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Preist

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[45] **Oct. 28, 1975**

[54] ELECTRON BEAM ELECTRICAL POWER TRANSMISSION SYSTEM

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[73] Assignee: **Varian Associates,** Palo Alto, Calif.

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[21] Appl. No.: **389,915**

[52] **U.S. Cl.** **315/5;** 315/3.6; 321/22; 321/32; 328/227; 328/233

[51] **Int. Cl.**^{2} **H01J 25/02**

[58] **Field of Search** 315/3.5, 3.6, 4, 5; 328/233, 227, 228; 321/8, 22, 32, 37

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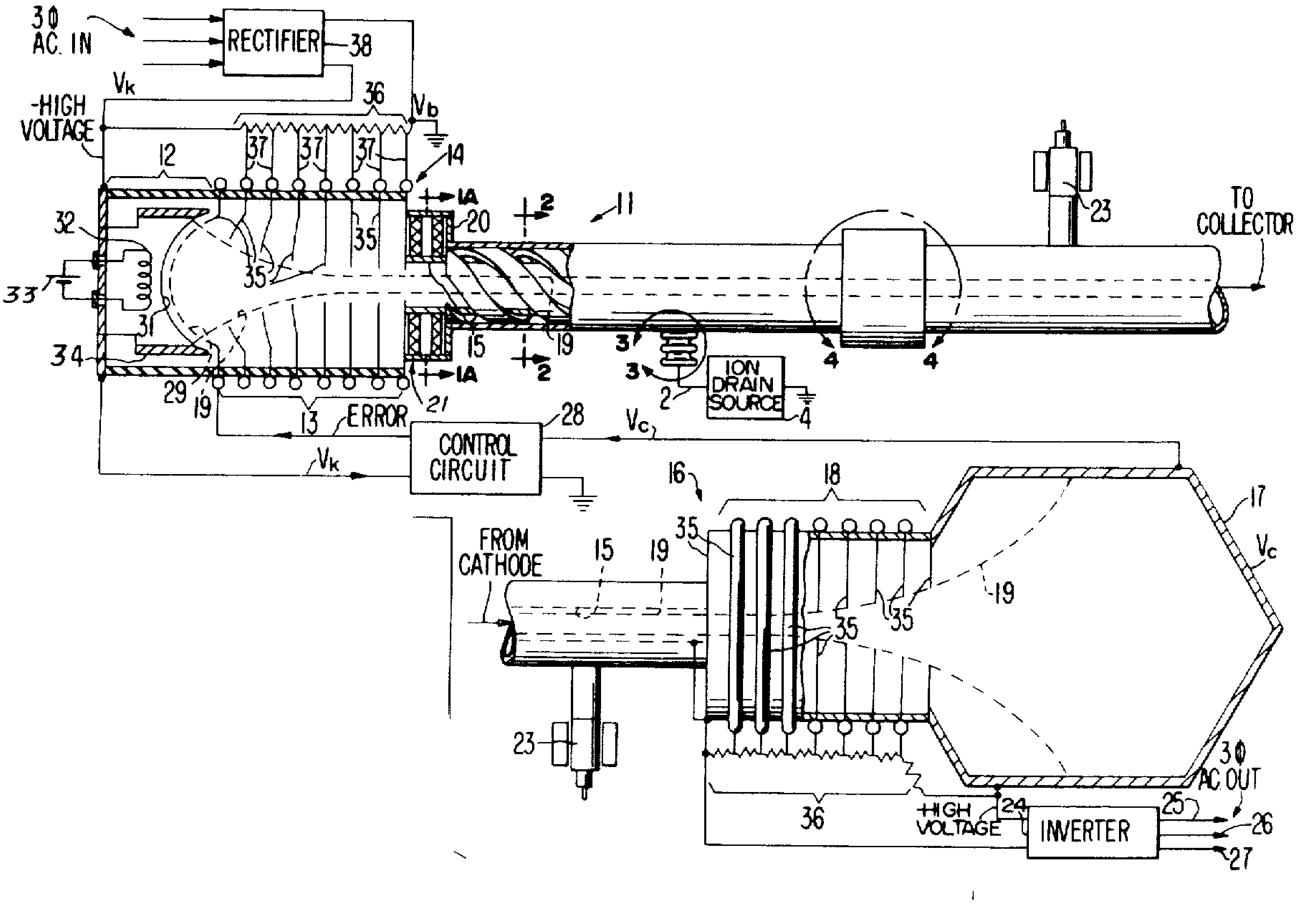
Primary Examiner—Saxfield Chatmon, Jr.
Attorney, Agent, or Firm—Stanley Z. Cole; D. R. Pressman; Richard B. Nelson

[57] ABSTRACT

Electrical power is transmitted from a transmitting location to a remote receiving location by means of an electron beam injected into an evacuated magnetically shielded pipe extending between the transmitting location and the receiving location. The beam is magnetically focused within the evacuated pipe. Electrical power to be transmitted is put into the beam in the form of kinetic energy by accelerating the beam to a high kinetic energy. The kinetic energy is extracted from the beam at the receiving location and converted into potential electrical energy for application to the load. In one embodiment, the kinetic energy is extracted from the beam by collecting the beam current at a potential substantially equal to the potential of the source of the electrons, i.e. cathode potential, and causing the collected beam current to flow through the load to develop the depressed collector potential. In another embodiment, radio frequency accelerator means are utilized for r.f. current density modulating and accelerating the beam. The radio frequency current modulation on the beam is extracted at the receiving end by means of a radio frequency circuits coupled to the beam. The extracted radio frequency energy is rectified for application to the load. In another embodiment, AC power at conventional AC power frequencies, as of 60 Hertz, is extracted from the beam by sequentially directing the beam into a plurality of depressed collectors coupled to respective primary windings of power transformers for deriving AC output power for application to a load.

