United States Patent

[11] 3,611,032

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[21] Appl. No. **833,436**
[22] Filed **June 16, 1969**
[45] Patented **Oct. 5, 1971**
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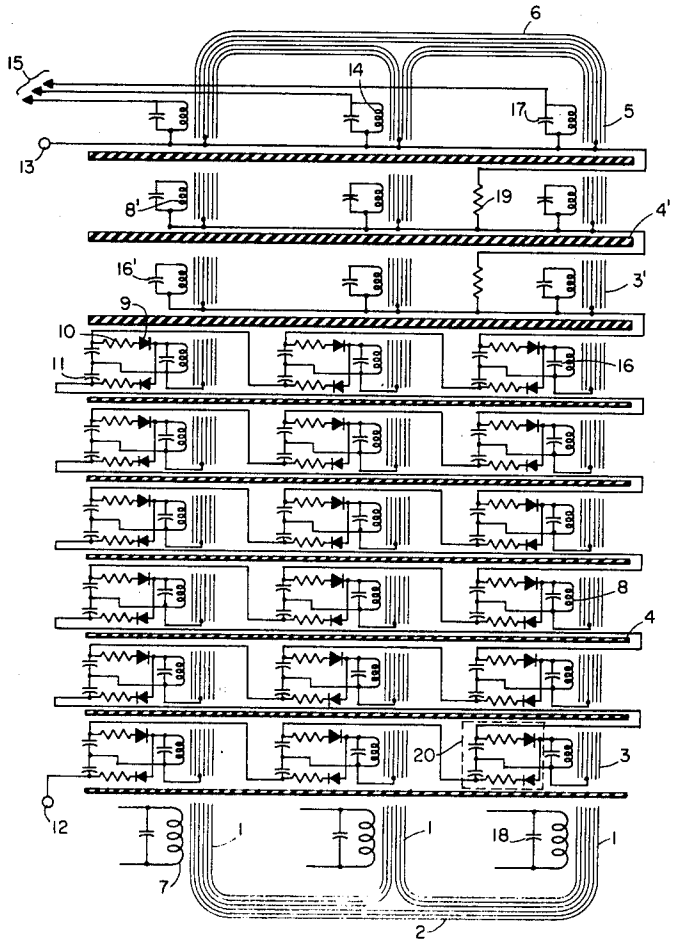
[54] **ELECTROMAGNETIC INDUCTION APPARATUS FOR HIGH-VOLTAGE POWER GENERATION**
16 Claims, 3 Drawing Figs.

[52] **U.S. Cl.** **317/14,** 336/178
[51] **Int. Cl.** **H07h 9/02**
[50] **Field of Search** 323/48; 317/50, 53, 14.3, 14.9; 336/178

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ABSTRACT: The power capability of insulating core-type transformers is greatly increased by creating additional magnetomotive force in certain secondary coils without any consequent power loss. At the same time, surge protection is provided for the primary power source without adversely affecting the auxiliary power source by using additional secondary cores with a resistive circuit isolating the high-voltage power supply from damaging high-voltage transient surges and providing artificial capacitance between the additional secondary cores and ground potential.



