

Aug. 2, 1966

A. B. TRENCH

3,264,590

CURRENT LIMITING REACTOR

Filed May 24, 1963

4 Sheets-Sheet 1

FIG. 1.

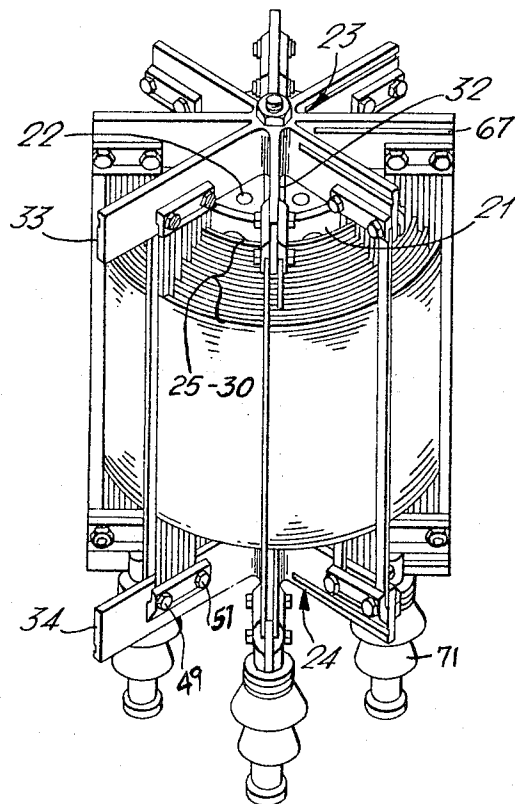
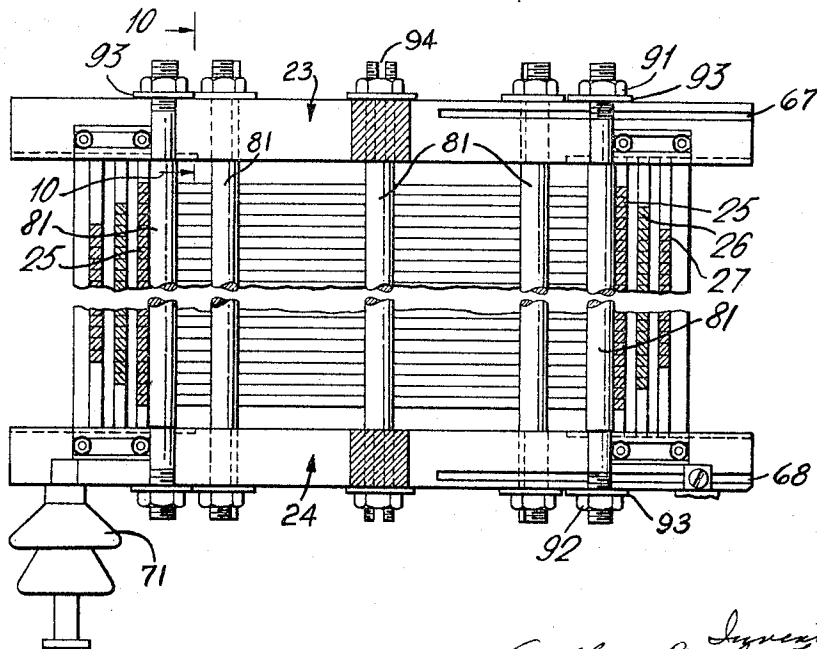


FIG. 9.



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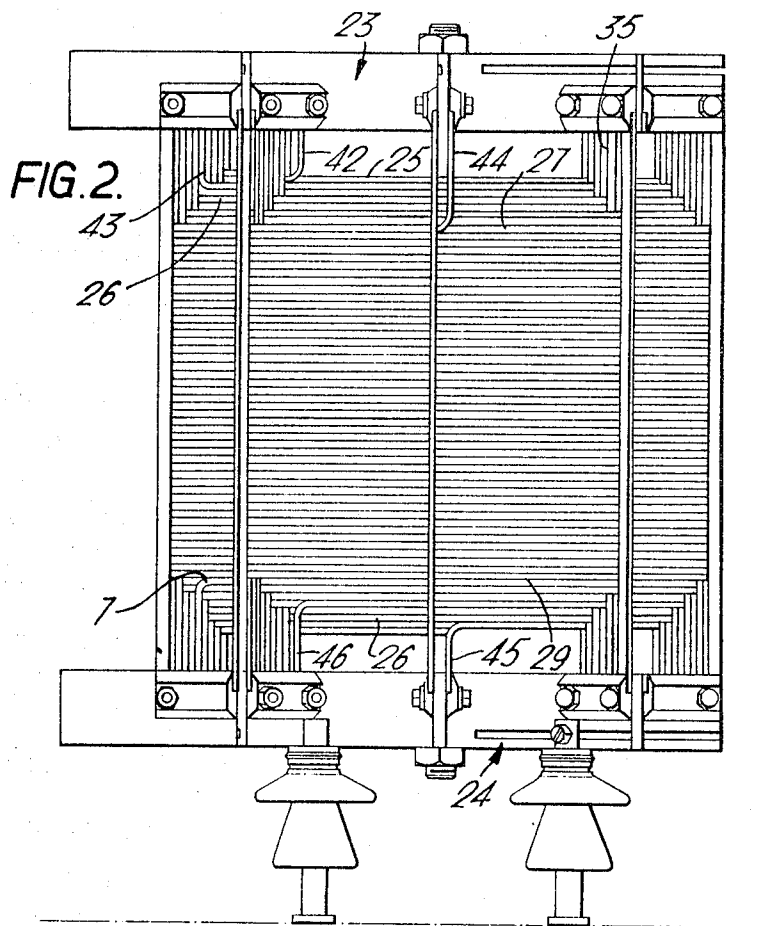
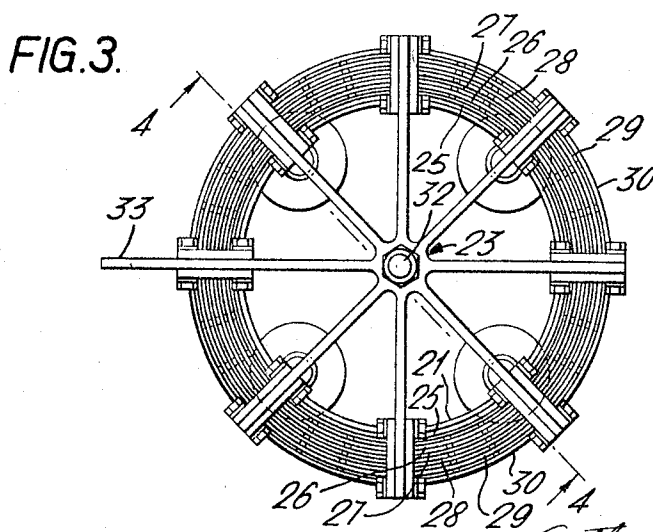
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4 Sheets-Sheet 2