15 Claims, 21 Drawing Figures



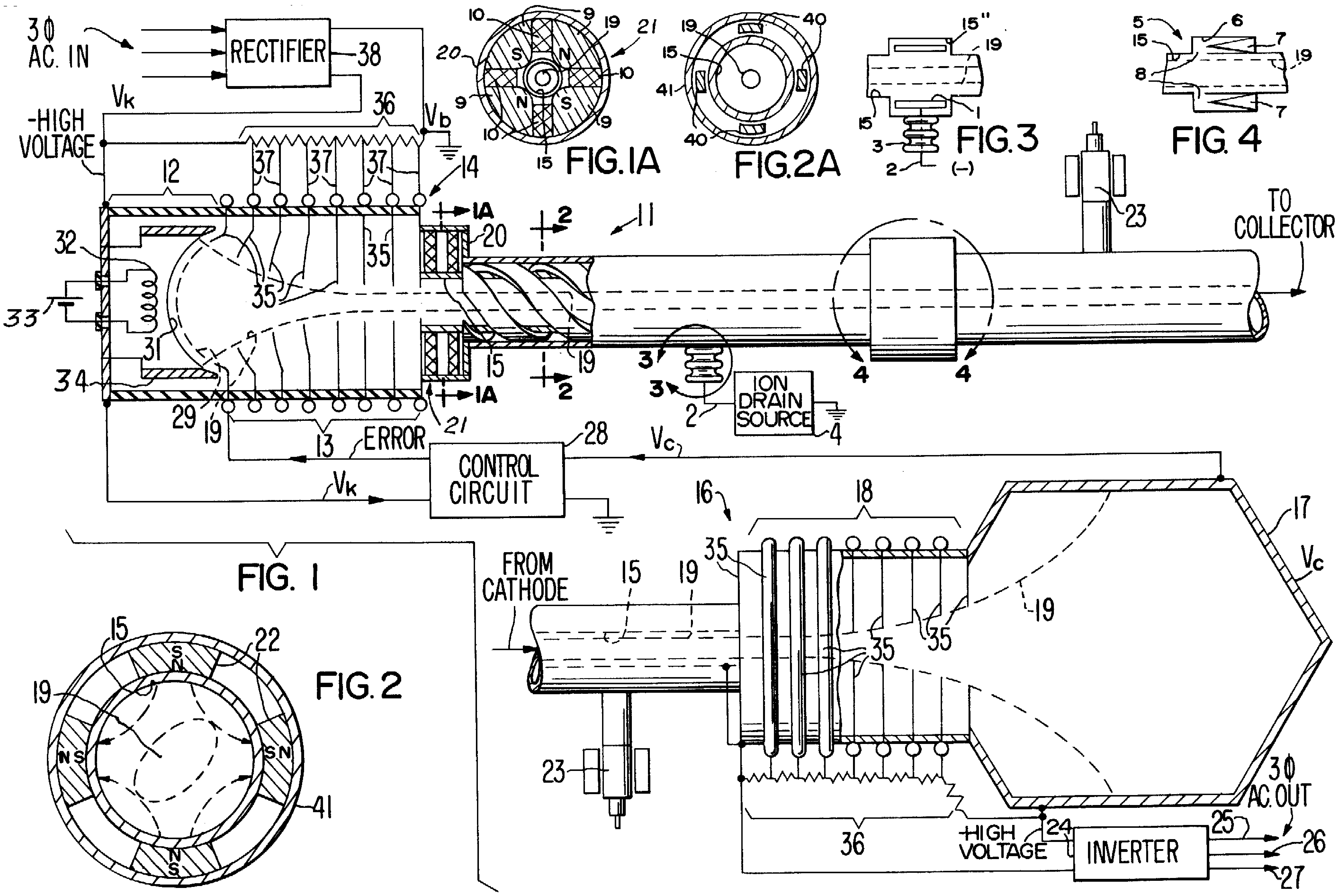


FIG. 1

FIG.1A

FIG.2A

FIG.3

FIG. 4

FIG. 2

FIG. 8

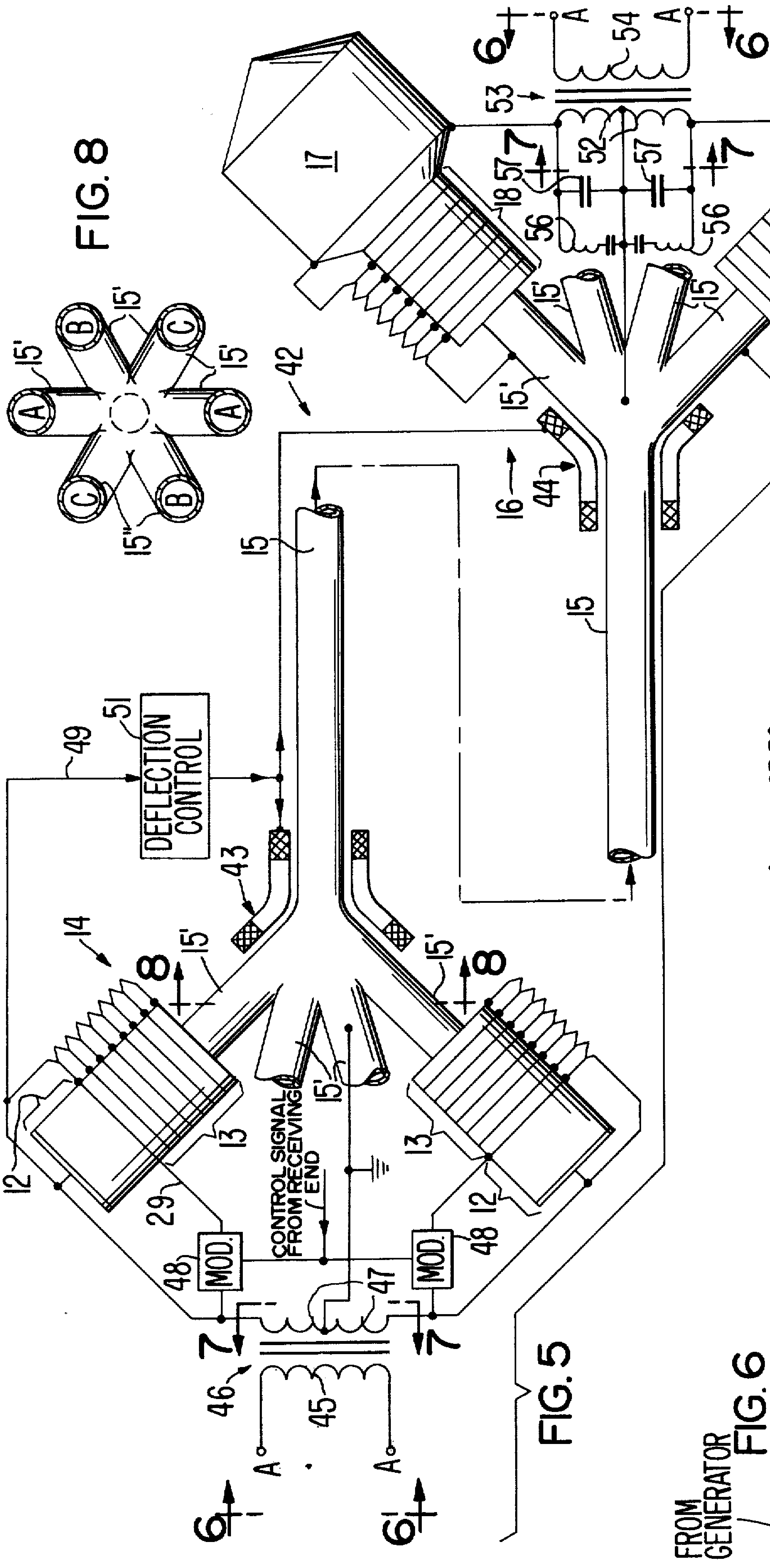


FIG. 5

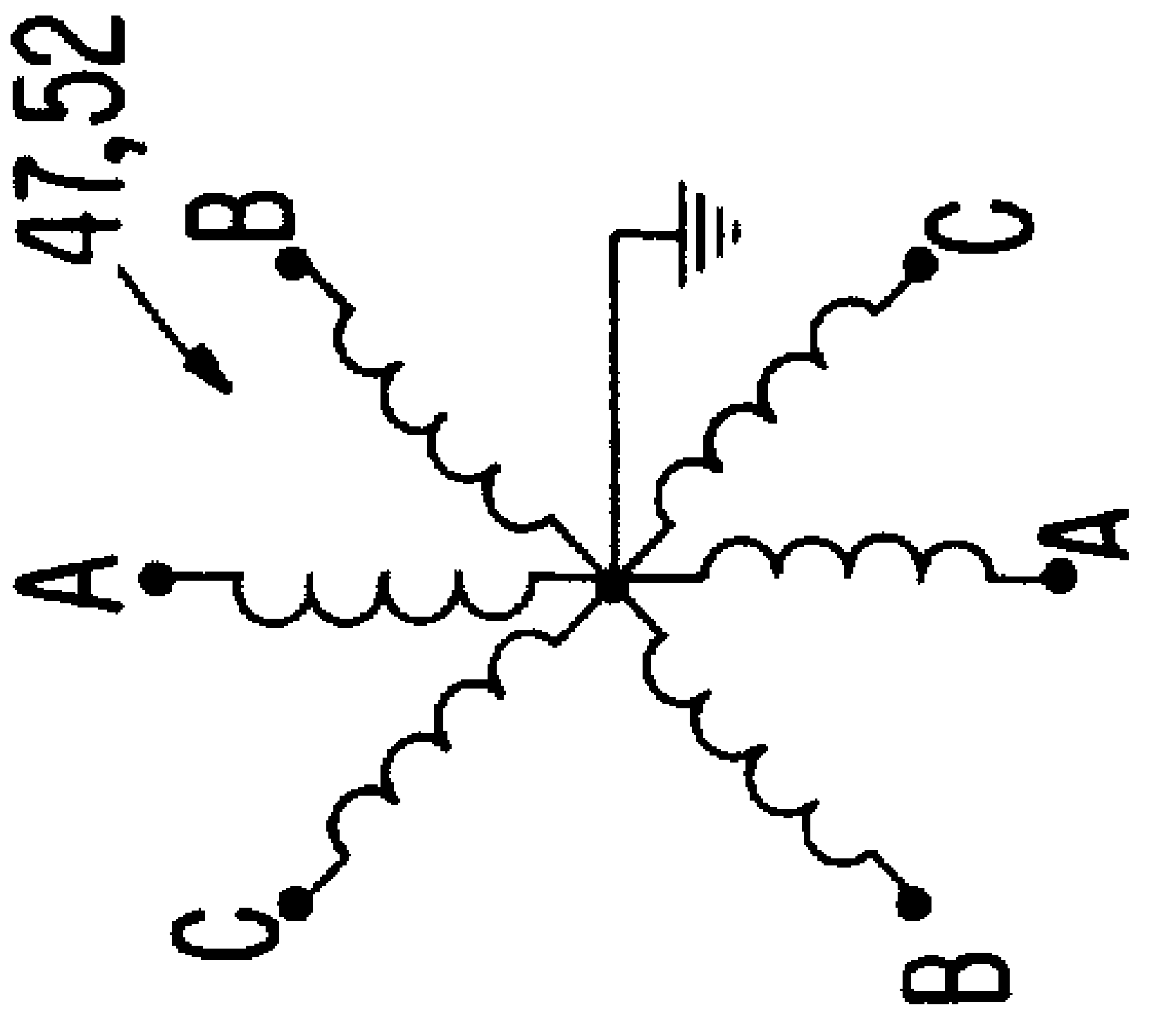


FIG. 7

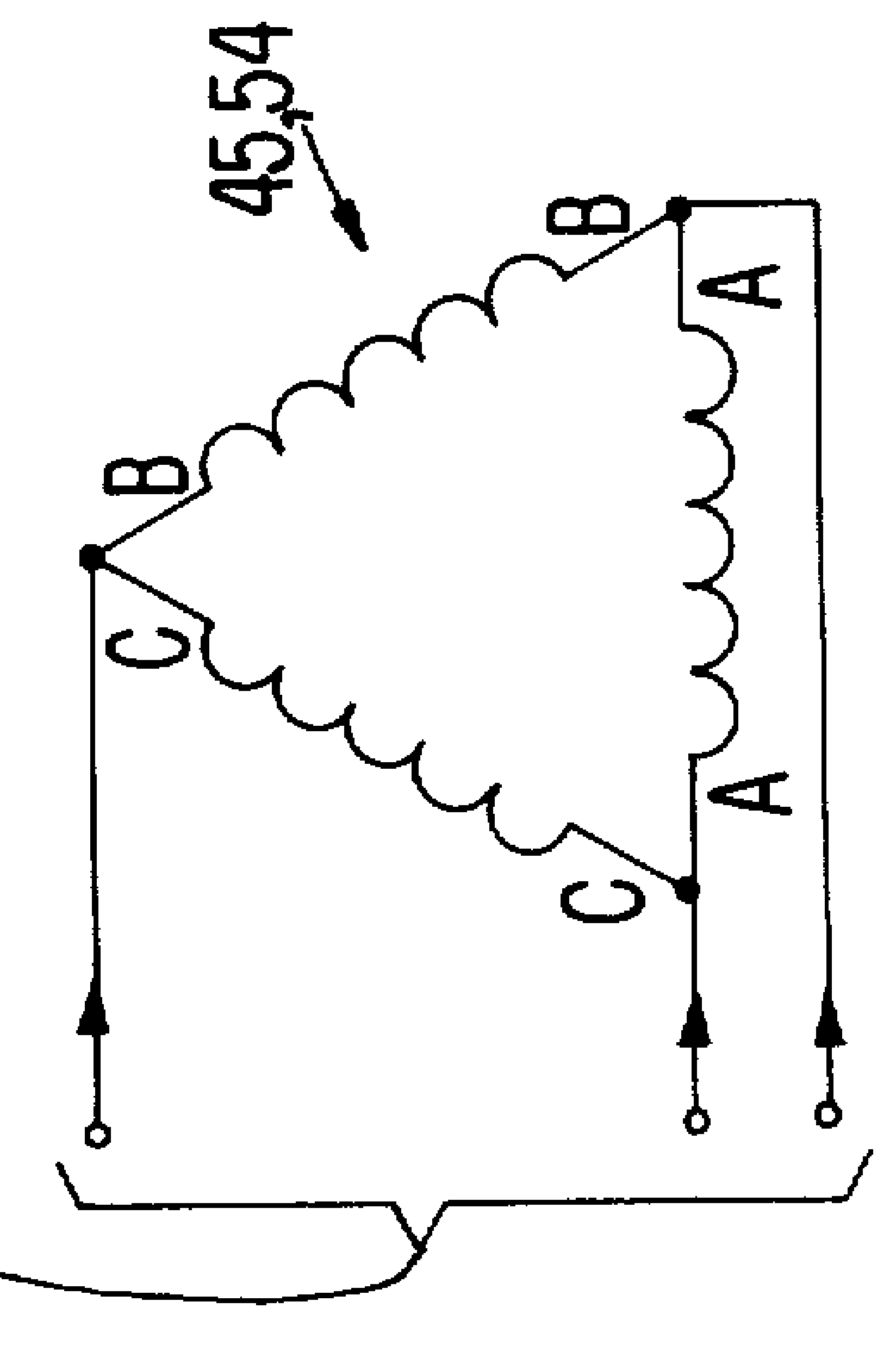
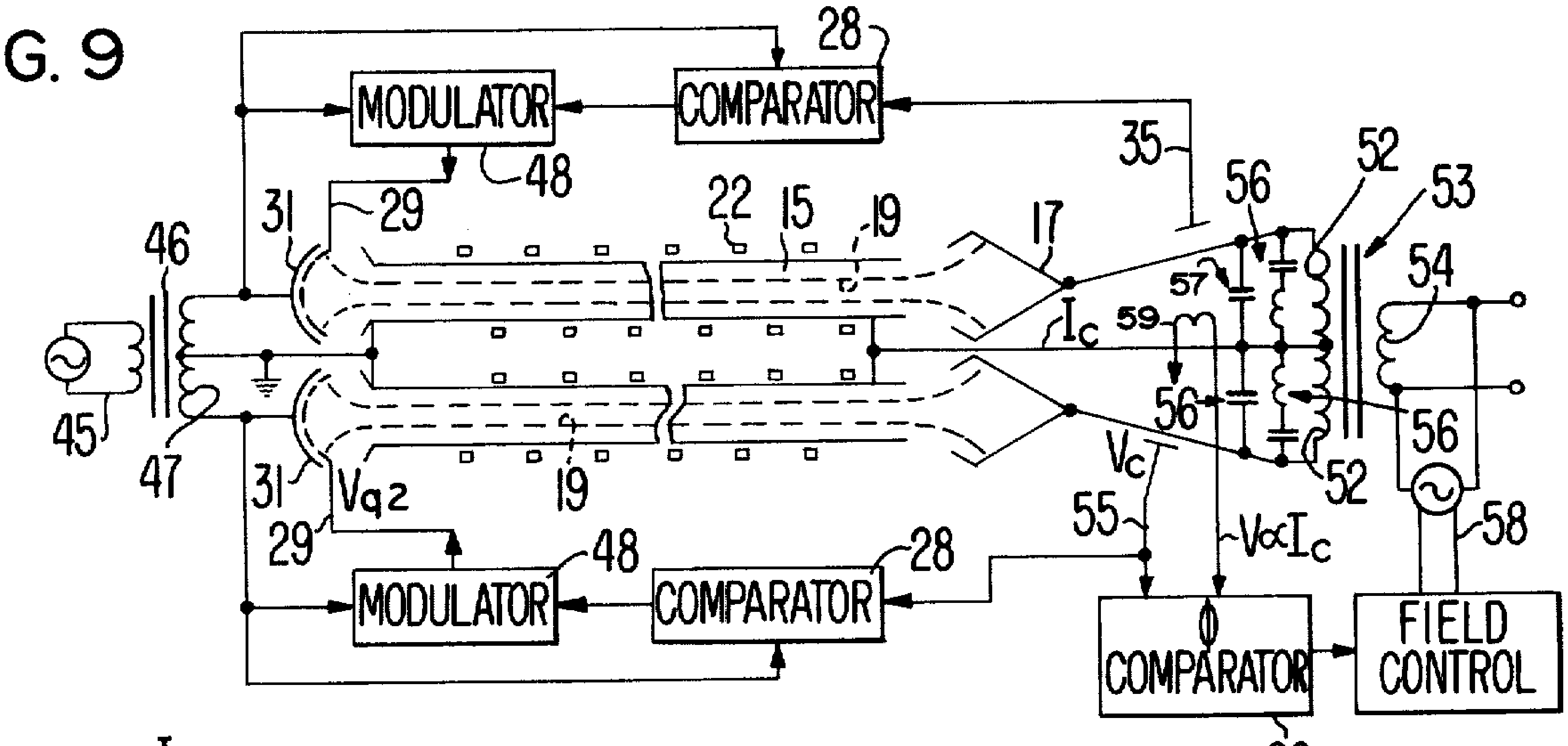