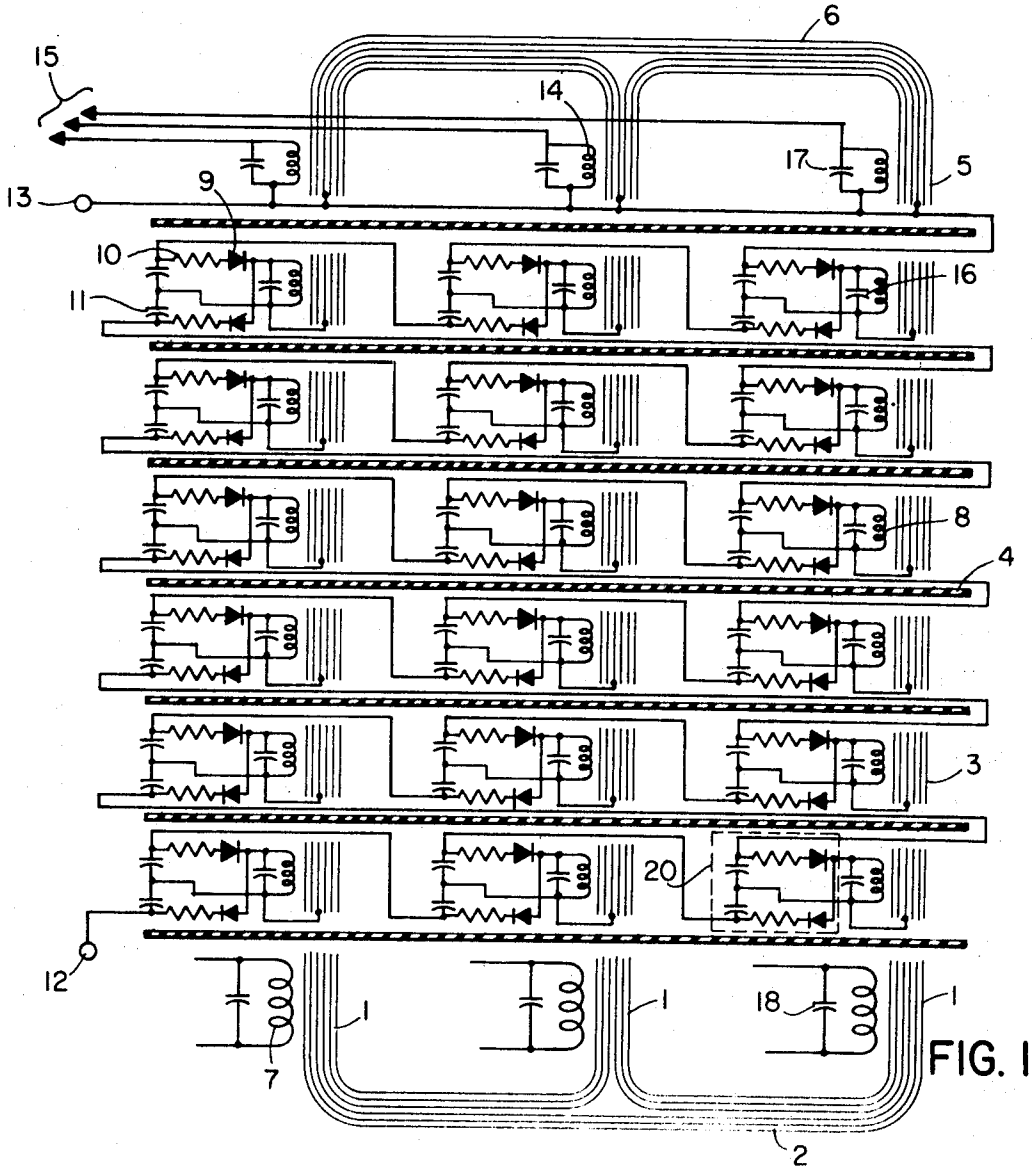


FIG. 1

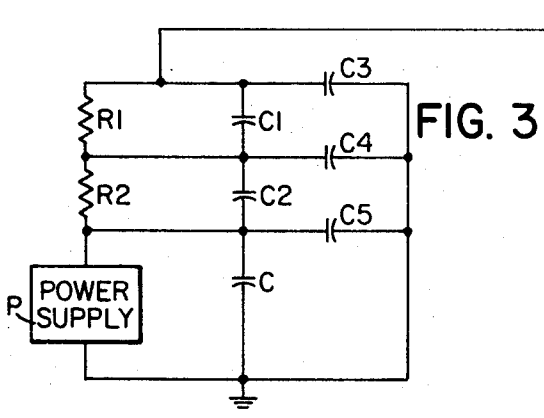


FIG. 3