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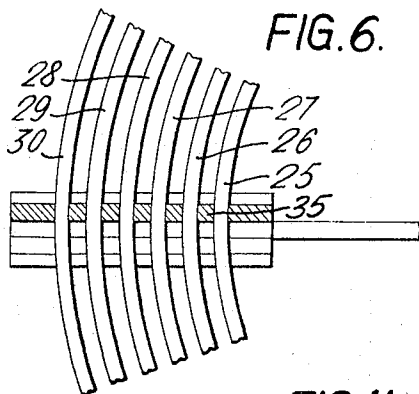
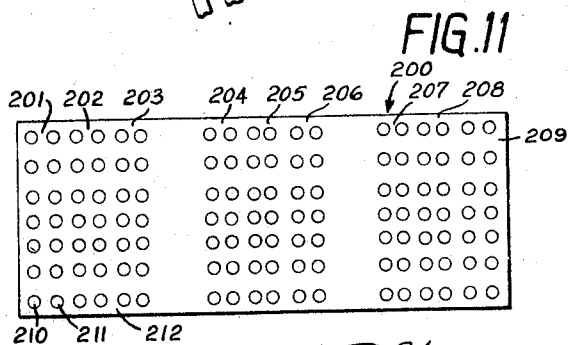
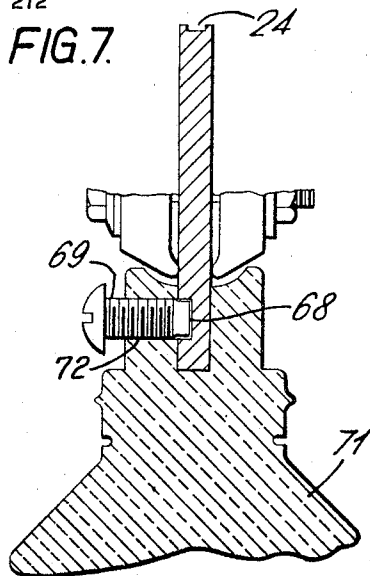
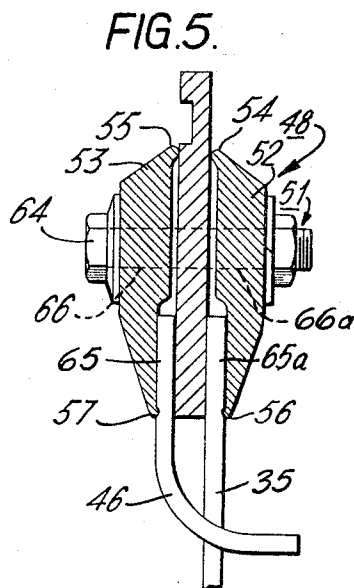
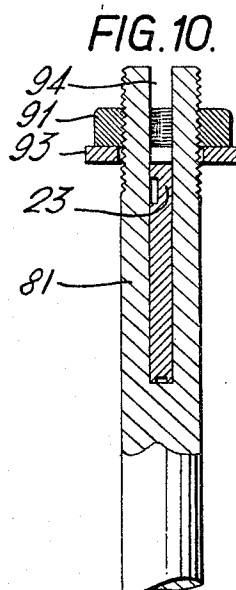
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CURRENT LIMITING REACTOR

Filed May 24, 1963

4 Sheets-Sheet 4



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3,264,590

CURRENT LIMITING REACTOR

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Filed May 24, 1963, Ser. No. 282,937

Claims priority, application Great Britain, May 29, 1962,
20,614/62

11 Claims. (Cl. 336—60)

The present invention relates to electrical inductive devices having a plurality of coaxially disposed coils electrically connected in parallel. Each coil consists of a single conductor having a single turn per axial pitch.

