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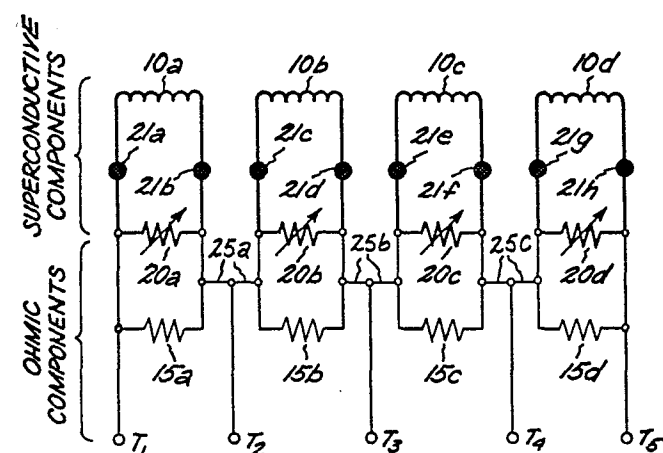
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Electric circuit for high uniformity magnetic field.

A plurality of superconductive coils are disposed in parallel with superconductive switching elements to form a plurality of superconductive current loops. The current loops are connected by bridging conductors connecting the current loops so that the superconductive coils are connected in series. The circuit is energized by establishing a main current in the series connected superconductive coils with the superconductive switches in the ohmic state. The switches are then switched to the superconductive state when the desired current level is reached. The main power supply is then removed. Adjusting currents are subsequently independently established in the superconducting loops as needed. With this circuit and method, a means is provided for establishing high uniformity magnetic fields. As an additional benefit, the present method offers significant manufacturing advantages in the testing of superconductive joints.



ELECTRIC CIRCUIT FOR HIGH UNIFORMITY MAGNETIC FIELDBackground of the Invention

The present invention is related to circuits and methods for providing high uniformity magnetic fields and is particularly relevant to the construction of magnet structures employed in nuclear magnetic resonance (NMR) imaging systems.

5 In NMR imaging systems, particularly those employed in medical diagnostic imaging, it is necessary to provide a constant magnetic field. Moreover, it is highly desirable that this magnetic field exhibit an extremely high degree of
10 spacial uniformity. This uniformity requirement typically means that there should not be more than between about 10 and 100 parts per million variation in field strength in the volume being imaged. At present, magnetic fields for NMR imaging are provided either by permanent magnets, resistive
15 magnets or magnets based on superconductor technology. Superconductive methods for providing the constant, uniform magnetic field provides two distinct advantages. Firstly, superconducting coils which form current loops carrying 1,000 amperes or more can be used to achieve high strength
20 magnetic fields, up to a strength of 1.5 Tesla or more. The strength of this field is important in that it is closely related to the signal to noise ratio found in NMR imaging systems. Secondly, superconductive coils provide a significant advantage in that once current has been
25 established in the coil or coils, it persists indefinitely. Resistive magnets in particular do not possess this advantage. Furthermore, permanent magnet systems are difficult to construct so as to possess the desired degree of magnetic field uniformity.

30 Present designs for superconductive magnets for use in NMR imaging systems typically employ a set of from about 4 to 6 superconductive coils. These coils are

typically disposed on or about a cylindrical surface and are axially aligned so as to provide a relatively uniform magnetic field within a central bore of the NMR magnet. The present approach taken to magnet design is the construction of a multiple coil set with each of the superconductive windings connected in series and carrying the same current. Thus, at present, coil geometry and coil current are considered together as the design variables for producing the desired "ideal" uniform magnetic field. For example, a four coil set is considered as a single entity. Since conventional designs require the same current in each one of the superconducting coils, the natural choice for providing this feature is to employ superconducting coils which are connected in series. However, as the result of even slight manufacturing variations from the ideal coil structure current, undesirably large variations in field uniformity can result. Prior practice has been to provide separate correcting coils to compensate for these manufacturing variations.