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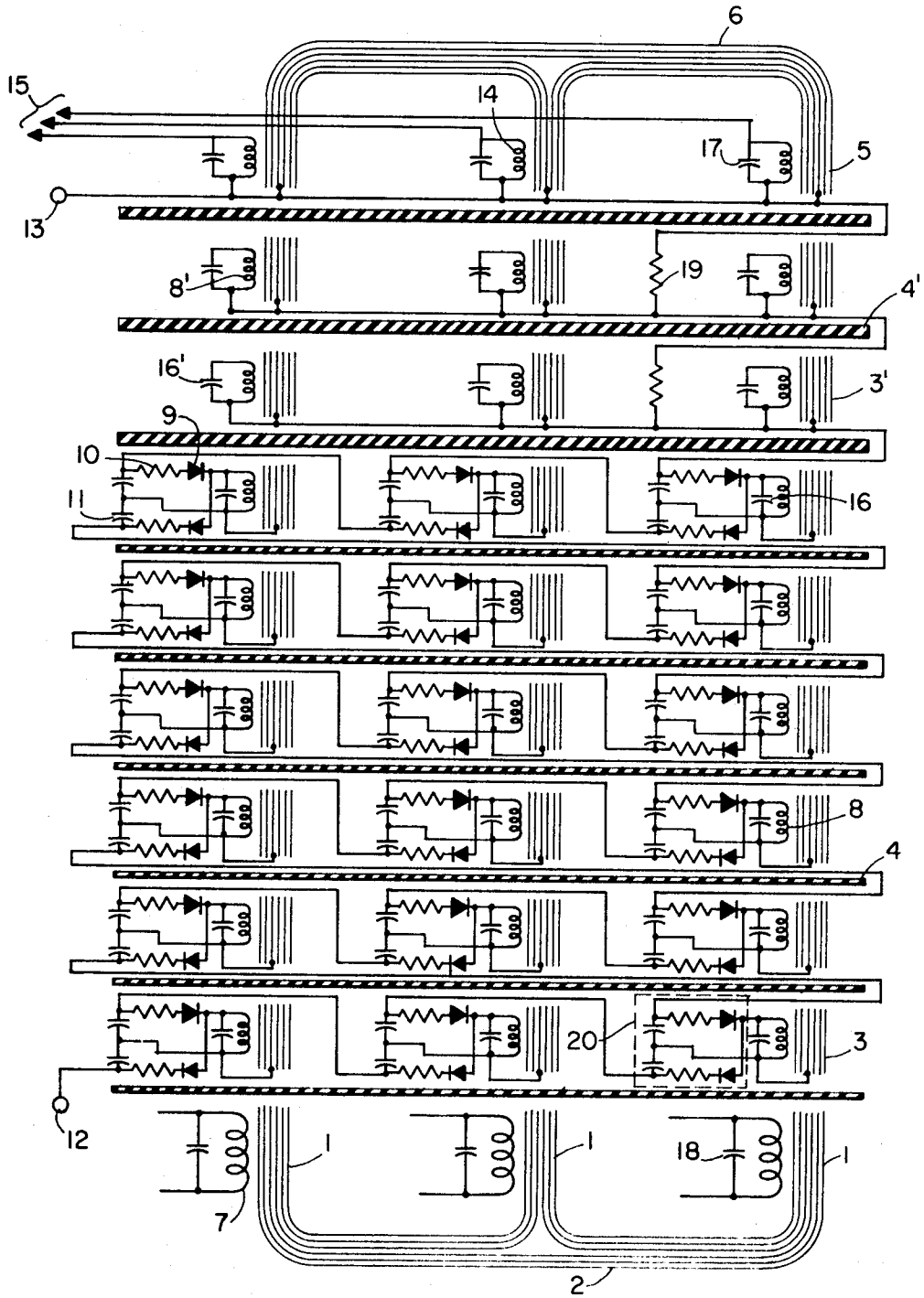