The coil construction is applicable to coils, transformers, wave traps, reactors or the like. The description herein will however be limited to current limiting reactors and wave traps in electrical power transmission systems.

It is common practice in prior electrical devices to provide plural, parallel, current-sharing wires, rather than a single wire, to constitute a single conductor. By providing plural wires, objectionable losses and heating effects due to eddy currents and I^2R losses are minimized. Also, the extremely large diameter necessary for single strand wires is not mechanically feasible.

In the inductor art, current sharing between the various plural, parallel conductors has generally been accomplished by a technique known as transposition. In transposition of windings, the individual strands or conductors must be maintained at the same average diameter to insure equal current distribution between the various conductors. Otherwise, the A.C. impedance of one strand is considerably less than that of the others and most of the current will flow through this strand, causing excessive heating thereof and possible overload, leading to reactor malfunction. This is accomplished by changing the diameter of each winding as it assumes a different axial position, thus necessitating substantially right angle bends in the strands in both the radial and axial directions. Right angle bends, however, are undesirable because they are time consuming to fabricate and result in very bulky mechanical configurations for substantial currents. Because of the radially extending wires necessary in transposed conductors and their mechanical interference with the axial turns, a great number of transposed conductors cannot be utilized in prior art reactors. Consequently, large current capacity inductors require a small number of relatively large diameter wires. However, large diameter wires are undesirable because of the substantial power losses therein and the difficulty in handling attendant therewith.

Fabrication of reactors having transposed windings requires the mechanically complex operation of simultaneously winding and transposing all of the conductors about a common axis. The process of transposing constitutes the formation of a rotation, or intertwining, of the conductors about one another so as to produce the desired effective electrical equality between them. It clearly follows that all of the conductors must be handled simultaneously to achieve these transposition configurations throughout the winding. This process is difficult to perform and demands much manual labor on the part of skilled operators.

It is thus seen that prior art inductors employing transposed conductors are difficult to design mechanically and electrically because of their involved geometric configuration and are not easily manufactured.

In addition, conductor diameter is generally the last parameter determined in the design of inductors with transposed conductors. In consequence, conductors of non-standard size, which must be especially manufac-

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tured at great cost are usually employed in order to achieve the necessary balanced current distribution.

It is an object of the present invention to provide a coil and method of manufacturing coils in which the prior requirement for transposing of parallel conductors is completely eliminated.

It is another object of the present invention to provide a reactor coil that is designed with a minimum of mechanical and electrical effort.

It is a further object of the present invention to provide a current limiting reactor capable of large current capacity and having a plurality of parallel conductors wherein the current in each conductor is relatively small compared with total reactor current to thereby minimize eddy current and I^2R power losses.

It is a further object of the present invention to provide a new and improved current limiting reactor wherein standard cables are utilizable for the conductors in virtually all desired configurations and wherein the various conductors are connected in parallel between a pair of reactor terminals and the induced E.M.F. in each of the plural coils is substantially equal so excessive current is not drawn by any of the coils.

It is an additional object of the present invention to provide a current limiting reactor wherein a plurality of parallel solenoidal coils are employed for the reactive element and the E.M.F. across all coils is maintained substantially equal by merely designing the number of turns in the coils to the proper value.

It is still a further object of the present invention to provide a new and improved reactor coil which occupies minimum space and is not bulky or difficult to manipulate in manufacture.

Yet another object is to provide a new and improved reactor which is easily fabricated and lends itself to automatic construction techniques and methods.

The present invention contemplates the solution of these and other objects by utilizing a plurality of helical coaxially disposed coils, said coaxial coils being connected in parallel and having relative lengths and cross sectional areas such that the induced E.M.F. across each coil is substantially equal. Thereby, the current through one coil does not become excessive and the unit is not subject to burn-out. The coils connected in parallel are wound concentrically about a common axis so there is a single turn per axial pitch.

According to the present invention, the solenoidal coils are wound to satisfy the simultaneous equations governed by the formula:

$$\sum_{r=1}^p M_{rs} n_r n_s i_r = E$$

where

$r=1, 2, 3 \dots p$;

$s=1, 2, 3 \dots p$;

M_{rs} —the specific mutual reactance between the r th and s th coil in which "specific" means the mutual reactance that would exist if each coil consisted of only one effective turn, but is otherwise physically unchanged;

n_r —the number of turns or windings in coil r ;

n_s —the number of turns or windings in coil s ;

i_r —the designed current in coil r , which is preselected;

p —the total number of parallel coils in the reactor; and

E —the designed voltage drop across the reactor with the coil parameters selected so that the current distribution between the various coils is compatible with the heat dissipation capabilities of the coils.

By this equation, the mutual and self-inductance of each coil may be easily computed by hand or computer techniques since the geometric configuration of each coil is extremely regular. When utilizing this design formula,

it is possible to preselect the particular cross sectional area of each conductor, the number of coils employed, and the current in each coil maintaining the sum of all of the currents equal to the rated total current of the reactor unit.) After these quantities are preselected, it is then necessary only to determine the winding pitch and diameter of each coil. Since conductor size is predetermined, it should be apparent that standard size conductors may be utilized in the present invention, thus obviating an important contribution to the cost of prior art reactors.