FIG. 6

FIG. 9



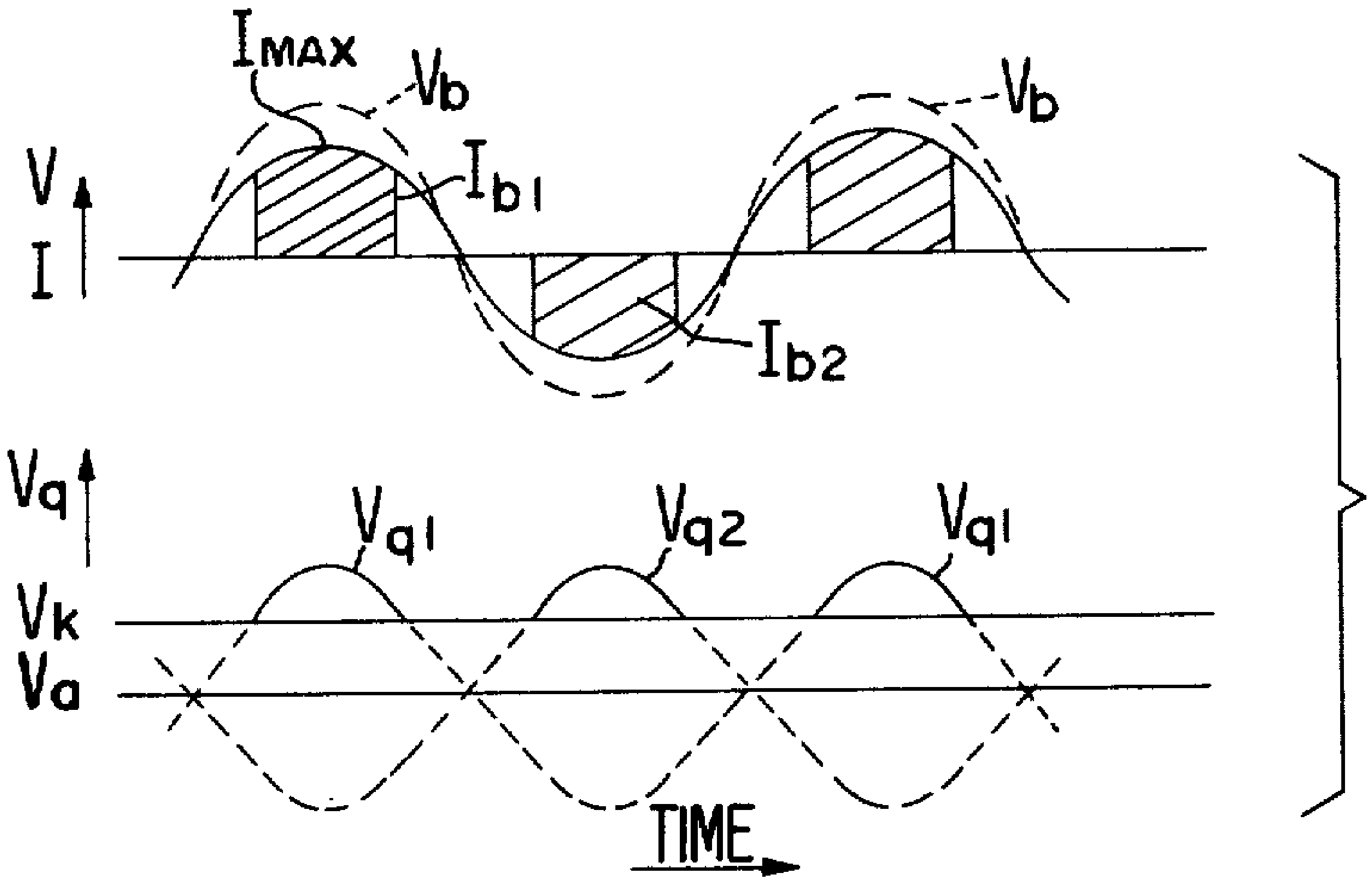


FIG. 10

FIG. 11

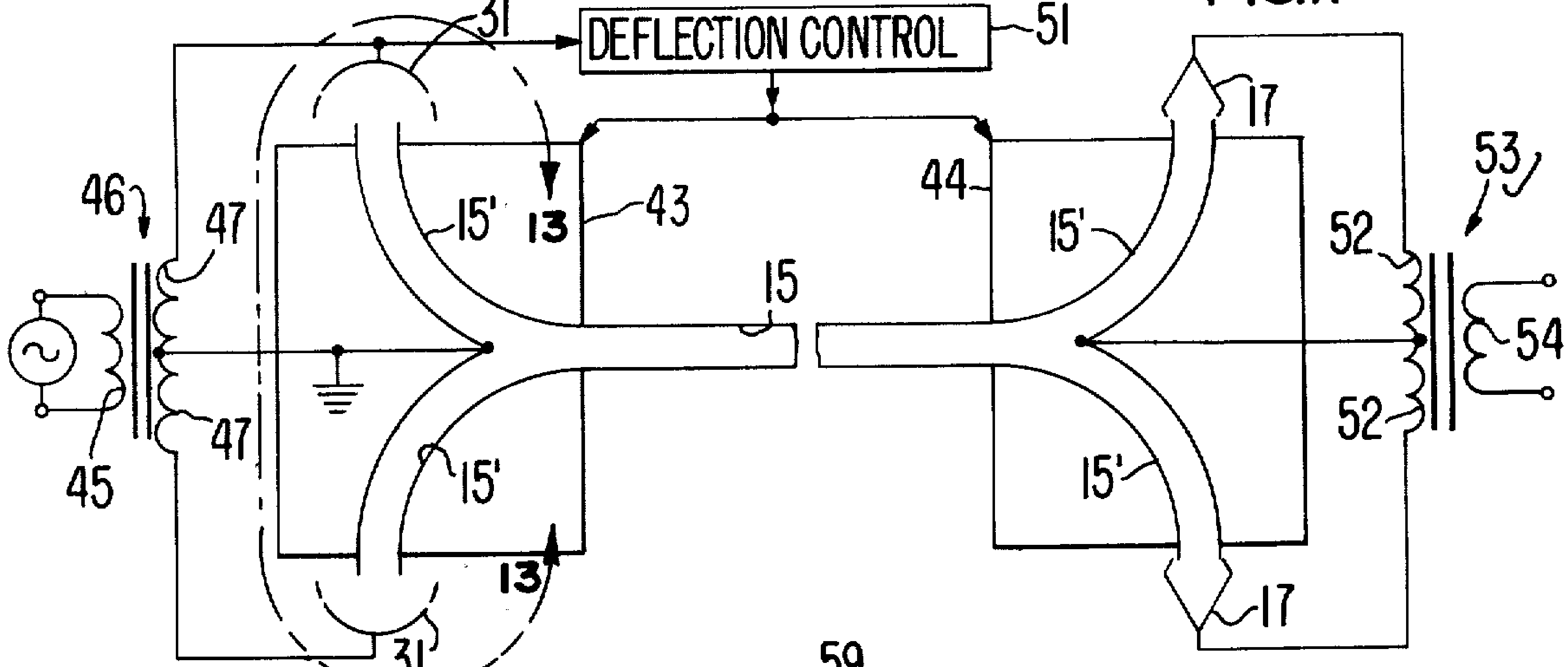


FIG. 12

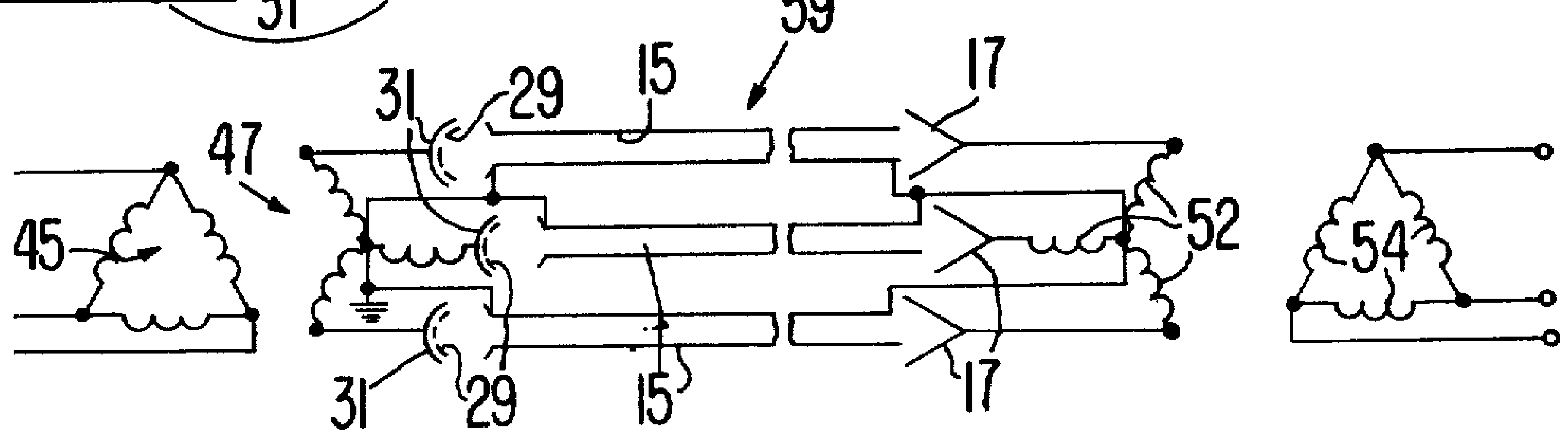


FIG. 13