FIG. 2

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ELECTROMAGNETIC INDUCTION APPARATUS FOR HIGH-VOLTAGE POWER GENERATION

BACKGROUND OF THE INVENTION

High-voltage power supplies of the type which are the subject of this invention are used, for example, to supply the acceleration voltage to charged particle accelerators used extensively in science and industry. Typical applications of such particle accelerators include nuclear research, industrial radiation processing, X-ray generators and electron microscopes. Charged particle accelerators typically comprise a high-voltage power supply connected to an evacuated acceleration tube. The source of the charged particles is located at the high-voltage end of the acceleration tube and it requires electrical energy to energize various accessory power supplies associated with the generation and focusing of the charged particle beam. Existing techniques for supplying this auxiliary source of electrical energy include the use of isolation transformers with high-voltage insulation between the primary and secondary windings, mechanical couplings such as insulated shafts or belts which turn a generator located in the high-voltage area, and dual-function power supplies of the insulating core transformer, or other inductively coupled types, in which a single unit generates both the high acceleration voltage and the auxiliary source of electrical energy. Charged particle accelerators are subject to occasional spark breakdown between the high-voltage terminal and ground resulting in high-voltage surges which may overstress parts of the power supply with consequent component failure. These damaging voltage surges can be greatly reduced in their magnitude by the insertion of an impedance, such as a resistor, in the connecting link between the power supply and the acceleration tube. In the event of a spark in the acceleration tube, the energy associated with the resulting voltage surge is then largely dissipated across the series impedance and the power supply is protected from the surge voltage. However, surge-limiting impedances of the described type cannot be used with dual-purpose power supplies which supply auxiliary electrical energy as well as the high accelerating voltage because the voltage drop caused by the series impedance, while negligible in comparison with the high voltage, would be an unacceptably high proportion of the low auxiliary source voltage.

The conventional insulating core transformer has previously had the disadvantage of nonuniformity of the magnetic field particularly as the number of secondary cores increases. The magnetic field lines originating in the primary cores begin to take a leakage path rather than through the intended magnetic circuit thereby decreasing the total power output that would otherwise be available if all the magnetic flux could be controlled.

SUMMARY OF THE INVENTION

This invention relates to the prevention of damage to high-voltage power supplies when subjected to voltage surges such as may occur when sparking takes place in an externally connected load. In particular, this invention is concerned with the prevention of surge damage to power supplies which are used for the dual purpose of simultaneously generating a high voltage and an auxiliary lower voltage, this lower voltage being insulated from ground by the full value of the high voltage. Included in the scope of this invention is a technique whereby the power capability of transformers of the insulating core type can be greatly increased in comparison with the ratings of such transformers built by conventional methods.

It is, therefore, a general object of the present invention to provide a new and improved electromagnetic induction apparatus.

Another object of the present invention is to provide a new and improved surge protection system for power supplies of the multiplier type where energy is supplied to a plurality of cascaded voltage generators by an alternating magnetic field.

Yet another object of the present invention is to increase the power output and the efficiency of the magnetic circuit in electromagnet induction apparatus.

The invention can be used with any power supply of the voltage multiplier type where energy is supplied to a plurality of cascaded voltage generators by an alternating magnetic field. A capacitance connected in parallel to the secondary coils is used to increase the uniformity of the magnetic field distribution in an insulating core transformer thus greatly increasing the power capability of the transformer. The application of this refinement is not restricted to insulating core transformers using an integral surge-limiting impedance and auxiliary power source only, but may be used in insulating core transformers without either surge impedance or provisions for an auxiliary power source where the purpose is only to increase the power capability of the insulating core transformer.

DESCRIPTION OF THE DRAWINGS

The invention can best be understood from the following description by reference to the following drawings in which:

FIG. 1 is a schematic representation of a three-phase power supply for the production of a high-voltage DC simultaneously with a source of three-phase AC isolated from ground at the DC potential including flux equalization devices in accordance with the principles of the present invention but not including the surge-limiting impedance.