For many designs of the reactor, it is necessary for the different coils to be terminated at different points around the periphery of the common axis. To connect the coils together in parallel relationship and to the external circuit, a connector having a plurality of spider arms extending radially from the common coil axis is provided at each end of the coil structure. The end of the coil is connected to the arm to which it is closest by conductors extending parallel with the axis of the coil.

The coils are windable either on themselves or spaced from each other as determined by the presence or absence of insulation therein. The spacing of adjacent coils may be radial, axial, or both. It is generally preferable, however, for the various coils to be radially spaced from each other to permit maximum cooling. Otherwise, temperature rise as large currents are supplied to the reactor becomes excessive.

In one embodiment of the invention, the entire apparatus is secured together by the oppositely located spider arms and an insulated rod or plurality of insulated rods extending between the spiders. In this embodiment, the windings of the coils are located about an insulated sleeve having a plurality of ventilating holes which permit circulation through the inductor structure of air or a suitable insulating, coolant gas or liquid. In other embodiment of the present invention, the coils are secured in place by a plurality of insulating binding posts, extending between the two spiders about the interior periphery of the coil construction.

With the present invention, it is not necessary for the conductors to be of the same dimensions, nor it is necessary for them to carry the same current densities. In fact, it is frequently not desirable for all of them to have identical current densities because interior conductors possess an inherent tendency to increase in temperature to a greater extent than those at the exterior, due to their more confined heat-dissipating environment. Accordingly, it is desirable for the interiorly located conductors to carry smaller current densities than the outer conductors to enable them to generate power losses consistent with their thermal capacities. In the present invention, the conductor currents may be preselected so as to best suit their thermal capacities in each particular location, which results in an appreciable saving of conductor material, otherwise unobtainable with transposed windings. With the present invention, the conductor currents may be selected in this manner while maintaining the induced E.M.F. in the parallel coils substantially equal.

Accordingly, it is yet another object of the present invention to provide a new and improved current limiting reactor wherein cooling of the reactor coils is promoted since the various parallel connected coils are not of the same cross sectional area but have cross sections such that the outer coils carry greater current than the inner coils while still maintaining the induced E.M.F. in the coils substantially equal.

Because the coils are substantially cylindrical in shape, each comprising a single layer helix, and because there are no interfering transpositions of conductors required between them, they may be wound at high speed in a continuous operation. This operation is carried out by winding the convolutions of the coils one after another. Since this procedure is not possible with transposed windings where all of the conductors must be simultaneously and intricately intertwined during fabrication, the manu-

facturing process of the present invention is highly advantageous in that it lends itself to facile and complete or semi-automatic reactor unit fabrication.

The invention is illustrated by way of example in the accompanying drawings, wherein:

FIGURE 1 is a perspective view of a current limiting reactor constructed in accordance with the present invention;

FIGURE 2 is a side elevational view of the reactor of FIGURE 1;

FIGURE 3 is a top plan view of the reactor of FIGURE 1;

FIGURE 4 is a fragmentary sectional view taken through the lines 4—4 of FIGURE 3;

FIGURE 5 is a side view of the clamping structure illustrated in FIGURE 4 wherein the clamp is shown as being taken along the lines 5—5;

FIGURE 6 is a fragmentary sectional view of the parallel spaced conductors taken along the lines 6—6 of FIGURE 4;

FIGURE 7 is an illustration of the insulating feet as secured to the reactor spider arms;

FIGURE 8 is a plan view of another embodiment of the present invention;

FIGURE 9 is a side fragmentary sectional view of the embodiment of FIGURE 8;

FIGURE 10 is a sectional view taken along lines 10—10 of FIGURE 9; and

FIGURE 11 is a partial sectional view of a wave trap.

Referring now to the drawings, shown in FIGURE 1 is a current limiting reactor. The air core reactor consists of a central apertured sleeve 21, electrically conductive spiders 23 and 24 at opposite ends thereof, and a plurality of concentrically disposed coils 25—30 (see also FIGS. 3 and 4). Cylindrical sleeve 21 includes a plurality of substantially circular apertures 22 in the walls thereof. Apertures 22 permit the flow of air or some insulating coolant, such as freon gas, to circulate throughout the reactor to maintain the temperature thereof at a reasonable level.

Spiders 23 and 24 include a plurality of radially extending members (in the illustrated embodiments, eight in number), for effecting connections between the ends of the coils. These coils are usually of different lengths and hence terminate at various peripheral locations. The coils, 25 to 30, inclusive are concentric about a common axis along which insulating rod 32 extends. Rod 32 compresses spiders 23 and 24 toward each other to provide mechanical stability for the entire structure. Arms 33 and 34 of spiders 23 and 24, respectively, extend radially to a greater extent from rod 32 than the other arms of spiders 23 and 24 to establish connections between the reactor and the electrical circuitry of a distribution system. In this manner, all of the reactor except the extending portions of arms 33 and 34 may be completely enclosed in a sealed casing to permit circulation of a coolant around the coils. Coils 25—30 are concentrically wound about a common axis whereat is located rod 32 and are radially separated from each other by a plurality of insulating spacers 35.

As best seen in FIGURES 2, 3 and 4, each of the coils 25—30 is a single strand coil and there is only one turn of conductor per axial pitch. Thus, as illustrated in FIGURES 3 and 4, coil 25 includes but a single strand or conductor extending in a direction about the axis of rod 32 and at a substantially constant radial distance therefrom. This arrangement is maintained throughout a complete pitch of each winding and may be referred to as a helical winding. As best illustrated in FIGURE 4, the conductor in coil 25 does not extend parallel to spiders 23 and 24 but is inclined with respect thereto by an amount commensurate with winding pitch.