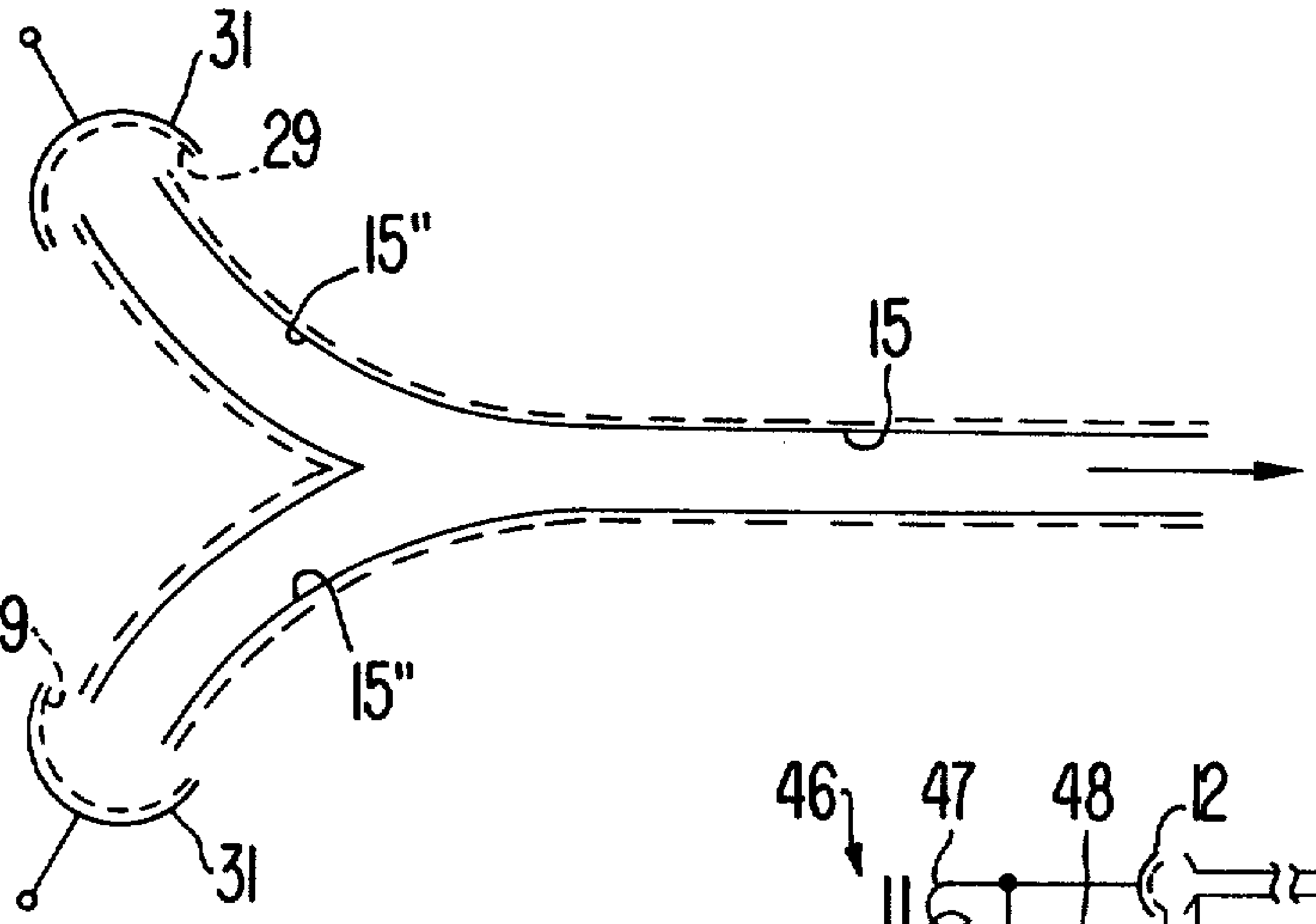


FIG. 14

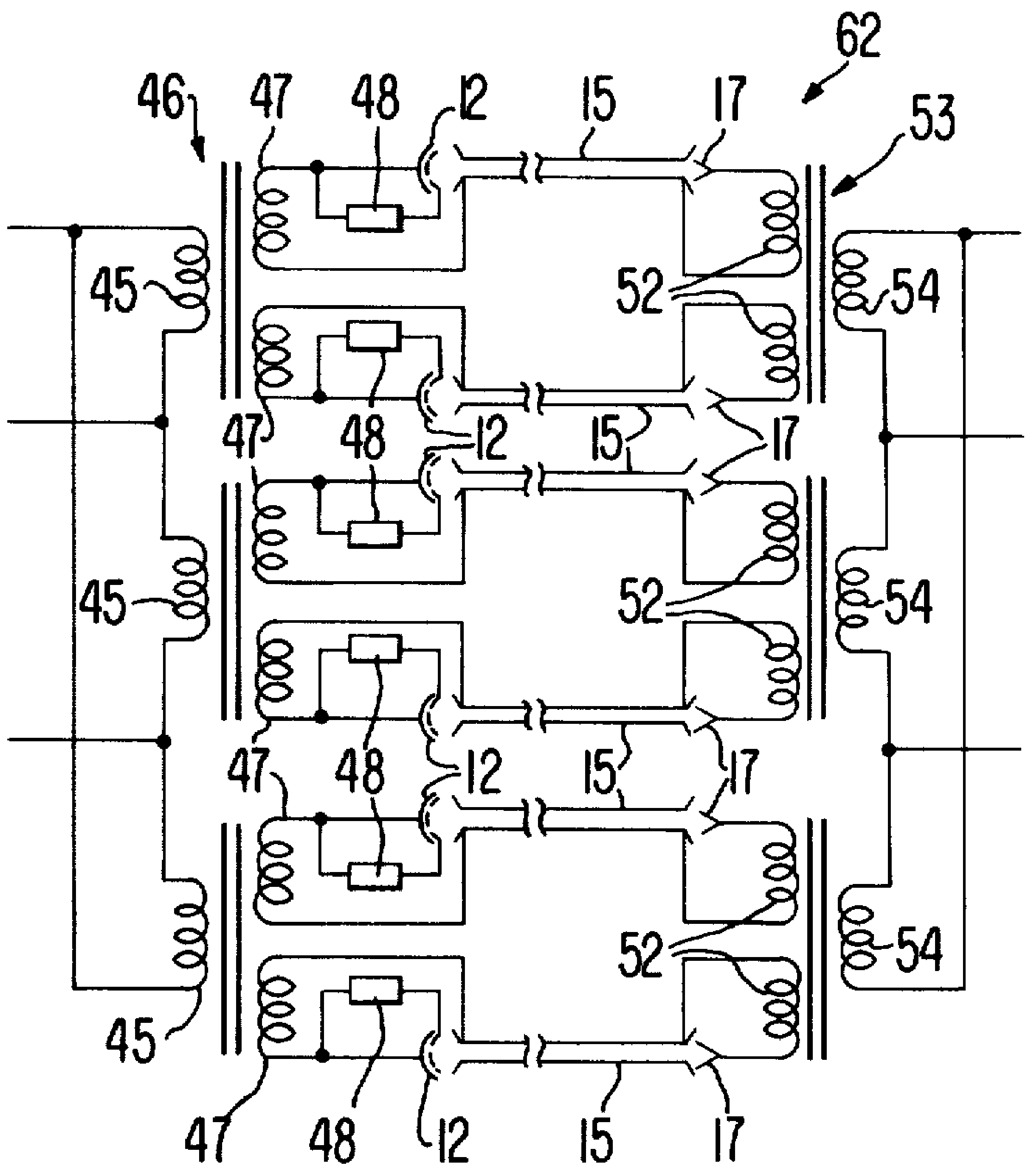


FIG. 15

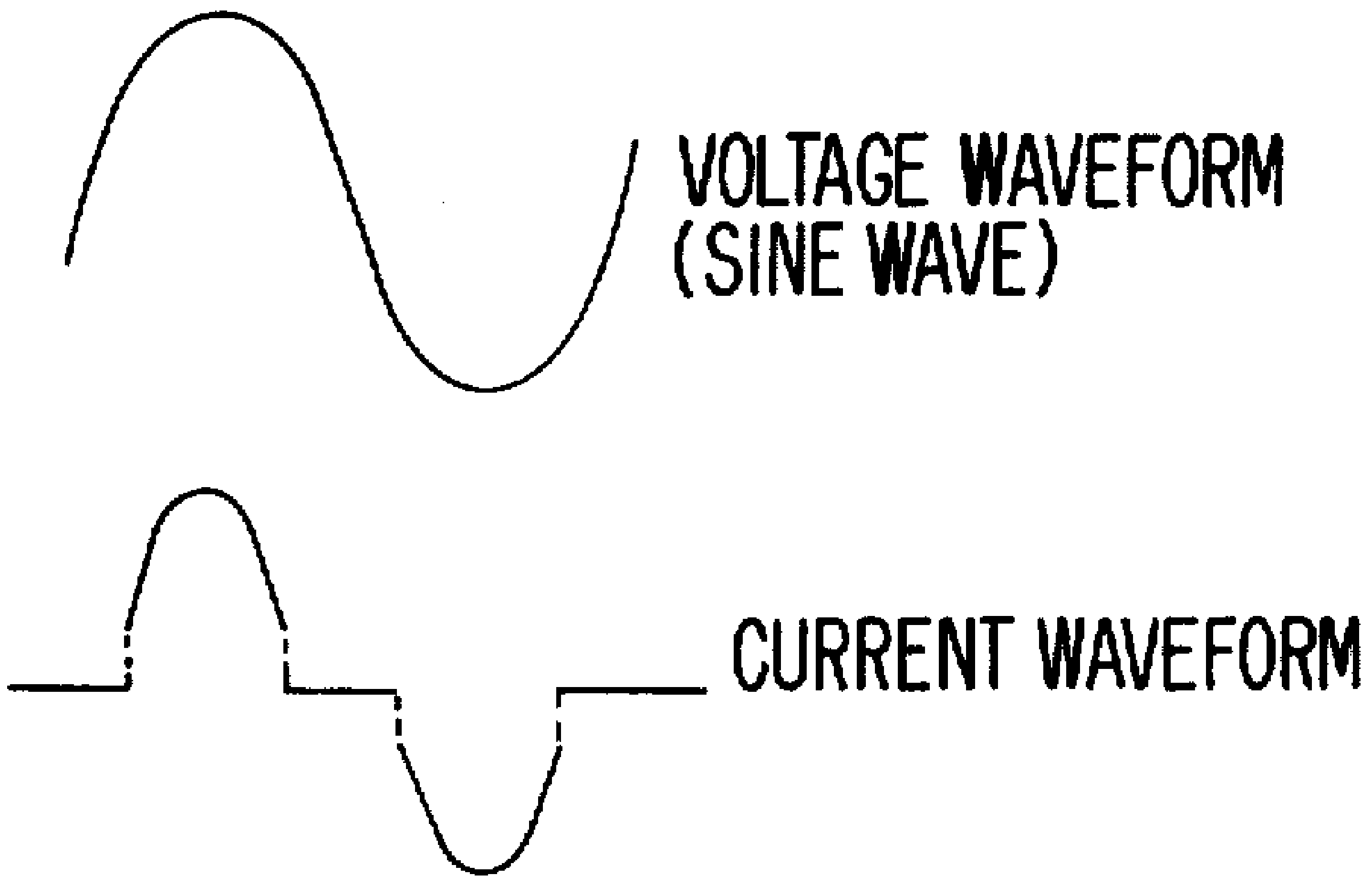
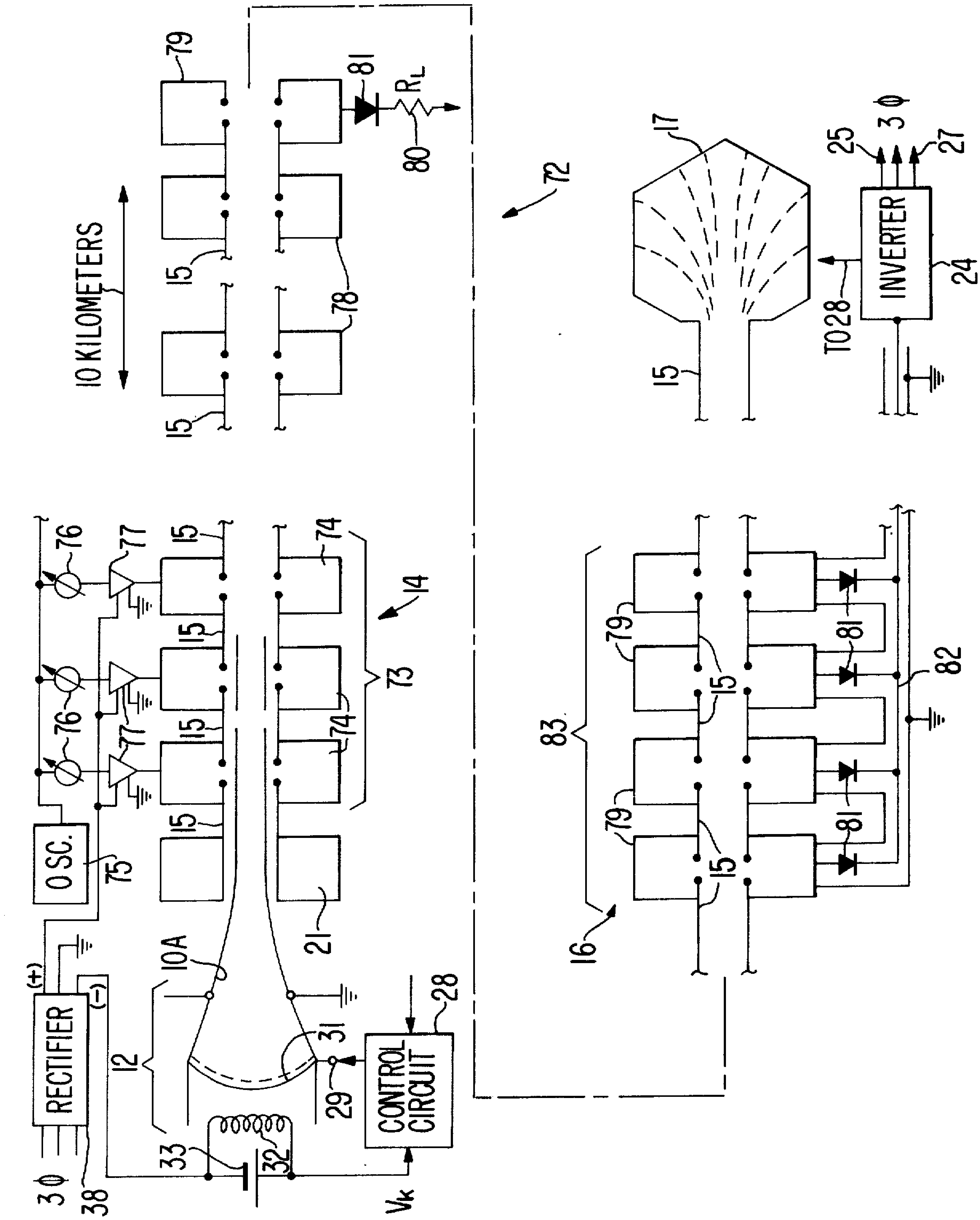