One of the problems associated with the construction of superconductive circuits is the fabrication of joints between superconductive wire structures. Superconductive joints have often been found to be weak links in superconducting current loops. Accordingly, the number and kind of superconductive joints can pose manufacturing problems. In particular, in the connected coil for NMR magnets discussed above, it is a fact that the failure or weakness of a superconductive joint is difficult to pinpoint during or after manufacture and testing. For example, in a typical four coil structure of prior design, there are five superconductive joints. In such an integral structure, it is impractical to test the current carrying capacity of each individual joint as it is made. A test of the complete circuit is conceivable although still inconvenient. Failure of any of the joints at this late stage entails extensive disassembly before repair can be made.

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Accordingly, it is seen that it is important to be able to construct superconductive magnet structures, particularly for NMR imaging, which exhibit a high level of spacial field uniformity and yet at the same time are easy to manufacture and test. It is also seen that it is desirable to be able to correct for inevitable variations in coil manufacturing. It is also seen that it is desirable to be able to relax coil manufacturing tolerances by providing post-manufacture correction modes.

10 Summary of the Invention

 In accordance with a preferred embodiment of the present invention an electric circuit for providing a high uniformity magnetic field comprises a plurality of superconductive coils together with a plurality of superconductive switch elements connected in parallel with the coils so as to form a number of superconductive current loops. Adjacent loops are connected by a bridging conductor so as to connect the superconducting coils in series. Each superconductive loop may also be constructed in such a way that the loop requires only a single superconductive joint. In the present invention the bridging conductors may be ohmic or superconductive with the preferable embodiment including an ohmic (for example, copper) conductor connected in parallel with a superconductive conductor with both conductors being disposed within the coolant medium. The circuit of the present invention also preferably includes a number of protective ohmic resistor elements connected in parallel with each of the superconductive coils.

 The circuit of the present invention is particularly advantageous in that it provides a method for establishing currents in each of the superconductive coils in an independent fashion so that individual adjusting currents may be supplied to each superconductive current loop separately.

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Accordingly, it is an object of the present invention to construct an electric circuit for providing a highly spacially uniform magnetic field.

It is also an object of the present invention to
5 provide a superconductive magnet circuit having a plurality of current loops which may be independently controlled.

It is a still further object of the present invention to provide a circuit having a relatively low number of superconductive joints.

10 It is yet another object of the present invention to provide a superconductive magnet circuit in which manufacturing and testing may be performed in a modular fashion.

Lastly, but limited hereto, it is an object of
15 the present invention to provide a superconductive magnet circuit which is particularly useful for NMR imaging.

Description of the Figures

The subject matter which is regarded as the invention is particularly pointed out and distinctly claimed
20 in the concluding portion of the specification. The invention, however, both as to organization and method of practice, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying
25 drawings in which:

Figure 1 is a schematic electric circuit diagram illustrating a conventional superconductive magnet circuit;

Figure 2 is a schematic diagram illustrating the circuit of the present invention.

30 Figure 3 is a schematic diagram illustrating another embodiment of the present invention.

Detailed Description of the Invention

Before considering the circuits shown in Figures 1 and 2, it is noted that, in the figures, superconductive
35 circuit elements are drawn using heavier lines than the lines drawn for ohmic elements. It is also noted that

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superconductive joints are shown as relatively large, crosshatched circles. Conventional or ohmic joints are shown as smaller, open circles. These conventions help to clarify the operation and the differences between the two circuits shown. The superconductive paths are shown as heavy lines in Figure 4. Small circles indicate resistive joints either between resistive conductors or between a resistive conductor and a superconductor. Where a resistive joint is shown joining a superconductive element, it is understood that a superconductive path exists between the superconductive elements at that point.