FIG. 2 is a schematic representation of a three-phase power supply for the production of a high-voltage DC simultaneously with a source of three-phase AC isolated from ground at the DC potential including surge impedance limiting circuitry with magnetic flux equalizing circuitry in accordance with the principles of the present invention.

FIG. 3 is a simplification showing the equivalent circuit of a power supply incorporating this invention in order that its method of operation when subjected to transient voltage surges may better be described.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIG. 1, a three-phase insulating core transformer power supply is shown. The magnetic circuit comprises three identical ferromagnetic primary cores **1** interconnected by a ferromagnetic return yoke **2**. A plurality of ferromagnetic secondary cores **3** are stacked on the primary cores to form three identical columns. The secondary cores **3** are insulated from one another, the primary cores and the upper return cores **5** by sheets of insulation material **4**. The magnetic circuit is completed by an upper ferromagnetic return yoke **6**. Primary coils **7** surround each primary core **1** and an alternating magnetic field is established in the elements of the magnetic circuit by supplying a three-phase alternating current to the three primary coils **7**. Each secondary core **3** is surrounded by a secondary coil **8** in which an alternating voltage is induced due to the alternating magnetic field in the secondary cores **3**. Typically this alternating voltage is rectified by a voltage doubler circuit **20** consisting of rectifiers **9**, current-limiting resistors **10** and capacitors **11**. The direct current outputs of the voltage doubler circuits **20** are connected in series so that their individual outputs add up to give a high direct voltage which appears across the output terminals **12** and **13**. If terminal **12** is at, or near, ground potential then the terminal **13** will be the high-voltage output connection to which the acceleration tube or other high-voltage load is connected. An important feature of the insulating core transformer consists of the connection of each secondary core **3** to one end of its associated secondary coil **8** thus ensuring a constant voltage gradient in each sheet of insulation. Three additional secondary coils **14** provide a source of auxiliary three-phase power at the high DC potential with respect to ground. These three coils are arranged in a Y-connection with the output terminals **15** referenced to the high-voltage DC output **13** as the three-phase system neutral connection. Capacitors **16**, **17** and **18** are associated with a flux-equalizing refinement and their function will be described later.

Insulating core transformer power supplies of the type described above have been manufactured and operated successfully at output voltages up to 750 kv. DC. Attempts to

build such power supplies for higher voltage ratings have revealed a weakness inherent in most forms of high-voltage power supplies; namely, under conditions in which the externally connected load sparks, the resulting surge gives rise to a nonuniform voltage gradient among the components comprising the power supply. This nonuniformity is caused by various capacities and inductances, both intentional and unintentional between the various components which dictate the transient voltage distribution during the time of the surge. This phenomenon is well known to those skilled in the art and it can be shown by a theoretical analysis that the maximum value of this transient voltage gradient will appear across components at the high-voltage end of the power supply. In high-voltage power supplies of the type shown in FIG. 1, this transient condition leads to a breakdown of the insulation sheet nearest to the high-voltage output connection. From the foregoing it must not be construed that this effect does not occur at voltages below 750 kv.; rather, the magnitude of the transient voltage surge impressed upon the upper sheet of insulation is not great enough to cause failure of that sheet in insulating core transformer power supplies designed for operation at 750 kv. and below.

These transient voltages can be isolated from the power supply by inclusion of an electrical impedance connected between the power supply and the load. However, such an impedance has an undesirable effect on the auxiliary power source as has been described previously. The manner in which this invention seeks to avoid these difficulties is best understood by a consideration of FIG. 2 which shows the power supply of FIG. 1 modified by the addition of one or more secondary cores 3', sheets of insulation 4', secondary coils 8', capacitors 16' and resistors, 19. The purpose of coils 8', and capacitors 16' can be ignored at this time.