FIG. 16


RECTIFIER
(+)
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3 Φ
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OSC.
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CONTROL CIRCUIT
33
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Vk
10 KILOMETERS
79
78
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RL
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INVERTER
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3 Φ
83
16
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FIG. 17

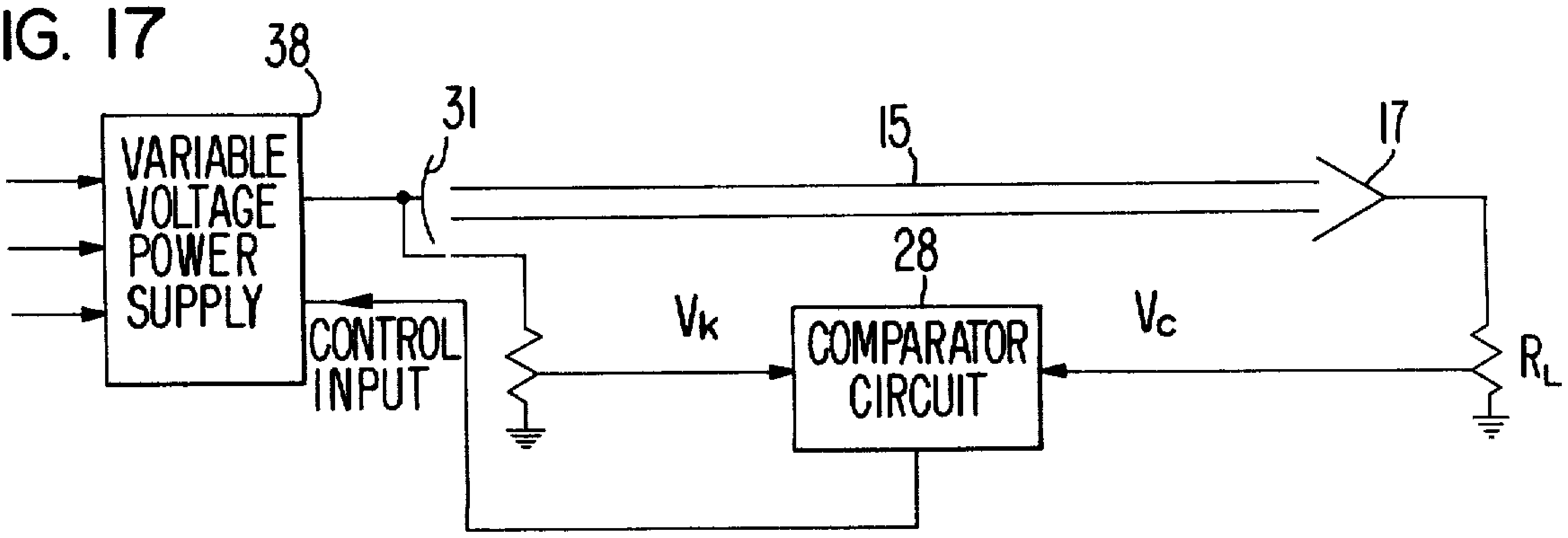


FIG. 18

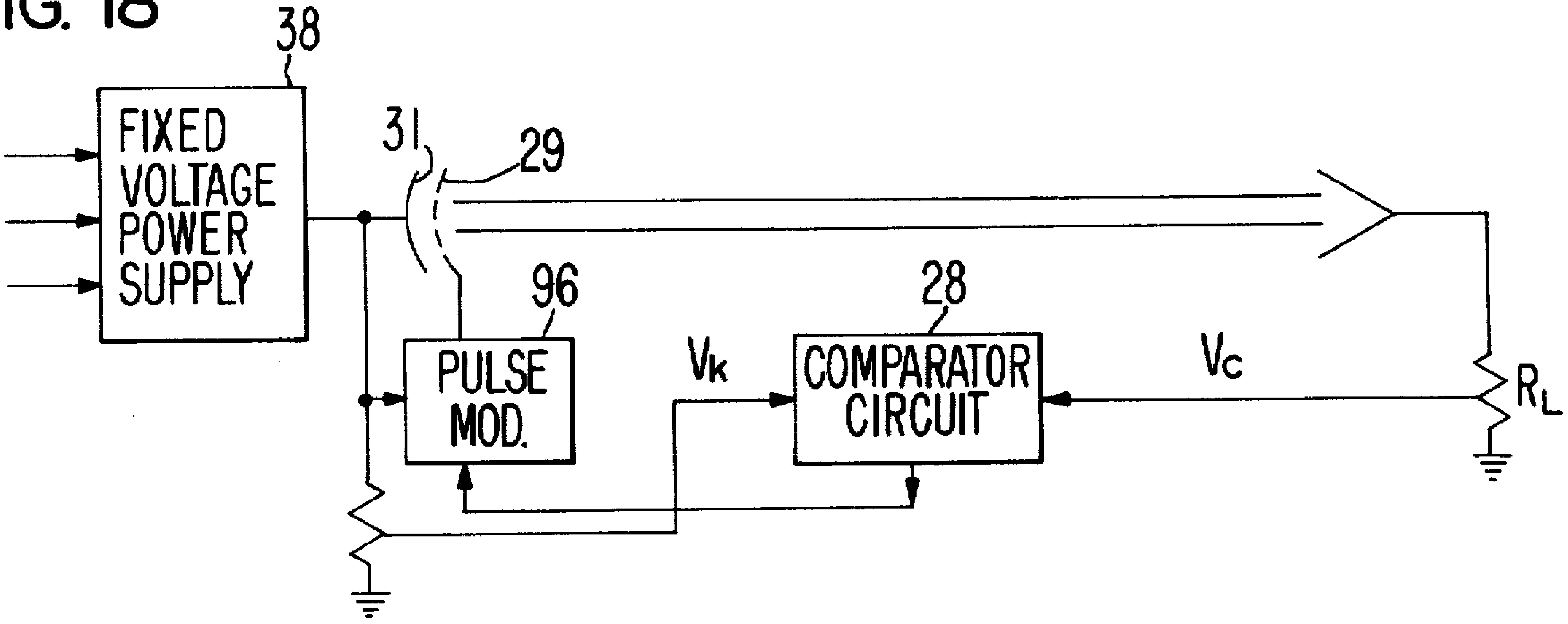
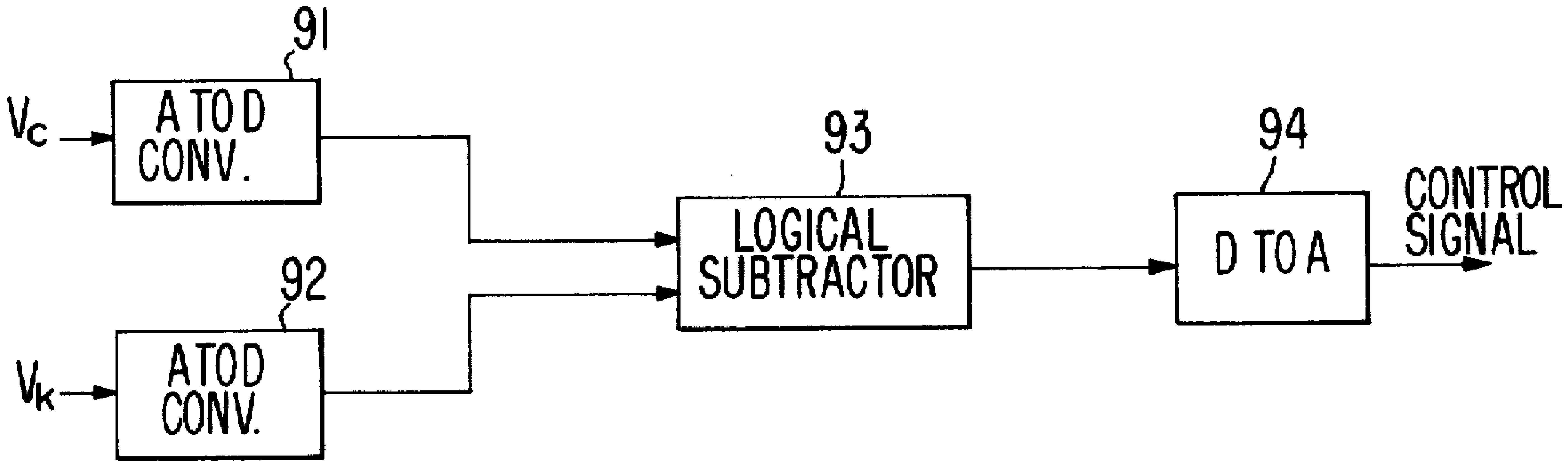


FIG. 19



ELECTRON BEAM ELECTRICAL POWER TRANSMISSION SYSTEM

BACKGROUND OF THE INVENTION

The present invention relates in general to electrical power transmission systems utilizing an electron beam as the power transmitting medium and, particularly, to improved means for imparting kinetic energy to an electron beam and for extracting the kinetic energy from the beam at a remote location.

DESCRIPTION OF THE PRIOR ART

Heretofore, it has been proposed to transmit vast quantities of electrical power from a transmitting location to a remote receiving location by means of an electron beam traveling within an evacuated magnetically shielded pipe or cable employing "strong" magnetic focusing along the pipe to prevent unwanted beam interception by the walls of the pipe. Such a system is disclosed in U.S. Pat. No. 2,953,750 issued Sept. 20, **1960.**

In this prior proposed scheme, it was contemplated that kinetic energy would be imparted to the beam at the sending end by accelerating the beam to a high kinetic energy, as of 100 MeV, by a modified betatron type induction accelerator machine. In the modified betatron, the beam, while magnetically contained within a helical magnetic cable (pipe), was caused to pass through a plurality of accelerating gaps for increasing the kinetic energy of the beam in a steplike fashion. That is, the accelerating electrical field, produced across the respective gaps by an AC potential applied in synchronism with pulses of the beam, caused the beam to be accelerated to the high output kinetic energy. It was contemplated that the high energy pulses of beam current could be at AC power frequencies of 25 or 60 Hertz or, as an alternative, the pulse repetition rate could be in the radio frequency range by utilizing a radio frequency cavity resonator at each of the accelerating gaps in the helical cable.

The kinetic energy of the high energy pulses of beam current was extracted at the receiving end by means of a reverse type accelerator which decelerated the beam pulses in accordance with the amount of power demanded by the load. The decelerated (unused) pulses of beam current were returned to the sending end by means of return magnetic cables or pipes connected back to appropriate ones of the electron beam accelerating machines. The returning beam pulses were 180° out of phase with the transmitted pulses of beam current leaving the machine. In this manner the unused energy of the beam was returned to the betatron accelerating machine.

It was concluded, in the above cited prior patent, that the radio frequency alternative was not feasible for transmitting relatively large amounts of power. On the other hand, a problem with the use of magnetic induction accelerators operating even at conventional power frequencies is that a vast amount of iron must be used causing attendant iron losses due to hysteresis effects.

SUMMARY OF THE PRESENT INVENTION

The principal object of the present invention is the provision of an improved electrical power transmission system employing an electron beam as the power transmission medium.

In one feature of the present invention, first and second electron guns at the transmitting end of the power transmission system are energized with beam voltage in 180° out of phase relation such that alternate guns conduct during each half-cycle of the applied A.C. power, whereby a full wave rectification effect is obtained by the self-rectifying action of the electron guns at the transmitting end of the system.