Figure 1 illustrates a conventional electric circuit for a superconductive magnet for NMR imaging employing four superconductive coils 10a, 10b, 10c, and 10d. These coils are connected in series, each being joined to a single other coil by a superconducting joint, such as joint 11a, 11b or 11c. Superconductive switch 20 is connected to one end of the series connected coils by means of superconductive joint 11d. Switch 20 is also connected to the other end of the series connected coils by means of second superconductive joint 11e. This completes the superconductive current loop in which the same current flows in all of the circuit elements, namely switch 20 and coils 10a-10d. Switch 20 is typically a length of superconductive material disposed in proximity to a heat source which is capable of raising the temperature of the superconductive material to a temperature above its critical value. When thermal energy is applied to the switch, switch 20 is made to exhibit a finite resistance R . The resistance of switch 20 (in its resistive state) produces further resistive (I^2R) heating of the material in switch 20. This in turn leads to rapid quenching of the current flowing in the superconductive loop.

Figure 1 also illustrates the fact that it is highly preferable to dispose ohmic resistance elements in parallel with the superconductive coils. Accordingly, ohmic

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resistor elements 15a-15d are shown connected in parallel with superconductive coils 10a-d, respectively. Resistance elements 15a-d serve a protective purpose. Under normal (superconductive) operating conditions, all of the loop current flows through the superconductive elements. These elements are maintained below the critical temperature, which is typically above 4.2°K, by immersion in a coolant such as liquid helium. The whole circuit is disposed within a cryostat to maintain the helium in the liquid state.

Since the superconductive elements exhibit zero resistance the preferable current path is the single superconductive loop shown in heavy lines in Figure 1. However, if for some reason one of the coils or joints were to become resistive the protective ohmic elements provide an alternate current path and a location for the dissipation of the electric magnetic energy stored within the corresponding superconductive coil. Since these protective devices do not have to be maintained below a critical temperature, they may be located either inside or outside the cryostat structure.

For a proper appreciation of the present invention, it is also desirable to possess an understanding of the operation of a superconductive circuit such as that shown in Figure 1. In particular, the method for establishing a current in the superconductive loop should be understood. In normal operation, superconductive switch 20 of Figure 1 is forced into the resistive state. At the same time superconductive coils 10a-10d are maintained below the critical temperature, in the superconductive state. At this point direct current power supply 30, approximating an ideal current source is connected to terminals T_1' and T_2' , as shown. The supply current is slowly increased to the desired current value which can be as much as 1,000 or 2,000 amperes. Once the design current is reached, switch 20 is cooled down to below the critical temperature, at which time, a closed superconductive current loop is therefore formed. The current from power supply 30 may then be

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reduced to zero, and power supply 30 may be removed from the circuit.

It should be noted that while both Figures 1 and 2 illustrate circuits employing four superconductive coils, any reasonable number of coils may be employed to provide the desired field homogeneity. It should also be noted that the design of Figure 1 requires $n + 1$ superconductive joints, where n is the number of superconductive coils in the circuit. In Figure 1, $n = 4$ and accordingly five superconductive joints are provided. While coils 10a-d are manufactured as closely as possible to design specifications dictated by the desired spacial homogeneity, inevitable manufacturing variations and departures from the ideal occur. The design of the circuit of Figure 1 does not permit individual adjustment of the current in the superconductive coils since the series connection dictates that the same current flows in each coil.

It is also seen in Figure 1 that the superconductive elements of the circuit comprise an integral assembly. In particular, it is seen that testing of the circuit requires the simultaneous testing of all of superconductive coils 10a-d, all of the superconductive joints 11a-e and superconductive switch 20. If unexpected quenching or field drift is perceived, it is difficult to determine which of the elements of the superconductive circuit is at fault. If a problem exists in one of the superconductive joints, the specific problem is difficult to isolate since any of the five joints could in fact be causing a problem.