In the event that a spark or surge takes place in apparatus connected to the high-voltage connection 13, it is intended that most of the surge voltage will appear across the resistors 19 and that the energy associated with the surge will be therein dissipated. The active part of the high-voltage power supply will therefore be protected from damaging high-voltage transient surges. The number of additional cores, sheets of insulation and resistors used will depend upon the voltage rating of the power supply. The impulse voltage withstand capability of both the insulation sheets 4' and the series-connected resistors 19 must be equal to the full-rated voltage of the power supply since the peak value of the transient voltage surge to which these components will be subjected is approximately equal to the full-rated power supply voltage. The auxiliary three-phase AC power source is largely unaffected by the additional surge-isolating components since the magnetic flux is maintained in the upper secondary cores independently of the surge resistors.

The simple form of three-phase insulating core transformer power supply as just described and shown in FIG. 2 exhibits an effect which is detrimental to its performance if large currents are to be obtained at high-voltage outputs. This effect manifests itself by a lower magnetic flux density in those secondary cores furthest away from the primary coils 7. The cause of this effect is inherent in the nature of the insulating core principle and is due to the presence of the insulating sheets 4 which introduce gaps of high magnetic reluctance between the secondary cores 3. In power supplies with many secondary cores, the total magnetic reluctance of each of the three legs of the magnetic circuit becomes comparable with the reluctance between the legs with the consequence that a considerable magnetic leakage path exists between the three legs. Thus those magnetic field lines originating in the primary cores do not all reach the uppermost cores in each leg but preferentially travel along the leakage path. In a typical case for an insulating core transformer power supply rated at 3 million volts, it was found that the magnetic flux density in the uppermost secondary cores was only one-third of that in each primary core. It will be understood that the leakage flux will be even greater if additional secondary cores with their associated insulation gaps are incorporated in order to install a surge-limiting impedance of the type which is the subject of this invention. The existence of such a substantial leakage flux reduces the power output capability of a given size of magnetic circuit when compared with a similar circuit without leakage.

By the application of another novel technique, greatly increased power may be obtained from an insulating transformer power supply even when the number of insulation gaps 4 and secondary cores 3 are made large in order to incorporate a surge protection impedance. Referring again to FIG. 1 which schematically shows an insulating core transformer power supply without surge protection impedance, the magnetic flux density can be made the same in every secondary core by the addition of capacitors 16, 17 and 18 across each respective transformer coil. These capacitors 16, 17 and 18 will cause a higher current to flow in each respective coil without dissipating any additional power other than an increased resistance loss in each coil and the dissipation loss in each respective capacitor. These additional losses are trivial when compared with the advantages of such a system inasmuch as the additional current flowing in each respective coil provides a magnetomotive force which serves to drive the magnetic field through the insulation gap 4 adjacent to the coil in question. It is, therefore, possible to select values of capacitors which will cause that amount of additional current to flow in each coil to give uniform flux density throughout the magnetic circuit.

It is expected that some decay in flux density will occur in the upper sections of the insulating core transformer power supply when a current is drawn from it. This is caused by the demagnetizing effect of the load current flowing in the coils and some degree of compensation for this can be provided by intentionally choosing different values for capacitors 16 and 17 such that the magnetic flux density in the upper secondary cores 5 is higher than that in the lower cores when no current is drawn from the power supply. This technique of flux equalization as applied to insulating core transformers will hereafter be referred to as the continuous excitation principle. In some cases, it may not be necessary to provide capacitors across every coil and a satisfactory approximation to continuous excitation may be made by connecting capacitors across a few coils only.

Referring again to FIG. 2, the continuous excitation principle can be applied to an insulating core transformer using an integral surge-protecting impedance by providing secondary coils 8' with capacitors 16' whose sole purpose is to provide a localized magnetomotive force in the vicinity of the insulation gaps 4'. There are no external connections to the coils 8' other than those required to interconnect between the three phases and the secondary cores in order to establish the DC potential of the subject cores, coils and capacitors.