In another feature of the present invention, first and second convergent evacuated envelope portions are disposed to receive first and second electron beams from first and second electron guns and to direct the respective beam via convergent beam paths into a common beam path and wherein magnetic focusing is employed for focusing the beams within the first and second convergent envelope portions.

In another feature of the present invention, an alternating potential is applied between the cathode and anode of an electron gun at the transmitting end of the system for generating beam current from that gun during only alternate half cycles of the applied beam potential, a beam current control electrode is provided in the electron gun and energized with a control potential such that the current from the gun is limited to less than a full half cycle of the applied alternating potential, whereby beam conduction is limited to periods of the power cycle wherein the beam voltage has substantial amplitude to avoid undesired transit time effects and to reduce the requirements of the beam focus system to accommodate beams of widely varying current and velocity.

In another feature of the present invention, the collected beam current at the receiving location is directed, in sequential half-cycles of the power frequency through bucking connected halves of balanced winding means of an output transformer to avoid undesired D.C. saturation effects of the transformer core and to eliminate certain undesired harmonics.

In another feature of the present invention, the secondary windings of the output power transformer of a three phase electron beam power transmission system are connected in the delta configuration to eliminate output power at the third harmonic of the power frequency and multiples thereof.

In another feature of the present invention, current is sequentially directed into various primary windings of the output transformer for obtaining A.C. output power in the load and wherein a series tuned odd harmonic filter is connected across each of the primary windings for by-passing odd harmonic content of the collected beam current.

In another feature of the present invention, pulses of beam current are sequentially transmitted from the transmitting location to the receiving location and the pulses are sequentially directed through primary windings of a transformer in such a way as to produce A.C. output power in the load. A control electrode is provided for shaping the pulses of beam current to eliminate or reduce certain undesired odd-order harmonic beam current content therein such as the fifth, seventh, eleventh, etc.

In another feature of the present invention, pulses of beam current are transmitted from the transmitting location to the receiving location wherein they are collected sequentially in different collecting structures. The collected current is directed through primary windings of an output transformer. The phase of the collected current is compared with the phase of the collector potential to derive an error signal for correcting the power factor of the load.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic longitudinal sectional foreshortened view, partly in block diagram form, of an electron beam power transmission system incorporating features of the present invention.

FIG. **1A** is a sectional view of the structure of FIG. **1** taken along line **1A—1A** in the direction of the arrows,

FIG. **2** is an enlarged sectional view of a portion of the structure of FIG. **1** taken along line **2—2** in the direction of the arrows.

FIG. **2A** is a view similar to that of FIG. **2** showing an alternative embodiment of the present invention,

FIG. **3** is an enlarged schematic detail view of a portion of the structure of FIG. **1** delineated by line **3—3**,

FIG. **4** is a schematic longitudinal sectional view of a portion of FIG. **1** delineated by line **4—4**,

FIG. **5** is a view similar to that of FIG. **1** depicting an alternative embodiment of the present invention,

FIG. **6** is a schematic circuit diagram of the winding portion of the transformers of the circuit of FIG. **5** delineated by line **6—6**,

FIG. **7** is a schematic circuit diagram of the winding portions of the transformers of FIG. **5** delineated by lines **7—7**,

FIG. **8** is a transverse sectional view of a portion of the structure of FIG. **5** taken along line **8—8** in the direction of the arrows,

FIG. **9** is a schematic diagram, partly in block diagram form, of an electron beam power transmission system incorporating alternative embodiments of the present invention,

FIG. **10** are waveforms of beam voltage, beam current, and grid voltage for an electron beam power transmission system employing an interrupted beam,

FIG. **11** is a schematic line diagram of an electron beam power transmission system employing alternative features of the present invention,

FIG. **12** is a schematic line diagram of a power transmission system employing alternative embodiments of the present invention,

FIG. **13** is a schematic line diagram of an alternative embodiment to a portion of the structure of FIG. **11** delineated by line **13—13**,

FIG. **14** is a schematic circuit diagram for an electrical power transmission system incorporating features of the present invention and depicting an alternative embodiment,

FIG. **15** is a plot of current and voltage waveforms for one phase of the power transmission system of FIG. **14**,

FIG. **16** is a view similar to that of FIG. **1** depicting an alternative embodiment of the present invention,

FIG. **17** is a schematic circuit diagram, partly in block diagram form, of a control circuit useful in a power transmission system of the present invention,

FIG. **18** is a view similar to that of FIG. **17** depicting an alternative embodiment of the present invention, and

FIG. **19** is a schematic circuit diagram, in block form, of the comparator circuit useful in the embodiment of FIGS. **17** and **18**.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIGS. **1** and **2** show an electron beam power transmission system **1** incorporating features of the present invention. System **1** includes an electron gun **12** and a DC beam accelerator section **13** at the power transmitting end **14** of an elongated evacuated envelope **15** which extends for a substantial distance, e.g. 0.1 to 1,000 miles, to a remote power receiving location **16** at the receiving end of the transmission system **1**. At the receiving location **16**, an electron beam collector structure **17** is connected to the evacuated envelope **15** by a DC beam decelerating section **18**.

Briefly, electron gun **12** serves to form, accelerate and project a beam of electrons **19** into the beam accelerator section **13** which accelerates the beam to a very high energy, as of in excess of 0.1 million electron volts MeV, and preferably in excess of 0.5 MeV. In this manner, substantial kinetic energy is imparted to the electron beam.

Although a separate accelerator section **13** is employed in the embodiment of FIG. **1**, this is not a requirement. If the beam voltage is below 0.25 MeV, the anode of the gun **12** may be operated at 0.25 MeV for accelerating the beam up to 0.25 MeV. Actually the accelerating section **13** can be considered as part of the anode structure of the gun **12**.

The beam **19** is then projected axially into the elongated envelope **15**. The beam is magnetically confined in envelope **15** by a quadrupole magnetic beam focus structure **22** to avoid substantial interception on the walls of the evacuated envelope. An astigmatic magnetic lens system **21** (See FIGS. **1** and **1A**) is provided between the accelerating section **13** and the entrance to the elongated envelope **15** to provide a smooth magnetic focusing transition of the electron stream from the accelerator into the quadrupole beam focus field in envelope **15**.

The magnetic lens system **21** comprises one or more quadrupole lenses. Each quadrupole lens includes four magnetic poles of alternating polarity around the envelope **15** which are energized by electric coils **10** wound around the poles **9**. A tubular magnetic shield **11** surrounds the poles **9**.

The quadrupole magnetic beam focus structure **22**, more fully described below, spirals around envelope **15** to provide "strong" magnetic beam focusing of the type described in the aforecited U.S. Pat. No. 2,953,750. The envelope **15** is evacuated by means of a plurality of glow discharge getter-ion vacuum pumps **23** or any other suitable vacuum pump disposed at suitable intervals along the pipe **15** in gas communication therewith for evacuating same to a relatively low pressure as of 10^{+7} torr. Thus a beam can be transmitted for hundreds of miles through tubular envelope **15** without substantial loss of energy.

As an alternative to the use of the quadrupole lens **21**, the quadrupole beam focus structure **22** is extended into a transition region between the cathode **31** of the gun **12** and the entrance to pipe **15**. In this transition region, the quadrupole beam focus magnetic field intensity in the beam path gradually increases in strength from zero to its full value at the entrance to the main portion of the pipe **15** (see FIG. **13**).

At the power receiving location **16**, the beam is decelerated by a beam decelerator section **18** to a potential as close as possible to the potential of the source of electrons within the gun **12**, thereby converting the kinetic energy in the beam to potential electrical energy. The electrons of the beam, having low velocity (i.e., within 5% of the collector potential), are collected on the interior walls of the beam collector structure **17**, which operates close to the potential of the source of electrons within the gun **12**, whereby the beam energy converted to heat in beam collector **17** is minimized.

The collected beam current is caused to flow through an inverter load **24** to the vacuum envelope **15**, typically at local ground potential. The collected beam current is returned to the transmitting location **14** via the electrically conductive walls of the envelope **15**. The inverter **24** inverts the DC power to three phase AC output power which is supplied on output lines **25, 26** and **27**. In a typical example, the beam **19** has a current of 1,000 amps and is accelerated by the accelerator section **13** to a potential of one million volts, such that the power transmitted by the beam for transmitting location **14** to receiving location **16** is **1** gigawatt.

A control circuit **28**, as more fully disclosed below with regard to FIGS. **17–19**, monitors the potential V_C of the beam collector **17** and compares it with the potential V_k of the source of electrons to derive an error signal for controlling the beam current via a control electrode **29** in the electron gun **12** or adjustment of V_k, such that the power transmitted to the receiving end **16** is regulated to match the demand for power at the receiving end **16**.

The electron gun **12** includes a spherically concave thermionic cathode emitter **31** of sufficient area to emit the required electron current, such as 1,000 amps. Cathode emitter **31** is heated to thermionic emission temperature by means of a filiamentary heater **32**. Operating power is supplied to the filamentary heater **32** from a power supply **33**. A focus electrode **34** surrounds the peripheral edge of cathode emitter **31** to aid in shaping the electron beam in the region of cathode emitter **31**.

The control grid **29** is preferably of the type protected by a shadow grid wherein the shadow grid structure, operating at substantially cathode potential, is disposed immediately adjacent the surface of the cathode emitter **31** and the control grid has apertures in the shadow grid. As an alternative to a control grid, a modulating anode may be employed as the control electrode **29**.

The cathode emitter **31** is preferably dimpled, with the dimples having a lesser radius of curvature than that of the composite cathode emitter surface. The individual dimples in the cathode serve as separate cathode emitters for individual electron beamlets passing through the aligned openings in the shadow and control grid structures in a substantially non-intercepting manner. Such an electron gun and control grid structure is disclosed and claimed in U.S. Pat. No. 3,558,967, issued Jan. 26, 1971, and assigned to same assignee as the present invention.

In a typical example, thermionic cathode emitter **31** comprises an impregnated tungsten matrix cathode approximately 15 cm. in diameter and having an area of approximately 350 cm^2. At 1,000 amperes, such a cathode would operate at a current density of approximately 3 amperes per square centimeter. Tunsten matrix cathodes, impregnated with barium aluminate, can operate continuously for 5 years at this current density.

The beam accelerator section **13** is preferably of the type used with the Van de Graaffor Cockroft-Walton generators and is disclosed in an article entitled "Electrostatic Generators for the Acceleration of Charged Particles appearing in Reports on Progress in Physics, Vol. 11:1–18 (1948). Briefly, this type of accelerator includes a sequence of generally planar centrally apertured plate shaped electrodes **35** wherein the accelerating potential, as of 0.1 to 5 million volts, is evenly distributed among a number of the accelerating electrodes **35**. A potential divider **36** employs a string of resistors to divide the beam potential V_b for application of respectively increasing potentials to the respective ones of the accelerating electrodes **35**. The potential difference between successive electrodes **35** in the accelerator section **13** is preferably less than 200 kilovolts to prevent arcing between the adjacent electrodes **35**.

Electrodes **35** serve to provide a uniform beam accelerating electric field within the beam path **19**; the first few ones of electrodes **35** near the upstream end of the beam path **19** serve to focus and to converge the electron stream. In a typical example, the beam would be converted from a diameter of 15 cm. at cathode emitter **31** to approximately a diameter of 5 cm. at the output end of accelerator section **13**.

A three phase rectifier **38** receives the three phase input power from a power generator or the like and rectifies this three phase input to produce direct output current at a high negative cathode voltage V_k, as of –0.1 million volts to –5 million volts.

FIG. **2** shows, in section, the evacuated envelope **15** and beam focus structure **22**. More particularly, evacuated envelope **15** comprises a pipe made of an electrically conductive material, as of aluminum. In a preferred embodiment, the pipe also serves as the return electrical conductor of the power transmission system **1** such that the collected beam current flows back to the power supply of the electron gun **12** through a return path which is symmetrical relative to the beam **19**. In this manner, undesired magnetic defocusing of the beam by the magnetic field of the beam current loop is avoided. In the preferred embodiment, the pipe **15** is electrically insulated from earth such as by the ferrite permanent magnets **22**. In a typical example, aluminum pipe **15** has a diameter of approximately 10 cm. and a wall thickness of approximately 3 mm.