The problems described above however, have been significantly mitigated by the circuit of the present invention as shown in Figure 2. In particular, the circuit elements shown in Figure 2 may be divided into two groups: ohmic components and superconductive components. It is also seen that the superconductive components are further grouped into n distinct current loops, where here $n = 4$. For

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example, the first current loop comprises superconductive coil 10a, superconductive joint 21b, superconductive switch 20a, superconductive joint 21a and the associated connecting superconductive wire. Likewise, it is seen that there are
5 three other superconductive loops present in this circuit namely the loops including coils 10b, 10c and 10d, respectively. It is also seen that in the circuit of Figure 2 there are present a total of $2n$ superconductive joints, where n is the number of coils present. A significant
10 difference between the circuit of Figure 1 and that of Figure 2 is that each coil 10a-d is connected in parallel with an associated superconductive switch, 20a-20d, respectively. While the circuit of Figure 2 has an increased number of superconductive switches, it nonetheless offers a
15 number of manufacturing, design and operational advantages, which are more particularly discussed below. The superconductive loops of Figure 2 are connected by bridging conductors 25a, 25b and 25c, as shown, so that coils 10a-d are connected in series. While bridging conductors 25a-c
20 are shown in Figure 2 as ohmic components, it is also possible to employ superconductive components for these bridging conductors. For example, bridging conductor 25a could comprise a superconductive conductor extending between superconductive joints 21b and 21c. However, the bridging
25 conductors of the present invention are preferably ohmic and positioned as shown in Figure 2. As in Figure 1, the circuit of Figure 2 also preferably includes ohmic protective resistive devices 15a-d connected in parallel with superconductive coils 10a-d, respectively. The circuit of
30 Figure 2 also preferably includes terminals T_1 , T_2 , T_3 , T_4 , and T_5 to provide independent current adjustment in the four current loops shown.

As a result of size and design constraints, the superconductive coils of the circuit of Figure 1 are usually
35 fabricated separately, assembled and joined by means of special superconductive joints, as shown. As indicated

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above, this conventional approach requires $n + 1$ superconductive joints each of which must be tested simultaneously. While the circuit of Figure 2 as shown illustrates the presence of $2n$ superconductive joints, each separate
5 superconductive loop may be tested separately so that if a defect is detected, it is immediately known, with high likelihood, that the problem lies in either one or the other of the two superconductive joints in each separate loop. Furthermore, the circuit of Figure 2 is particularly
10 amenable to the construction of superconductive loops having only a single superconductive joint. For example, by forming switch 20a from the same length of superconductive wire as used to form coil 10a, it is possible to eliminate either joint 21a or 21b. In this case the circuit of Figure
15 2 possesses only n superconductive joints. Each such joint is found within a distinct, separately energizable loop. Accordingly, if a defect is found within the loop, the problem may be immediately determined to be within a single superconductive joint.

20 While the circuit of Figure 2 is adequate for carrying out the objects of the present invention and for purposes of illustration, a more preferred circuit is shown in Figure 3. Figure 3, however, illustrates only a single superconductive loop circuit, it being understood that the
25 modification indicated in Figure 3 is applicable to each of the four superconductive loops shown in Figure 2. In particular, in Figure 2 it is seen that the protective function of resistors 15a-d is at least partially defeated by the fact that switches 20a-d, respectively, are normally
30 in the superconductive state during a quench in coils 10a-d, respectively. This current would tend to be shunted through switch 20a rather than protective resistor 15a. This problem is alleviated through the use of the circuit of Figure 3 in which it is seen that coil 10x, provided with
35 center tap 18, is connected by lead 19 to a node between series connected protective resistors 16x and 17x. The

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series circuit comprising resistors 16x and 17x is in turn seen to be connected across coil 10x. This modification restores the protective function performed by resistors 15a-d in Figure 1. For correspondence with Figure 2, the symbol "x" in Figure 3 stands for the symbol "a", "b", "c" or "d" in Figure 2. Likewise, "y" stands for "a", "c", "e" or "g" and z stands for "b", "d", "f" or "h". Resistors 16x and 17x are preferably implemented by providing a center tap in a single, integrated resistor structure. As used herein and in the appended claims, however, the term "center tap" does not imply connection to the exact midpoint of the structure (coil or resistor) to which the term is applied. Furthermore, as in Figure 2, conductors which are necessarily superconductive are shown by heavier lines.