The windings 25—30 are coated with a suitable insulating material, such as varnish, enamel or the like so they may be wound on each other. However, it is usually de-

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sirable to space the individual coils 25-30 from each other by insulating spacers 35 to promote cooling the interior portions of each coil. Insulating spacers 35 are spaced from about the circumference of sleeve 21 between coils 25-30 to coincide with the position of the radially extending arms of spiders 23 and 24 which are in alignment. As best illustrated in FIGURE 6 there are a plurality of such elongated spacers 35 extending between each of the various coils 25-30. The insulating spacers 35 extend between the spiders 23 and 24 and maintain the radial position of each of the windings 25-30 substantially constant and provide space for air or coolant circulation therebetween. Radial spacing between the various coils 25-30 of the reactor is achieved by proper selection of the number of spacers. The width or number of the insulating spacers is varied to accommodate different radial spacings between adjacent coils.

As noted particularly from FIGURE 4 and from the respective drawings of FIGURE 1, each of the coils 25-30, which are of the barrel or solenoidal type has a different length in order to achieve the necessary balanced E.M.F. relationship necessary in coils connected in parallel.

As illustrated in FIGURE 2, the winding of innermost coil 25 terminates at a different peripheral point than the winding of its adjacent coil 26 which also terminates at a still different point than that of its outwardly adjacent winding 27. In order to connect these windings and all of the other coils of the reactor in parallel, conductors 42, 43 and 44 extend in the same direction as the axis of the coils between the terminations of coils 25, 26 and 27, respectively (the other terminations not being illustrated) and the radially extending arms of spiders 23. Similarly, conductors 45, 46 and 47 connect the other end of coils 25, 26 and 27, respectively, to appropriate arms of the opposite spider 24. It is important that conductors 42 to 47 extend substantially parallel to the common axis of all of the coils 25-30 so they will have minimum effect on the induced E.M.F. in each coil. By maintaining the connecting conductors 42-47 substantially parallel to appropriate arms of the axis of coils 25-30, i.e., substantially perpendicular to the windings of the coils (no induced E.M.F. in the various connecting conductors results to adversely affect the voltage across the reactor terminals).

The conductors are connected to the spiders by the clamping structure 48 illustrated in FIGURE 5. Each clamp 48 mounted on the arms of spiders 23 and 24 serves the dual purpose of maintaining spacers 35 in place and of effecting electrical connections between the coils and the arms of the respectively one of spiders 23 and 24. Each clamp is secured to its respective spider arm by a pair of nut-bolt assemblies 49 and 51 (see FIGS. 1 and 5). Clamp 48 comprises a pair of insulating bars 52 and 53 substantially rectangular in cross-section. The insulators 52 and 53 are disposed on opposite sides of the spider arm to which it is secured and have projections 54 and 55 along one edge thereof abutting the spider arm. The projections 54 and 55, located at one edge of insulators 52 and 53, respectively, engage opposite sidewalls of the spider arms with which it is associated. Claws 56 and 57, located on the other edge of insulators 52 and 53, respectively, engage suitable slots in each of insulating spacers 35, extending from the arm of one spider to an arm of the other spider and terminal winding, terminal 46, which is the terminal end of a coil.

Recesses 65, 65a are provided at the end of insulating members 52 and 53 in proximity to claws 56 and 57, respectively, so that the insulating spacer 35 and winding terminal 46 fit in the grooves formed between the insulators 52 and 53 and the spider arm. Insulating members 52 and 53, as well as the spider, are provided with bores 66 through which a bolt 64 extends for securing the insulators to the spider arm.

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The arms of spiders 23 and 24 are provided with grooves 67 and 68 for receiving set screws 69 to maintain insulating feet 71 in place, as illustrated in FIGURES 4 and 7. A threaded bore 72 is provided in one side of foot 71 perpendicular to the wide face of spider arm 24, as illustrated in FIGURE 7, for securing the set screw 69 therein, whereby the screw extends into the groove 68. When employing the reactor structure in a vertical position as illustrated, it is necessary to employ grooves only in the lower spider arms. However, grooves are provided in both spider arms 23 and 24, respectively, on the top and bottom of the reactor for uniformity of spider fabrication and for the possibility of supporting the reactor in other positions. When the reactor is positioned so its axis is in the horizontal plane, supporting insulators 71 are positioned perpendicular to the common axis of coils 25-30 rather than parallel thereto as illustrated. In such an arrangement, it is necessary to employ the grooves of both spiders 23 and 24 for securing the support insulators 71 therein. The number of supporting insulators 71 necessary is dependent upon their relative size to the total reactor structure. The radially extending grooves 67 and 68 on the spider arms are provided for variably positioning the feet 71 to maintain mechanical balance for the reactor.