The beam focus permanent magnets **22** are disposed around pipe **15** at 90° spacing for a quadrupole type of "strong" magnetic focusing. In strong magnetic beam focusing a quadrupole magnetic field is provided which has flux lines which lie in planes almost perpendicular to the direction of the beam. The flux lines are made to rotate about the beam by spiraling permanent magnets **22** around pipe **15**. The permanent magnets are radially polarized, with the magnetic poles alternating in polarity in the circumferential direction around the pipe **15**. Although the preferred embodiment utilizes a quadrupole magnetic structure, other multiple pole structures may also be used, such as 6, 8, 10 or 12 poles etc. Also other types of magnetic focusing may be employed such as a series of discrete magnetic lenses or a confining magnetic field.

As an alternative to the use of permanent magnets for producing the beam focus magnetic field, electromagnets are employed. The electromagnetic equivalent is useful where operating temperatures are encountered which are outside of the rated operating temperature range of the permanent magnet material. A quadrupole electromagnetic beam focus structure comprises four conductors **40** spiraling around the pipe **15** in 90° circumferentially spaced relation (see FIG. 2A), and energized with direct current of opposite direction in adjacent conductors **40**.

An electron traveling parallel to the beam path **19** will interact with a magnetic vector at right angles to its direction of travel. The field has a strength proportional to the distance between the electron and the axis of the beam path. The magnetic vector rotates in a direction around the pipe at twice the rate of the quadrupole rotation. The magnetic vector will cause the electrons to follow a helical path. The magnetic focusing force of the quadrupole field on the electron, when the electron is far from the axis, is larger than the defocusing force when the electron is near the axis. As a result, there is a net time averaged inward focusing force.

In this kind of focusing, the magnetic field need only provide a focusing force that is sufficient to compensate for the difference between the space charge forces, which tend to defocus the beam, and the beam self focusing magnetic field. The problem of focusing the beam is less severe at high beam voltage since the space charge forces are reduced at a given current flow and the self magnetic field of the beam tends to compensate the space charge repulsion. This means that smaller focusing fields can be used to confine the beam. For example, at one million volts, eight-ninths of the space charge force is neutralized by the self-magnetic field of the beam current. Since the focusing force is proportional to the distance of the electron from the axis of the pipe **15**, the beam will tend to follow the center of pipe **15** even if the pipe has curvature.

Magnetic focusing results in ion trapping, which leads to plasma instability. Residual gas molecules within the pipe, when struck by electrons produce positive ions which are attracted toward the center of the beam. The positive ions in the center of the beam tend to neutralize the space charge repulsion, causing the beam to condense toward the center. Therefore, ion drainage or neutralization is required. The simplest way to obtain ion neutralization is to turn off the beam periodically for a few microseconds to allow the ions to move to the wall of the pipe **15**, where their charge will be lost. The time required for ion neutralization of the beam at a pressure of 10^{-7} torr at an electron energy of **1** megavolt is about 5 milliseconds. Thus, the beam is turned off by means of grid **29** every few hundred microseconds, for a few microseconds, causing any ions that have formed to mutually repel each other and drain to the wall. As an alternative, (shown in FIG. 3) insulated negative electrodes may be provided at suitable spacings along and within the pipe **15** for generation of periodic electric fields (potential wells) for drawing the ions to the electrodes. More particularly, each ion drain may include an enlarged diameter section of the pipe **15'** to provide an annular recess to receive a metallic ring shaped drain electrode **1** supported from a conductive post **2** via a feedthrough insulator **3**. The post **2** is connected to source of negative potential **4**, as of −100 to −1,000 V, for collecting and draining positive ions from within the pipe **15**. Various suitable ion draining electrodes and schemes are disclosed in U.S. Pat. No. 2,963,605 issued Dec. 6, 1970.

In a preferred embodiment, the permanent magnets **22** are made of grain oriented ferrite particles with a BH product of nearly 4 million gauss-oersteds. Such a material is commercially available at 2,000 gauss and 2,000 oersteds in which the ferrite particles are bonded in a flexible plastic so that half of the energy product of the oriented ferrite is sacrificed for the convenience of flexible plastic bonding. Such a material has sufficient magntic energy for this application. This material is also relatively inexpensive in large quantity. Any other permanent magnetic material might be substituted.

For a permanent magnet focus system capable of focusing, for example, a one megavolt, 1,000 ampere beam, the energy stored in the focusing field is 0.69 joule per meter of length; therefore, 16,000 cubic inches of one million gauss-oersted magnetic material per mile of line length would be required. The magnets **22** are placed external to the vacuum envelope **15** so as not to contaminate the vacuum. A tubular magnetic shield **41** surrounds magnets **22**. In a typical example, the magnetic shield **41** may comprise a spiral wound soft iron tape 0.010 inch thick. The focusing magnetic field required inside of the pipe **15** for focusing the beam is in the range of 100 to 200 gauss.

The vacuum envelope **15** is evacuated by a plurality of glow discharge getter ion vacuum pumps, such as VacIon pumps commercially available from Varian Associates of Palo Alto, Cal. These pumps have no moving parts, produce extremely clean vacuums free from any oil contamination and consume very small amounts of power when pumping on a closed system. In addition, these pumps have very long life under these conditions. Approximately 18 8-liter per second vacuum pumps **23** are required for each mile of length of the pipe **15**. Such a vacuum system would consume approximately 0.54 watt per mile (3,000 volts at 180 microamperes).

Under certain operating values of beam voltage and current and as a function of the diameter and length of the pipe **15**, microwave electromagnetic interaction may be obtained between space charge waves of the beam **19** and microwave energy propagating within the pipe **15**. This results in undesired velocity and current modulation of the beam as well as the generation of undesired amounts of microwave energy within the pipe **15**. Accordingly (See FIG. **4**), wave traps **5** or other means of coupling a lossy material to the microwave electromagnetic fields within the pipe **15** are located along the pipe for absorbing the undesired microwave energy to damp out undesired microwave oscillations. In a typical mode trap **5**, an evacuated chamber **6** containing an array of resistive card wave energy absorbers **7** is coupled to the microwave fields of the pipe **15** via a suitable coupling slot or hole **8**. As an alternative, the inside wall of the pipe **15** may be coated with a lossy coating of a lossy allow of Al, Fe and Co, such as Kanthal.

As another alternative, the pitch of the spiraling quadrupole beam focus magnet structure is varied by, for example, ± 20% in a random way to avoid cumulative fast wave beam-field interactions and their resulting oscillations.

At the receiving location **16** the beam decelerating section **18**, similar to the beam accelerator section **13** except turned end-for-end, serves to decelerate the beam to a beam voltage as close as possible to the voltage of the cathode emitter **31**, namely, V_k without reflecting beam current to the decelerator section **18**.

The decelerated beam is received within the depressed beam collector structure **17**; the collector operates at a potential V_c approximately equal to the decelerated beam or source potential V_k. In a preferred embodiment, the depressed collector structure **17** is of the type disclosed and claimed in U.S. Pat. No. 3,453,482 issued **1** July 1969 and preferably includes the improvement of the center spike as disclosed and claimed in copending U.S. Pat. No. application Ser. No. 283,433 filed 24 Aug. 1972, both assigned to the same assignee as the present invention. The depressed collectors of this type are very efficient and operate with beam collecting efficiencies of 98%, i.e., only 2% of the transmitted power is lost in the collector **17**. However, in one gigawatt transmission system with 98% beam recovery, there is still **20** megawatts of power which must be dissipated in the collector **17.**

The collector **17** is preferably of the water or liquid cooled type disclosed in U.S. Pat. Nos. 3,374,523 issued 25 Mar. 1968 and 3,414,757 issued 3 Dec 1968 and assigned to the same assignee as the present invention. The collector should be scaled in size such that the power dissipation on the interior surfaces thereof results in a power density of below 1 kilowatt per square centimeter.

One main advantage of the electrical power transmission system **11** of the present invention is that it provides means for transmitting a gigawatt quantity of electrical power at relatively low cost per mile and low loss. This is because of the elimination of high voltage, the source of most of the problems in conventional transmission lines from the main portion of the line. Energy is transmitted instead of kinetic form by means of a beam of electrons. The high energy electron beam is launched, transmitted through evacuated pipe **15** and recovered with losses low enough to be competitive with conventional overhead high voltage transmission lines. The economic savings in right-of-way cost and ecological advantages of less ozone generation and elimination of unsightly towers excavations in either underground or above ground installations justify its use. Pipe **15** may be installed underground in a ditch or, for above ground systems, can simply lie on the surface or be supported by bents, a catenary, or existing bridge structures.

FIGS. **5–8** show a polyphase electric power transmission system **42** similar to that previously described with regard to FIGS. **1–2** with the exception that the rectification and inversion functions have been combined with the transmission system. More particularly, six separate electron guns **12** and their respective beam accelerator sections **13** are disposed at the transmitting location **14** for projecting six separate electron beams into respective pipes **15'**. Each pipe is magnetically shielded and provides strong magnetic focusing and converges toward the common magnetically shielded and magnetic focused pipe **15** leading to the receiving location **16.** A magnetic deflection yoke **43** is provided at the confluence of the respective beam input pipes **15'**, at the transmitting location **14**, for sequentially and selectively deflecting the electron beams from respective ones of the electron guns **12** into common pipe **15.**

Similarly, at the receiving location **16** the main transmission pipe **15** splits into six separate pipes **15'** each leading to a respective beam decelerator section **18** and a depressed collector **17.** A magnetic deflection yoke **44** is provided for sequentially deflecting the output electron beam into respective ones of the output pipes **15'**. Deflection yokes **43** and **44** are of the conventional type used in cathode-ray tubes or in accelerator-to-target deflection systems of high energy particle accelerating machines such as at the Stanford Linear Accelerator Center at Stanford, Cal.

Input power to be transmitted to the receiving location **16** is supplied to the transmitting location **14** from a suitable generator, not shown. The three phase input power is applied to the primary windings **45** of an input transformer **46.** The primary windings **45** are connected in the delta configuration as shown in FIG. **6** and the secondary windings **47** of the input transformer **46,** as shown in FIG. **7,** are each center-tapped at ground or V_b potential and wound in a **6** phase configuration. The opposite ends of the center-tapped windings **47** are coupled to the cathode emitters of each of the pair of guns **12** for a respective phase of the three phase transmission system. For example, for the A phase, one end of the center-tapped winding **47** is coupled to one gun and the other end of the center-tapped winding **47** is coupled to the other gun. Due to the self rectification characteristic of the thermoionic diodes, each of the guns of a particular phase would, in the absence of a control electrode **29,** conduct only during one-half of the cycle, such conduction halves being 180° out of phase with respect to each other.

Control signals are applied to the control grids **29** via modulators **48** for limiting the beam conduction phase angle for each gun **12.** More particularly, the conduction phase angle is limited to a first approximation to $2p/360°$ where p is the number of phases for the polyphase transmission system **42.** In the case of a three phase system utilizing six electron guns, the beam conduction angle for each of the guns is limited to 60°, and would normally be centered on the time when the applied voltage is a maximum. The operation of the magnetic deflection yoke **43** is synchronized with the potentials applied to each of the respective guns via leads **49** which feed into a deflection control circuit **51** and which serve to synchronize the input and output beam deflectors **43** and **44,** respectively, such that the beam current is directed into the proper beam collector **17.**

At the power receiving location **16,** each phase of the three phase system has its respective pair of collectors connected to opposite ends of one of three center tapped primary windings **52** of an output transformer **53.** The secondary windings **54** of the output transformer **53** are connected in the delta configuration as shown in FIG. **6.** An output voltage Vc is sensed across each of the respective phases of the output primary windings **52** via voltage sensors **55** (See FIG. **9**) and these voltages are fed back to the gun modulators **48** to control the amount of the beam current drawn from each of the respective guns such that the power delivered to the load is equal to the power demanded by the load as more fully described below with regard to FIGS. **17–19.**

Due to the relatively short conduction phase angle for each of the electron guns and therefore the short phase angle for current delivered to each of the respective collectors, the current pulses delivered to the primary windings **52** of the output transformer **53** will be rich in harmonics of the power frequency.