The operation of the circuit of Figure 2 is also significantly different from the operation of the circuit of Figure 1, particularly with respect to persistent current initiation. In a typical startup sequence, superconductive coils 10a-d are reduced to a temperature below their critical temperature so as to be superconductive. Switches 20a-d are placed in their resistive states and a main current power supply is connected to terminals T_1 and T_5 . As in the circuit of Figure 1, the current is slowly increased until the nominal design current is reached. At this time, switches 20a-d are switched to the superconductive state so as to establish a plurality of superconductive current loops each of which possess the same nominal current. However, depending upon the stability of the power supply and the switching time sequence for switches there may be some slight variation in the currents in the four loops. However, the modular and independent design of the present invention precludes this aspect of the circuit from posing any problems. At this point in time, the main power supply is usually disconnected from terminals T_1 and T_5 . After this, conventional measurement methods may be employed to determine the uniformity of the magnetic field.

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Calculations may then be performed to produce coil current corrections which would produce a more uniform field. The current variations are typically seen to be in the order of 100 milliamperes, rather than 1,000 amperes. Power supplies for providing these relatively small levels of adjusting currents can be controlled much more accurately than the main power supply. Accordingly, in accordance with the present invention adjusting currents are provided for coils 10a-d independently. For example, if it is determined that a small adjustment is desired for the current in coil 10b, then the main power supply is reconnected across terminals T_1 and T_5 . A correction power supply is then connected across terminals T_2 and T_3 . The current from the main supply is then returned to its previously applied value, so that the currents in the superconductive switches are then approximately zero. The switches are turned to their resistive states and the current in the adjusting power supply is adjusted to its desired value. The switches are then returned to their superconductive states. The current from all power supplies is set to zero and they are removed from the circuit. In this manner, the currents in all n of the coils may be adjusted independently. This method offers the advantage that the same main current power supply is used repeatedly. Accordingly, less stringent requirements on the accuracy of the main power supply are required. Furthermore, stability of the main current power supply is only a factor over the length of time it takes to fine tune the current in the independent loops. Typically, this is only a matter of minutes.

While the superconductive material of the present invention may comprise any material exhibiting superconductive properties, superconductors comprising niobium-titanium filaments disposed within a copper or aluminum matrix have been found to be particularly useful in the design and construction of NMR magnet coils. In the same way, liquid helium is the preferred coolant for use in

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the cryostat to maintain the superconductive material below its critical temperature.

Accordingly, it is seen that the circuit of the present invention can act to reduce or eliminate the need
5 for correction coils that are often employed in NMR imaging magnets. Furthermore, it is seen that the present invention provides an opportunity for limiting the testing requirements for the superconductive joints in a multicoil magnet. The circuit of the present invention also provides an
10 opportunity for the construction of a superconductive coil and superconductive switch from the same length of superconductive conductor. Another very significant advantage of the circuit of the present invention is that the spacial homogeneity of the magnetic field may be accurately
15 and precisely controlled by means of independently establishing correcting currents in the superconductive loops.

While the invention has been described in detail herein in accordance with certain preferred embodiments thereof, many modifications and changes therein may be
20 effected by those skilled in the art. Accordingly, it is intended by the appended claims to cover all such modifications and changes as fall within the true spirit and scope of the invention.

CLAIMS

1. An electric circuit for providing a high spacial uniformity magnetic field comprises:
 - a plurality of superconductive coils;
 - a plurality of superconductive switch elements,

5 each element being connected in parallel with one of said plurality of coils so as to form a plurality of superconductive current loops each such superconductive loop having at least one superconductive joint; and

 - a plurality of bridging conductors connecting said

10 current loops so that said superconductive coils are connected in series, said plurality of bridging conductors being one less in number than the number of superconductive coils.
2. The circuit of claim 1 in which each of said

15 superconductive current loops possesses a single superconductive joint.

