filter at frequencies of 200 megacycles or higher is completely satisfactory, special design considerations become important in the optimization of performance at frequencies of 100 megacycles per second or less. In order to extend the band of acceptable attenuation to frequencies which are very low indeed, shunt capacitors may be connected between the power conductor **11** and the conductive tubing **12** at either or both of its ends. Such a construction is illustrated in FIG. 4 and described in greater detail below. It is important to realize, however, that even without the use of these supplementary capacitors, extremely high attenuation requirements can be met for power components in the microwave range and extending all the way down through the UHF bands to the VHF bands. Still more remarkable is the fact that this wide-band performance is obtained by means of a relatively simple unitary circuit element which provides uniformly distributed inductance and capacitance. If one chooses to use the supplementary capacitors shown in FIG. 4, satisfactory attenuation may be obtained at frequencies below one megacycle.

In FIG. 3 is shown a filter rather similar to that of FIG. 1 which is equipped with certain fittings to facilitate connection of the filter in an electrical circuit. Employing like reference numbers for similar elements in FIGS. 1 and 3, it may be pointed out that magnetic material **14** in FIG. 3 is retained in place by means of rubber disks **21** and **22**, and that the ends of power conductor **11** are connected to feed-through insulators **23** and **24**. Conductive tubing **12** is shown soldered to a metal supporting disk **25** which is suitable for mounting in the wall of a screened enclosure or shielded room in which sensitive tests are to be made. The embodiment shown in FIG. 3 represents a working embodiment of the invention in which magnetic material **14** is formed into a body 5 inches long and the assembly included within conductive tubing **12** which is a cylinder 8 inches long. The power conductor **11** is helical in configuration and includes 35 turns of wire, imparting to the filter an inductance of approximately 26 microhenries. The distributed capacitance of the filter in this particular embodiment is approximately 3000 micromicrofarads. Although ordinary powdered iron is used in the magnetic material **14** in the embodiments which have so far been described, various experiments have been performed in order to determine whether other magnetic materials might be sufficiently superior to powdered iron in order to warrant additional expense involved in the use of such materials. For instance, various ferrite materials have been tested in order to increase the inductance of the filter, and various particle sizes of magnetic material have been tried in order to optimize the relationship between resistivity and permeability of the magnetic materal. Iron produced by the "carbonyl" process has been tested, and tests have even been made employing mixtures of iron and barium titanate as magnetic material **14** in order to maximize the dielectric constant of the material and hence the distributed capacitance of the filter. Although some minor improvements in performance have been made by means of the use of these materials, such improvements have tended to take place in the higher-frequency ranges of the filter performance, where

the performance was already entirely satisfactory when judged by commonly applicable performance requirements. Moreover, the use of these materials other than iron has sometimes impaired the performance of the filter in the low-frequency ranges where the performance requirements are more critical. Hence, I presently favor the use of ordinary powdered iron in the magnetic material in view of the fact that ordinary powdered iron seems to give the best performance at the low frequencies and also gives entirely satisfactory performance at the high frequencies. One further elaboration which has been tried is the use of barium titanate in the form of a coating between the magnetic material and conductive tubing. Such use of barium titanate is predicated upon the assumption that the high dielectric constant of barium titanate will increase the distributed capacitance of the filter sufficiently to improve its performance. Once again, it appears that the simpler configurations without the use of barium titanate give very satisfactory performance, and that adequate capacitance can be obtained without the use of this dielectric material. The distributed capacitance can be enhanced by specially shaping the inner surface of conductive tubing **12** as by the helical "threads" shown at **27**.

A commercial configuration of filter according to my invention is shown in FIG. 4 of the drawing, wherein supplementary shunt capacitors **31** and **32** are employed at the respective ends of the filter for improvement of the lower-frequency performance. The filter of FIG. 4 is designed to carry 30 amperes of power current through conductor **11**, and gives good attenuation performance at all frequencies above 1 megacycle per second. Even when these supplementary capacitors are employed in order to improve the low-frequency performance of the filter according to my invention, the capacitance of these supplementary capacitors is but a small fraction of the capacitance required in prior-art filters.

One method by which a filter as shown in FIG. 4 may be assembled includes the following steps:

(1) Insert the helical power conductor **11** through a hole in a rubber disk **34**.

(2) Connect the end of power conductor **11** to capacitor **31** by means of a screw fitting **35**.

(3) Insert conductor **11**, rubber disk **34** and capacitor **31** into conductive tubing **12** and solder in place at one end of the conductive tubing.

(4) Insert some resin into conductive tubing **12** and bake the assembly in order to adhere rubber disk **34** to the inner surface of conductive tubing **12**.

(5) Fill conductive tubing **12** up to a desired point with electrically conductive magnetic material **14** such as the powdered iron mixture designated E–91–E by the McMillan Industrial Corporation, Ipswich, Mass. Again bake the assembly in order to stabilize mechanically the magnetic material **14**. The E–91–E mixture includes the following ingredients:

524.2 weight parts of Ancor 1025 iron powder as produced by Hoeganaes Sponge Iron Corp., Riverton, N.J.

51 weight parts of Epon 828 epoxy resin as produced by Shell Chemical Company.

43.8 weight parts of RD–1 butyl glycidal ether as produced by Ciba Co., Kimberton Pa. (This serves as a reactive diluent.)

3.8 weight parts of dimethylaminoethanol.

(This serves as a hardener when the mixture is baked.)

(6) Connect conductive link **37** to capacitor **32** by means of screw fitting **38**. Connect conductive link **37** at its other end to a connector block **39**.

(7) While conductor **11** is stretched slightly so that its end extends out of the conductive tubing **12**, fasten the end of filamentary conductor **11** to connector block **39** and solder the connection.