When designing the reactor of the present invention, the windings in each coil must be arranged to satisfy the simultaneous equations governed by the formula:

$$\sum_{r=1}^p M_{rs} n_r n_s i_r = E$$

where

p = the number of coils in the reactor;

$r = 1, 2, 3 \dots p$;

$s = 1, 2, 3 \dots p$;

(r and s may or may not be equal)

n_r and n_s = the number of turns in coils r and s , respectively;

M_{rs} = equals the specific mutual reactance between the r th and the s th coil, in which "specific" means the mutual reactance that would exist if each coil consists of only one effective turn, but is otherwise physically unchanged;

i_r = current designed to flow through coils r which is pre-selected; and

E = the designed voltage drop across the reactor with the coil parameters selected so that the current distribution between the various coils is compatible with the heat dissipation capabilities of the coils.

Since each coil is connected in parallel, E is, of course, the same throughout the design equations. In the reactor design, initially, an educated guess as to the number of conductors and the size thereof is made. The conductor is preferably designed to be of standard size and low current rating to minimize losses. This is desirable because it does not necessitate manufacture of special conductors for fabrication of the reactor windings. Conductor size, of course, determines maximum current in a particular coil which governs maximum temperature increase of the reactor from no load to full load.

Of course, the diameter of each coil must be greater than the interior coil to which it is adjacent by an amount greater than the adjacent conductor diameter plus insulation. It is preferable, moreover, to design coil diameter slightly greater than this minimum quantity to permit coolant circulation. Axial winding pitch obviously cannot be smaller than the width of the conductor plus insulation thickness thereon which comprises the particular coil. The axial pitch can exceed this minimum value depending upon the number of turns of conductor in the coil and the overall length of such coil thus obviating the necessity for insulated conductors when the coils are spaced apart both radially and axially to an extent sufficient to prevent electrical leakage therebetween.

After determining the size of each conductor, which

ascertains its current, each coil diameter and each winding pitch, the number of windings in each coil is computed from the equation by solving for mutual and self reactance. This may be accomplished by manual or automatic computation methods.

For many applications, it is desirable for the currents flowing through interior coils 25, 26 and 27 to be less than that flowing through exterior coils 28 and 29 because of the ability to cool the greater exposed surface area exterior coils more readily than the interior ones. The criteria in designing the number of coils and the current through each coil is that the sum of the current through all of the parallel connected coils be equal to the designed maximum current of the reactor unit and that the temperature rise be within the designed limits.

If it is desired to provide a 300 volt reactor having a 600 ampere rating at 60 cycles and an 80° C. temperature rise from no load to full load, continuous operation, a reactor is fabricated having seven concentric coaxial cylindrical coils connected in parallel. The four most interior coils are wound from a 1/4" x 3/16" conductor while the three most exteriorly located coils are wound with a 1/4" x 1/4" conductor. With this size conductors, the four inner coils carry 80 amps each, while the outer three coils carry 93 1/3 amps each.

The winding pitch of the four interiorly located coils is 7/32"; that is, in coil 25 the distance between the upper edge 61 of winding 73 (FIGURE 4), is separated from the upper edge 74 of winding 75, of the next adjacent turn of conductor in the winding of the same coil, by a distance of 7/32" where points 61 and 73 lie in a plane parallel to the common axis of coils 25-30. The four outer coils have a winding pitch of 9/32". It should be noted that in the example above, the winding pitch is 1/32" greater for both the inner four and outer three conductors than the conductor in the axial direction of the coils. Since coil windings are wound on each other, this 1/32" is merely indicative of the 1/64" layer of insulation on the strands. Consequently, the winding pitch in many cases is determined when conductor size is designed.

In the design described supra, coil diameter and number of coil turns are specifically designated in the table below:

Coil No.	Inside Diameter, Inches	No. of Turns
1 (interior-most) -----	16	100
2 -----	16 3/4	98.3
3 -----	17 1/4	86.4
4 -----	18 3/4	84.2
5 -----	20 1/4	71.7
6 -----	21	70.9
7 (exterior-most) -----	21 3/4	69.5

As pointed out supra, the frictional number of turns is achieved by extending connecting wires to the spider arms, such wires being parallel to the axis of the coils.

It is generally desirable when manufacturing the reactor as will appear from the next example to be described to wind the coils on each other in an axial direction because of the ease with which this may be accomplished compared to the difficulty in providing axial spacing between single turn layers. Accordingly, winding pitch is generally determined by selection of conductor size and is not usually a variable in determining the mutual and self-inductance of the coils.

Referring now to FIGURES 8-10 of the drawings, another embodiment of the present invention is disclosed. The reactor of FIGURES 8-10 is exactly the same electrically as that of FIGURES 1-7 and incorporates most of the features of the previously discussed reactor. However, the reactor of FIGURES 8-10 employs a plurality of insulating tie-rods 81, extending from the radially extending arms of spider 23 to corresponding arms of

spider 24. These rods are located interiorly of the innermost coils 25 and serve the same purpose as insulating sleeve 21 in the previously described embodiment but have the added advantage of permitting increased contact of a coolant gas or fluid with the most interior reactor winding 25.

The rods 81 are threaded at each end and clamp the spiders 23 and 24 together by compressional forces exerted by nuts 91 and 92, respectively, located at opposed ends of the tie-rods 81. A rubber washer 93 is provided, if desired, between each nut and its respective spider 23 or 24 for transmitting the compressional force exerted by nuts 91, 92 to the spiders 23 and 24.

A longitudinal slot 94 is provided in each insulating tie-rod 81 to permit the arms of the respective spiders to be inserted therein. The interior coil element 25 may be wound directly onto the tie-rods 81 such that the latter supports the coil.