A further feature of the invention enables the surge protection resistors to fulfill their purpose in a more efficient manner. This feature may best be understood by reference to FIG. 3 in conjunction with FIG. 2. In FIG. 3 that part of the device illustrated in FIG. 2 which generates the high voltage is represented as a power supply P across the output of which is an equivalent capacitor C. The surge protection impedances, 19 in FIG. 2, shown as two resistors R1 and R2 are each shunted by a capacitor of value C1 and C2 respectively. These capacitors are primarily formed by the capacitance between adjacent secondary cores 3' in FIG. 2. Capacitors C3, C4 and C5 are the stray capacitances between the components associated with the surge protection impedances and any neighboring grounded structure such as a containing vessel. The function of both R1 and R2 as has been previously explained is to isolate the power supply P from transient voltages generated by the connected load. It can be shown that for maximum effectiveness of R1 and R2 in performing their surge protection function, capacitors C, C3, C4 and C5 should be made as large as possible while capacitors C1 and C2 should be made as small as possible. The refinement to the

basic invention seeks to increase the surge protection ability of R1 and R2 by increasing the capacitances C, C3, C4 and C5 while decreasing the capacitances C1 and C2. For example, the insulation sheets 4' shown in FIG. 2 can be made thicker than the insulation sheets 4 in the voltage-generating part of the power supply. Moreover, since the main concern is to make the series combination of C1 and C2 much lower in value than C, the dielectric constants of the materials chosen for the insulation sheets can be different. For example, polyester film sold under the proprietary name Mylar has a dielectric constant about 1.5 times that of polyethylene while both materials have great dielectric strength. It is, therefore, beneficial to use Mylar for insulation sheets 4 and thicker pieces of polyethylene for insulation sheets 4' so that C1 and C2 are made small while C is made as large as possible. As a further feature of the invention, capacitors C3, C4 and C5 can be increased by making cores 3' in FIG. 2 larger than cores 3 so that the area exposed to grounded structures is increased resulting in a proportional increase in capacity. Conducting electrodes known as equipotential rings (not shown) are sometimes used to control the electric field gradient in the space between the power supply and its container. Typically, these equipotential rings are electrically connected to cores 3 and 3' so that further increase in capacitors C3, C4 and C5 is possible by using wider equipotential rings in conjunction with larger cores 3'.

Nothing in the foregoing description is meant to imply any restriction of this invention to use with either three-phase insulating core transformers or to DC power supplies. The surge-protecting impedance can be incorporated in any power supply either AC or DC in which a varying magnetic field is used to induce a voltage in coils which are electrically insulated one from the other and then connected in series to produce a high voltage. Moreover, this invention is not limited to power supplies using ferromagnetic cores. The principle of continuous excitation can be applied to insulating core transformers of any number of phases and intended to produce either AC or DC outputs.

I claim:

1. Electromagnetic induction apparatus for the simultaneous generation of high-voltage electrical power together with a lower voltage auxiliary power comprising:
a. a high-voltage output terminal,
b. a high-voltage intermediate terminal,
c. a low-voltage terminal,
d. first electrical insulating means for insulating said high-voltage intermediate terminal from said low-voltage terminal,
e. at least one auxiliary terminal electrically insulated from said low-voltage terminal,
f. means for creating a varying magnetic field,
g. a plurality of first electrical windings interposed between said high-voltage output and low-voltage terminals and coupled by said magnetic field,
h. means for electrically connecting said first electrical windings to create a high voltage at said high-voltage intermediate terminal,
i. at least one second electrical winding interposed between said high-voltage output and auxiliary terminal and coupled by said magnetic field,
j. second insulating means for insulating said second electrical winding from said high-voltage intermediate terminal; and
k. electrical impedance means connected between said high-voltage output terminal and said high-voltage intermediate terminal for providing surge protection for said high-voltage electrical power portion of said electromagnetic induction apparatus.