(8) Insert capacitor **32** in place in the end of conductive tubing **12** and solder at the end of conductive tubing **12**.

In the embodiment as shown in FIG. 4, capacitors **31** and **32** are rated at 600 volts DC, which is sufficient insulation for most power supplies where a filter is needed. Power conductor **11** comprises a 4-inch coil of No. 12 copper wire coated with tin and formed into a helix having a pitch of 7 turns per inch. The minimum clearance between helical conductor **11** and the inner surface of conductive tubing **12** is less than ⅛ inch.

Before insertion of conductor **11** in conductive tubing **12**, the inner surface of conductive tubing **12** is insulated with a film, approximately 3 mils thick, of non-conductive material. In the filter according to FIG. 4, conductive tubing **12** has an outside diameter of ¾ inch and is 7 inches long. The wall thickness of the conductive tubing in one case is .022" where the tubing is of steel and in another case is .032" where the tubing is of brass.

The insulating coating which I favor and which is applied to the inner surface of conductive tubing **12** is a three-layer coating, each of which is approximately 1 mil thick. I first apply a priming coat of polyvinyl butyral and then follow this priming coat by two successive coats comprising phenolic resin and polyvinyl butyral. After applying each of these coats by dipping, spraying, or brushing, I prefer to bake the coat for about 20 minutes at a temperature of approximately 250° F. An insulating coating as described gives adequate protection for potential differences of at least 1000 volts at 400 cycles per second.

Obviously, there are many different insulating materials which may be employed with satisfactory results. For instance, I have used a coating loaded with aluminum powder between the priming coat and two subsequent insulating coatings. For some frequencies it is possible to increase the attenuation by this means. I have also used an intermediate layer containing barium titanate. However, for the sake of simplicity, I prefer to use the three-layer coating as previously described.

It will be seen that a unitary aperiodic low-pass filter has been provided for accomplishing a filtering action which has previously been performed only by complicated arrangements of circuit components. However, the performance is far superior to the performance of the more complex prior art devices. The powdered iron or other magnetic material serves not only as a magnetic core but also, by reason of its moderate conductivity, as a lossy dielectric. For best results, the conductivity of the magnetic material should be substantial but should be considerably less than that of the copper power conductor. In view of the high density of magnetic flux in the immediate vicinity of the power conductor, it is desirable not to insulate this conductor, which would prevent contact with the magnetic material, but rather to insulate the magnetic material from the outer conductor at whose surface the magnetic flux density is not so great.

It will be apparent that various modifications of my filter may be made, employing these principles without departing from the spirit and scope of my invention as defined in the appended claims.

What is claimed is:

1. A low-pass filter comprising: an elongated electrically conductive sleeve member, said sleeve member when said filter is in operation, being grounded, a power conductor extending longitudinally of said sleeve member, said conductor being spaced from and enclosed within said sleeve member, a quantity of lossy magnetic material substantially filling the space within said sleeve member, said lossy material consisting essentially of a mixture of finely divided electrically conductive magnetic material and a resin, the electrical conductivity of said mixture rendering said filter aperiodic in its per-

formance, and insulating means insulating said conductor electrically from said sleeve member, the thickness of said insulating means being of the order of not exceeding three one-thousandths of an inch.

2. A filter according to claim 1, wherein said lossy magnetic material is in direct contact with said conductor.

3. A filter according to claim 1, wherein said insulating means is an insulating sleeve disposed adjacent to and enclosed by said conductive sleeve member.

4. A filter according to claim 1, wherein said insulating means comprises at least one coating of electrically insulative material applied to the internal surface of said sleeve.

5. A filter according to claim 1, wherein said lossy material consists essentially of:

524.2 weight parts of iron powder.
51 weight parts of epoxy resin.
43.8 weight parts of butyl glycidal ether.
3.8 weight parts of dimethylaminoethanol.

6. A filter according to claim 1, wherein said magnetic material is powdered iron.

7. A low-pass filter according to claim 1, further comprising at least one shunt capacitor connected between said sleeve member and said power conductor.

8. A low-pass filter comprising: an elongated tubular sleeve member formed of electrically conductive material, a central power conductor extending longitudinally of said sleeve member coaxially therewith, said conductor being spaced from and enclosed within said sleeve member, a quantity of electrically conductive lossy material having effective magnetic permeability at frequencies higher than one megacycle, said lossy material substantially filling the space within said sleeve member not occupied by said conductor, said lossy material having a conductivity sufficiently high with respect to render said filter continuously aperiodic and increasingly attenuative throughout a frequency range extending upwardly from a predetermined minimum frequency effectively to infinity, and insulating means interposed between said lossy material and the internal surface of said sleeve member for insulating said conductor from said sleeve member, said insulating means having a thickness of the order of not exceeding three one-thousandths of an inch.

9. A low-pass filter according to claim 8, wherein said conductor is in the form of a helix coaxial with said sleeve member.

10. A low-pass filter according to claim 8, wherein said lossy material consists essentially of a mixture of finely divided electrically conductive magnetic material and a resin.

11. A low-pass filter according to claim 10, wherein said magnetic material is powdered iron and said resin is an epoxy resin.

12. A filter according to claim 1, wherein said insulating means comprises a layer of electrically insulative material interposed directly between said lossy material and said sleeve, said layer being sufficiently thin to permit said lossy material to suppress operation of said sleeve as a coaxial transmission line.

13. A filter according to claim 8, wherein said insulating means comprises electrically insulative material in direct contact with said sleeve member and with said lossy material, said lossy material and power conductor forming an electrically conductive plug, said insulative material being sufficiently thin to suppress operation of said sleeve member and plug as a coaxial transmission line.

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