Spacers are provided between the adjacent coils in substantially the same manner as for the previously described embodiment and suitable spacers retaining the coils in radial spaced relation are present. Likewise, insulating feet are located in the spider 24 and are radially adjustable for a particular mechanical spider configuration. The coil element terminations are connected in substantially the same manner to spiders 23 and 24 as in the embodiment of FIGURES 1-7.

In manufacturing the reactors of both embodiments the coils are successively wound one on another. In the embodiment of FIGURES 1-7, the most interior coil 25 is first completely wound on sleeve 21 with insulating clamps 52 and 53 slightly removed from their final position. A plurality of insulating spacers 35 are then placed in contact with the exterior surface of coil 25 in a circumferential spaced relationship. The spacers 35 are initially secured to the body by glue or some other bond which is not necessarily permanent. The second coil 26 is then wound concentrically with coil 25 on spacers 35. A further group of spacers are then placed on the exterior surface of coils 25. This operation is continued until the desired number of coils has been wound. Clamps 52 and 53 are then tightened with the spacer and coil terminations respectively engaging claws 56 and 57. In the embodiment of FIGURES 8-10, the same procedure is followed except that the first coil 25 is wound on the rods 81. FIGURE 8 illustrates three coils 25, 26 and 27 mound in concentric relationship.

The above described device may be used as a line wave trap wherein the power transmission lines are used for communication purposes. In this instance, the entire assembly may be line carried and accordingly, weight is an important consideration. In this use the post insulators 71 may be omitted. Furthermore, in this use, each coil may consist of two conductors tightly wound onto one another to form a layer. Several such layers coaxially spaced may be used to form an air core reactor. The spacing between the coils effectively provides an annular air duct extending axially the length of the coils. FIGURE 11 is a partial sectional elevational view illustrating a reactor 200 constructed in accordance with the present invention. The reactor 200 consists of concentric coils 201 to 209 each comprising two side by side conductors 210 and 211. Coils 201 to 203 are tightly wound one upon the other and form a layer 212 which is axially spaced from a layer 213 composed of coils 204 to 206 which is spaced from a layer 214 consisting of coils 207, 208 and 209. A number of such layers may be used depending upon the required rating of the trap. If desired the coils may be electrically paralleled with a condenser to provide a tuned trap. The conductors are insulated, e.g. varnished or the like insulated coating applied directly on the electrically conductive wire.

The following is a further typical design of a device for use as a wave trap or current limiting reactor constructed in accordance with the present invention:

	Winding	Conductor	Turns	Effective Winding Length, inches	Mean Diameter, inches	Current Density, Amps./in. ²	Conductor Weight, lbs.
$\frac{1}{2}$ " AXIAL COOLING DUCT							
A.-----	1	2 wide—6 A.W.G.-----	68.27	23.62	27.18	1,200	25.7
	2	-----do-----	66.13	22.88	27.48	1,200	25.2
	3	-----do-----	64.26	22.23	27.79	1,200	24.7
$\frac{1}{2}$ " AXIAL COOLING DUCT							
B.-----	4	2 wide—5 A.W.G.-----	59.08	22.79	29.16	1,100	30.1
	5	-----do-----	57.49	22.18	29.50	1,100	29.6
	6	-----do-----	56.10	21.64	29.84	1,100	29.3
$\frac{1}{2}$ " AXIAL COOLING DUCT							
C.-----	7	2 wide—4 A.W.G.-----	52.85	22.76	31.26	1,000	36.4
	8	-----do-----	51.63	22.23	31.64	1,000	39.0
	9	-----do-----	50.56	21.77	32.02	1,000	35.7
$\frac{1}{2}$ " AXIAL COOLING DUCT							
D.-----	10	2 wide—3 A.W.G.-----	48.73	23.43	33.48	1,000	45.3
	11	-----do-----	47.79	22.98	33.91	1,000	45.0
	12	-----do-----	47.02	22.61	34.33	1,000	44.8
$\frac{1}{2}$ " AXIAL COOLING DUCT							
E.-----	13	2 wide—3 A.W.G.-----	44.70	21.50	35.82	1,000	44.5
	14	-----do-----	44.14	21.22	36.24	1,000	44.5
	15	-----do-----	43.65	21.00	36.67	1,000	44.4
$\frac{1}{2}$ " AXIAL COOLING DUCT							
F.-----	16	2 wide—3 A.W.G.-----	42.62	20.53	38.15	1,100	45.3
	17	-----do-----	42.56	20.46	38.58	1,100	45.6
	18	-----do-----	42.55	20.45	39.00	1,100	46.1
$\frac{1}{2}$ " AXIAL COOLING DUCT							
G.-----	19	2 wide—3 A.W.G.-----	42.72	20.56	40.49	1,200	47.9
	20	-----do-----	42.89	20.62	40.91	1,200	48.8
	21	-----do-----	43.10	20.74	41.34	1,200	49.6

In the table on the foregoing pages, the letters A to G, respectively, each refers to the layer which consists of three windings. Layer A, for example, is equivalent to layer 212 in FIGURE 11, which consists of coils 201, 202, and 203. Layer B would be equivalent to 213 in FIGURE 11, while layer C would be equivalent to layer 214. The half-inch cooling duct referred to between each of the layers is an annular duct interrupted about the periphery of the coil by the spacers. This cooling duct extends throughout the axial length of the coils.