3. The circuit of claim 1 in which said bridging conductors are ohmic.
4. The circuit of claim 1 further including a

20 plurality of protective ohmic resistor elements, each ohmic element being connected in parallel with one of said plurality of coils.

5. The circuit of claim 1 further including means to independently set the current in each superconductive

25 current loop.

6. The circuit of claim 1 further including a resistor having a center tap connection connected across at least one of said superconductive coils, said center tap connection of said resistor being connected to a center tap

30 on said corresponding superconductive coil.

7. A method of establishing currents in a superconductive circuit including a plurality of series

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connected superconductive coils in parallel with superconductive switches, said method comprising the steps of:

- 5 establishing a main current in said series connected superconductive coils;
- switching said superconductive switches to the superconductive state; and
- independently establishing a correcting current in at least one of said coils.

- 10 8. The method of claim 7 in which said independent current correction establishing step comprises the steps of:

- reapplying the main current;
- switching said superconductive switches to the
- 15 resistive state; independently applying correcting current to at least one of said superconductive coils; and
- switching said superconductive switches to the superconductive state.

- 20 9. A superconductive current loop comprising:
- a superconductive coil;
 - a superconductive switch in series with said superconductive coil, said superconductive switch and said superconductive coil being formed from the same length of superconductive conductor; and
 - 25 a single superconductive joint connecting said superconductive switch said superconductive coil.

FIG. 1 (PRIOR ART)