2. The electrical induction apparatus as set forth in claim 1 wherein said second insulating means minimizes the capacitance between said high-voltage intermediate terminal and said high-voltage output terminal.

3. The electrical induction apparatus as set forth in claim 2 wherein said capacitance is minimized by increasing the thickness of the insulation.

4. The electrical induction apparatus as set forth in claim 2 wherein said capacitance is minimized by providing insulation having a lower dielectric constant.

5. The electrical induction apparatus as set forth in claim 1 wherein said first insulating means maximizes the capacitance between said high-voltage intermediate and said low-voltage terminal.

6. The electrical induction apparatus as set forth in claim 2 wherein said first insulating means maximizes the capacitance between said high-voltage intermediate and said low-voltage terminal.

7. The electrical induction apparatus as set forth in claim 1 wherein said apparatus further includes means for controlling the electrical field gradient by providing equipotential rings electrically connected to said first and second electrical windings and to said electrical impedance means in a predetermined manner and wherein the rings associated with said second electrical windings and said electrical impedance means have an increased surface area to maximize the capacitance to said low-voltage terminal.

8. Insulating core induction apparatus comprising:
a. a high-voltage terminal,
b. a low-voltage terminal,
c. at least one magnetic circuit interposed between said high and low voltage terminals,
d. at least one magnetic column included in said magnetic circuit, said column comprising a plurality of magnetic core segments electrically insulated one from the other,
e. means for generating a varying magnetic field in said magnetic circuit,
f. a plurality of electrical windings interposed between said high-voltage output and low-voltage terminals and coupled by said magnetic field and surrounding said magnetic core segments,
g. means for electrically connecting said electrical windings to create a high voltage at said high-voltage terminal; and
h. at least one capacitive element connected in parallel with at least one of said electrical windings.

9. The The insulating core induction apparatus as set forth in claim 8 having an auxiliary power source and wherein said apparatus further includes
a. a high-voltage intermediate terminal at the same potential as said high-voltage output terminal,
b. a high-voltage output terminal,
c. at least one auxiliary terminal electrically insulated from said low-voltage terminal,
d. at least one auxiliary electrical winding interposed between said high-voltage output and auxiliary terminal and surrounding one of said magnetic core segments; and
e. electrical impedance means connected between said high-voltage output terminal and said high-voltage intermediate terminal for providing surge protection for said high-voltage electrical power portion of said electromagnetic induction apparatus.

10. The insulating core induction apparatus as set forth in claim 9 wherein said magnetic column is extended to include additional electrically insulated magnetic core segments with said electrical impedance means electrically connected in a predetermined manner between said additional core segments.

11. The insulating core induction apparatus as set forth in claim 10 wherein said apparatus further includes
a. flux-equalizing electrical windings surrounding said additional electrically insulated magnetic core segments; and
b. a capacitive element electrically connected respectively in parallel with each of said flux-equalizing electrical windings.

12. The insulating core induction apparatus as set forth in claim 10 wherein said additional magnetic core elements are elongated to increase the stray electrical capacitance of said

additional magnetic core elements to said low-voltage terminal.

13. The insulating core induction apparatus as set forth in claim 10 wherein said apparatus further includes means for controlling the electric field gradient by providing equipotential rings electrically connected to said magnetic core segments and wherein the rings associated with said additional magnetic core segments have an increased surface area to maximize the capacitance to said low-voltage terminal.

14. The electrical induction apparatus as set forth in claim 10 wherein said capacitance is minimized by increasing the thickness of the insulation.

15. The electrical induction apparatus as set forth in claim 10 wherein said capacitance is minimized by providing insulation having a lower dielectric constant.

16. The insulating core induction apparatus as set forth in claim 10 wherein the insulation material between said core segments is selected to have a higher dielectric constant than the insulation material between said additional magnetic core segments to maximize the capacitance between the said high-voltage intermediate terminal and said low-voltage terminal.