The above wave trap wound from aluminum wire with double glaze insulation has a rating of 1.5 millihenries and 1600 amps. The same device as a current limiting reactor has a rating of 60 cycles, .565 ohm reactance, 1600 amps voltage drop 904 volts 1447 kvar.

The mean diameters given in the table are realized by winding the wire of one winding into the groove between the wires of an adjacent winding.

While I have described and illustrated several specific embodiments of my invention, it will be clear that variations of the details of constructions which are specifically illustrated and described may be resorted to without departing from the true spirit and scope of the invention as defined in the appended claims.

I claim:

1. An air core reactor comprising a plurality of separate, inductively coupled coils, concentrically disposed about a common axis, and selected coils being radially spaced from each other by a predetermined distance, said coils each having only one turn of conductor per axial pitch so that each coil has only one layer of winding, said

winding being untransposed by another coil, each coil winding being of a predetermined length with the respective coils terminating at peripherally spaced points about said common axis, and means for electrically connecting all of said coils in parallel said means making electrical contact with said coils at said peripherally spaced points.

2. An air core reactor adapted to be serially connected in a power transmission line comprising a pair of spaced spiders including electrically conducting arms radiating therefrom, a plurality of radially spaced layers of coaxial closely coupled coils disposed between said spiders with each of said coils being electrically connected selectively to said arms, each coil comprising an exact number of single turn per axial pitch electrically insulated and untransposed windings each of predetermined length and tightly wound one upon the other, said arms electrically connecting said coils in parallel.

3. An air core reactor comprising a plurality of separate, inductively coupled insulated coils, each of said coils being concentric about a common axis and radially spaced from each other by a predetermined, fixed distance, said coils being closely coupled and untransposed with each of said coils having only one turn per axial pitch, the conductor cross sectional area of each coil, the axial pitch, number of turns and diameter of each coil being such that the induced voltage across each coil is substantially equal for a preselected ratio of currents between said coils, and a spider electrically connecting all of said coils in parallel said spider including electrically conducting arms extending therefrom with said coils

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selectively connected electrically to said arms at various peripheral locations on said coils.

4. The reactor of claim 3 wherein the mutual and self-inductances of said coils as determined by the axial pitch, diameter and the number of turns in each coil satisfied the equations:

$$\sum_{r=1}^p M_{rs} n_r n_s i_r = E$$

where

p =number of coils in the reactor;

$r=1, 2, 3 \dots p$

$s=1, 2, 3 \dots p$

(r and s may or may not be equal)

n_r and n_s =number of turns in coils r and s , respectively;

M_{rs} =specific mutual reactance between the r th and the s th coil, in which "specific" means the mutual reactance that would exist if each coil consisted of only one effective turn, but is otherwise physically unchanged;

i_r =current designed to flow through coils r , respectively; and

E =designed voltage drop across the reactor with the coil parameters selected so that the current distribution between the various coils is compatible with the heat dissipation capabilities of the coils.

5. The reactor of claim 3 wherein the number of turns in each coil is different hence necessitating termination of certain of said coils at different peripherially spaced points about said axis.

6. The reactor of claim 5 wherein said electrically conducting arms of said spider extend radially of said axis, one of said arms being disposed at each end of said coils and conductors extending parallel to the axis of said coils and connecting the ends of said coils to said arms.

7. A current limiting reactor comprising a plurality of separate, inductively coupled circular coils said coils being closely coupled and untransposed, each of said coils being concentric about a common axis, and including only one turn per axial pitch, the cross sectional area of each coil being fixed and different than the cross sectional area of others of said coils, the conductor diameter of each coil, the axial winding pitch, number of turns and diameter of each of said coils being such that the induced voltage across each coil is substantially equal for a preselected ratio of currents between said coils, and electrically conducting spider means electrically connecting all of said coils in parallel.

8. The reactor of claim 7 wherein certain of said coils

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terminate at different predetermined peripheral points about said axis, and wherein a pair of electrically conducting spiders are provided, each of said spiders having arms extending from said axis, one of said spiders being disposed at each end of said coils, and electric conductors extending parallel to said axis between each coil termination and the arms of the spider.

9. The reactor of claim 8 including an insulating sleeve having ventilating apertures, said sleeve being secured to the interior of the coil having minimum radius, the arms of said spiders engaging opposite ends of said sleeve.

10. The reactor of claim 9 including a plurality of insulating spacers extending between said spider arms and interiorly of said coils, and means for securing said spider arms to said spacers.

11. The reactor of claim 1 wherein the mutual and self-inductances of said coils as determined by the axial pitch, diameter and the number of turns in each coil satisfies the equations:

$$\sum_{r=1}^p M_{rs} n_r n_s i_r = E$$

where

p =number of coils in the reactor;

$r=1, 2, 3 \dots p$

$s=1, 2, 3 \dots p$

(r and s may or may not be equal)

n_r and n_s =number of turns in coils r and s , respectively;

M_{rs} =specific mutual reactance between the r th and the s th coil, in which "specific" means the mutual reactance that would exist if each coil consists of only one effective turn, but is otherwise physically unchanged;

i_r =current designed to flow through coils r , and

E =designed voltage drop across the reactor with the coil parameters selected so that the current distribution between the various coils is compatible with the heat dissipation capabilities of the coils.

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