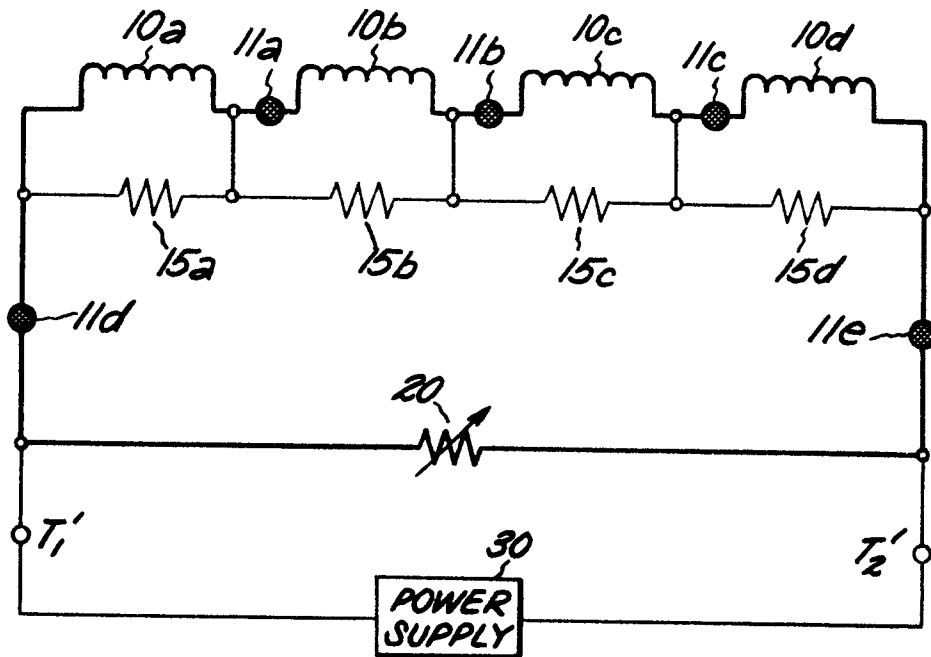


FIG. 2

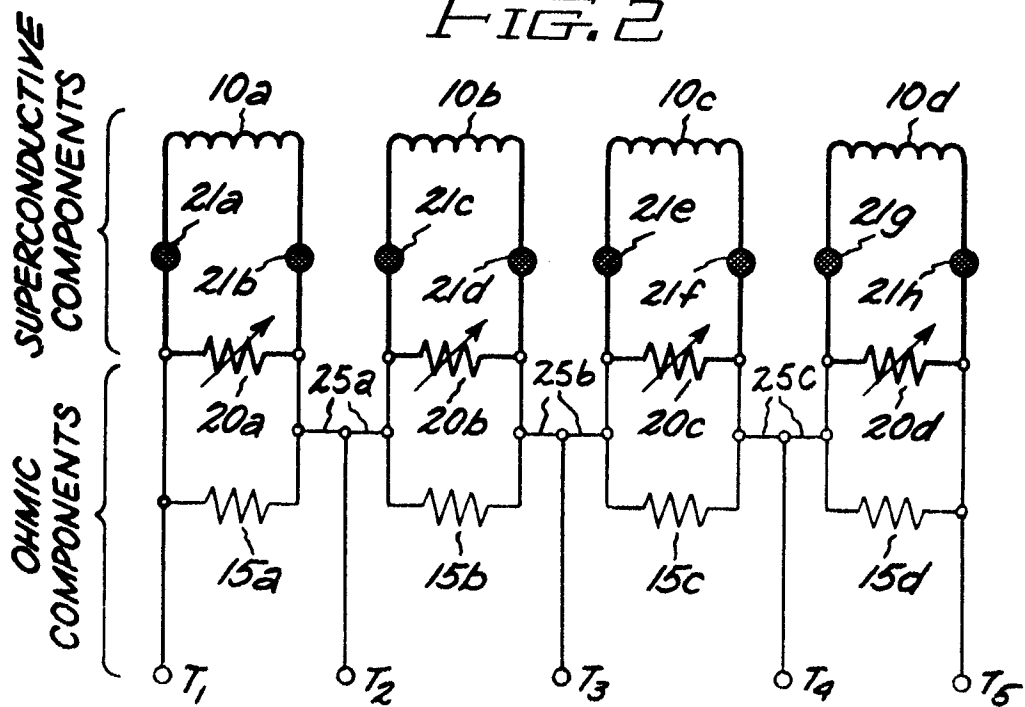
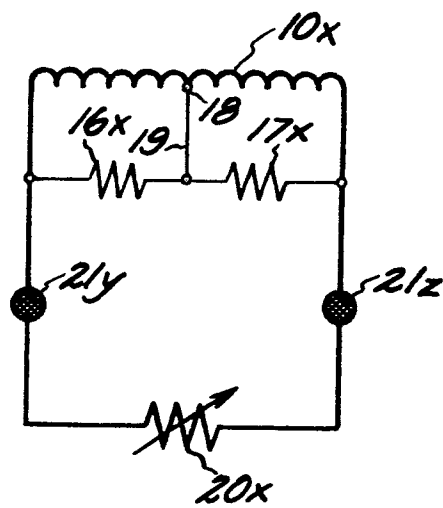


FIG. 3





DOCUMENTS CONSIDERED TO BE RELEVANT			EP 84113459.6
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
X	US - A - 3 263 133 (STEKLY) * Column 7, line 43 - column 8, line 10; fig. 3,7 *	1-5	H 01 F 7/22 H 01 L 39/16
Y	* Column 6, lines 10-41; fig. 4 --	* 6	
Y	DE - B2 - 2 153 562 (CGE) * Column 3, line 45 - column 4, line 16; fig. 1 *	6	
Y	GB - A - 1 179 740 (HITACHI) * Page 4, lines 46-101; fig. 13-15 *	1-5, 7-9	
Y	GB - A - 1 226 597 (GEC) * Page 2, line 113 - page 4, line 9; fig. 1,2 *	1,3-5	TECHNICAL FIELDS SEARCHED (Int. Cl.4)
Y	GB - A - 1 404 682 (OXFORD) * Totality *	2	A 61 B 5/00 G 01 N 24/00 H 01 C 7/00 H 01 F 5/00 H 01 F 7/00 H 01 F 36/00 H 01 L 39/00
Y	FR - A - 2 112 054 (CEA) * Claim 1; page 1, lines 3-37 *	7-9	
The present search report has been drawn up for all claims			
Place of search VIENNA		Date of completion of the search 01-03-1985	Examiner PIRKER
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			