However, the connection of the collectors **17** of each phase (three phase system) to opposite ends of the respective output primary windings **52** serves to cancel out the even harmonics of the power frequency (i.e. 60 Hz). In addition, the balanced connection of the collectors **17** relative to the centertap in the output primary windings **52** serves to prevent undesired saturation effects of the transformer **53** due to the DC component of current flowing through each primary winding **52.** The third harmonic and multiples thereof are effectively cancelled by using the delta connected secondary windings. The 5th, 7th, 11th, 13th, etc. odd harmonics are bypassed by means of multiplicity of series resonant filters, such as filter **56,** tuned for each respective odd harmonic and connected in shunt with the respective primary output winding **52.**

The delta winding connection for cancelling of the third harmonic and multiples thereof is only operative in a three phase system or multiples of a three phase system. Accordingly, in a single phase or two phase system series resonant bypass filters **56** are employed for each third harmonic or odd multiples thereof, such as 3rd, 9th, **15**th, etc.

Typically, the lowest harmonic will have the largest amplitude. Thus, a fifth harmonic filter **56** may suffice dependent upon the shape of the beam current pulse. Also the beam current pulse is preferably shaped by a waveform shaping circuit which shapes the control electrode potential to reduce the fifth, seventh, eleventh, thirteeth, etc. harmonics of beam current. Such a wave shaping circuit is contained within modulator circuit **48** and is operative upon the shape of the signal fed to control electrode **29.**

For example, for a beam current pulse train as shown in FIG. **10,** there is a certain value of beam conduction angle which will reduce any given harmonic of the pulse repetition frequency of beam current to zero. Thus, the wave shaping circuit controls the beam conduction angle to minimize the certain harmonic. Each of the primary windings **42** has a bypass capacitor **57** connected in parallel with the inductance of each of the primary windings **52** for bypassing harmonics of higher order than those filtered by filters **56.**

Referring now to FIg. **9,** there is shown an alternative electron beampower transmission system similar to that previously described with regard to FIG. **5** with the exception that a pair of magnetically shielded and magnetically focused pipes **15** are employed for each phase of the AC power transmission system. For example, in a single phase system two pipes **15** are employed. The pair of electron guns **12** for each phase of the AC power transmission system are connected in 180° out of phase relation by connection of the cathode emitters **31** to opposite ends of a center tapped secondary winding **47** of the input transformer **46.**

The advantage of the AC power transmission system of FIG. **9** is that the conduction phase angle can be increased to a value substantially in excess of the 60° conduction phase angle for the three phase system of FIG. **5.** This reduces the harmonic content in the beam current supplied to the output transformer **53.**

However, it is generally undesirable to employ the whole 180° beam conduction phase angle during each conductive half cycle of the applied alternating beam potential. The reason for this is that at relatively low values of beam voltage V_b, the electrons have relatively low velocities and thus correspondingly relatively long transit times through the pipe **15.** In such a case, some overtaking of the slow electrons may be obtained by subsequent fast electrons. This has a deleterious effect upon the beam collector efficiency since, for high collector efficiency, all the electrons at a given instant in time should have the same velocity. Also, such overtaking will cause distortion of the current waveform, usually increasing the unwanted harmonic content thereof. Also, the beam focus system, depending upon the particular magnetic focusing scheme employed, may not properly focus electrons over wide ranges of electron velocities.

Therefore, it is preferred to limit the conduction of beam current to only a portion of the cycle of applied beam voltage corresponding to a value of bean current greater than one-sixth of the peak or maximum beam current, i.e. $I_{MAX}/6$.

Referring now to FIG. **10,** there is shown the waveforms for beam current I_b, beam voltage V_b and control electrode voltage V_{g1} and V_{g2}. The beam conduction angle is readily controlled by applying a fixed DC negative bias voltage V_a to each of the respective control electrodes **29** such that the beam conduction angle is limited to that portion of the cycle corresponding to a respective grid voltage exceeding the cathode voltage V_k. The beam conduction angle can then be varied and controlled as desired by increasing or decreasing th magnitude of the dc negative grid bias voltage V_a.

Returning again to FIG. **9,** it is desirable to control the power factor of the load as reflected into each of the primary windings **52** of the output transformer **53** such that the collected beam current I_c is in phase with the respective collector potential V_c. Accordingly, a continuously variable reactance, such as that provided by a synchronous condenser **58,** is preferably connected across each of the respective output delta connected secondary windings **54.** A voltage is derived which is proportional to the collected beam current I_c. This voltage is derived from a current transformer **59** connected between the centertap of the primary winding **52** and the pipe **15.** This voltage is fed to one input of a phase comparator **60** for comparison with the phase of the respective collector voltage V_c as derieved from the sensor **55** to derive an error output which is fed to the field control of the synchronous condenser **58** for causing the condenser **58** to take the proper value of reactance to bring the beam collector current I_c into phase with the collector voltage V_c. The power factor control circuitry of FIG. **9** is also utilized to advantage in the system of FIG. **5.**

Referring now to FIG. **11,** there is shown an AC power transmission system similar to that of FIG. **9** wherein a common magnetically focused and magnetically shielded pipe **15** is employed for each phase of the AC power transmission system. More particularly, convergent and divergent pipes **15'**, as previously described with regard to FIG. **5,** are employed at the transmitting and receiving locations, respectively, for feeding the electron beams from the guns of each phase into the common pipe **15** and out of the common pipe to respective collectors of each phase. The deflection of the beams at the transmitting and receiving locations is obtained by a deflection control circuit driving each of the deflecting magnets **43** and **44** is response to inputs derived from the respective guns. The advantage of the system of FIG. **11** over that previously described with regard to FIG. **9** is that only one pipe **15** is required for each phase of the AC power transmission system.

Referring now to FIG. 13, there is shown an alternative embodiment to that portion of the structure of FIG. 11 delineated by line 13—13. More particularly, the input deflection magnet **43** is replaced by strong magnetically focused and convergent input pipes **15''**. However, magnetic deflection is still required at the receiving location.

Referring now to FIG. **12**, there is shown an alternative three phase power transmission system **59** incorporating alternative embodiments of the present invention. More particularly, the system is similar to that previously described with regard to FIG. **5** with the exception that only one pipe **15** is provided for each phase of a three phase system and collection of beam current through each phase of the three phase system occurs only once per cycle at the power frequency, as contrasted with twice per cycle at the power frequency as indicated in FIG. **10**. The windings **47** and **52** have only three phases as contrasted with six phases as shown in FIG. **7**.

The power transmission system **59** of FIG. **12** has the advantage of simplicity in that it provides only one pipe **15** per phase of the three phase system but it has the disadvantage that the harmonic content of the current delivered to the primary windings **52** of the output transformer is greater than that obtained in the system of FIg. **9**.

Referring now to FIGS. **14** and **15**, there is shown an alternative multiple pipe polyphase A.C. transmission system **62**. Transmission system **62** is similar to that of FIG. **5** with the exception that a pair of pipes **15** is provided for each phase of the polyphase system, as shown in the system of FIG. **9**. In this system **62**, the beam current through each of the pipes **15** does not have to be limited to 360/2p° of phase angle where p is the number of phases. In the case of three phase system, the conduction of current is preferably limited to a phase angle such that the current conducted has a value greater than one-sixth Imax, where Imax is the peak beam current for each phase. This means that current is conducted from each gun for approximately 120°–140° of phase angle of the input voltage waveform, as shown in FIG. **10**. This reduces the harmonic content in the current flowing in the primary windngs **52** of the output transformer **53**. One advantage of the system of FIG. **14** is that the filtering of undesired harmonics in the output of the transformer **53** is simplified at the expense of additional pipes **15**. A second advantage is the elimination of the magnetic deflectors **43** and **44**.

A further advantage of the system of FIG. 14 is that the beam current return paths are separate for each beam to prevent cross flow of beam return current flow with attendant potential differences between the various pipes **15** as encountered with unbalanced loads. However, the windings **47** and **52** are balanced in the transformers **46** and **53** to avoid D.C. saturation of the transformer cores, i.e., bucking connected for beam current flow.

As an alternative to the system **62** of FIG. **14**, the number of pipes **15** can be reduced to one per phase of the polyphase A.C. system by using a common pipe **15** per phase and employing the magnetic deflection system of FIG. **11** for sequentially deflecting beams from respective pairs of guns 12 into and out of the respective common pipe **15**. In this latter system, the input magnetic deflection can be eliminated since the input magnetic pipes **15'** will focus the respective beams sufficiently to allow the individual beams to negotiate the bends in the pipes **15'** at the confluence of the pipes **15** with the common pipe **15** as shown in FIG. **13**.

Referring now to FIG. **16**, there is shown an alternative transmission system **72** of the present invention. The power transmission system **72** of FIG. **16** is similar to that of the system of FIG. **1** with the exception that RF accelerator means **73** are employed for bunching and accelerating the bean to relatively high energies, for example, 100 MeV.

The radio frequency accelerator **73** comprises a plurality of individual cavity resonators **74**, as of 250 such cavities, sequentially arranged along the beam path **19** for successive electromagnetic interaction with the beam for velocity modulating the beam with RF energy at the resonant frequency of the resonators **74**. In a typical example, the resonators **74** are of the folded half wavelength type as used in the accelerator at the National Accelerator Laboratory of Batavia, Ill. The resonators are tuned to a suitable radio frequency, as of 30 megahertz, and are driven in the proper phase relation from a 30 megahertz oscillator **75** via phase shifters **76** and power amplifiers **77**.

The power amplifiers **77** are preferably conventional tetrodes providing high efficiency, i.e., greater than 90% in class C operation with small angle of current flow and possibly third harmonic squaring of the plate voltage. Phase-locked magnetron oscillators could also be utilized as a source of microwave energy for driving the cavities **74**, but a lower frequency has the further advantage of decreasing debunching effects due to both velocity spread and space charge effects.

For a finite beam of small diameter in pipe **15**, the longitudinal plasma frequency is proportional to the driving frequency. The plasma frequency for a 30 megahertz driving frequency is about 2,000 hertz for a 10 ampere, 100 megavolt beam. The corresponding debunching wavelength is 150 kilometers.

It is desired to maintain the electron bunches for more efficient RF energy extraction at the receiving location **16**. Accordingly, an inductive cavity, i.e. a cavity resonant slightly above the frequency of the RF driving energy, is placed on the beam **19** every few kilometers, such as **10**. These rebunching cavities **78** are excited by the bunched beam entering the cavity and the fields of the cavity interact back on the electron beam to velocity-modulate the bunched beam in such a manner as to cause a rebunching of the electron. Thus, the electron beam **19** is received at the receiving location **16** as a well bunched current density modulated beam of high velocity, as of 100 MeV. The beam is bunched at the frequency of the radio frequency accelerator, such as 30 meghertz.

At the receiving location a plurality of decelerating cavities **79**, tuned to the frequency of the radio frequency energy imparted to the beam, are successively coupled to the beam for extracting kinetic energy therefrom and converting same to RF energy. The decelerating cavites **79** are substantially identical to accerlating cavities **74** and each cavity is capable of generating a relatively high RF voltage thereacross on the order of 400 kV per cavity.

A rectifier load **81** is connected to each of the cavity resonators **79** for rectifying the RF energy extracted from the beam. The rectified DC energy is applied to an output coaxial line **82**. The output DC energy on line **82** is fed to the input of an inverter **24** for producing three phase output power on lines **25–27**.

Each of the resonators **79** of the output decelerator section **83** serves to extract kinetic energy from the beam. A sufficient number of output resonators **79** is provided for extracting the kinetic energy imparted to the beam by means of the accelerator section **73**. After the RF energy has been extracted from the beam, the beam may be collected on the pipe **15** or in a collector **17** coupled to the end of the pipe **15**. As in the other embodiments, an output signal is derived from the inverter which is a measure of the power demanded by the load. This load demand signal is fed to one input ot the control circuit **28** for controlling the beam current such that the power delivered to the load is equal to the power demanded by the load.

The inverter **24** may be replaced by two additional sets of rectifiers **81** which may comprise, for example, high power triodes. Each set of triode rectifiers is connected to a respective output bus similar to bus **82**. There is one output bus for each phase of a three phase system. Each output bus is connected to a primary winding of a three phase power transformer. The respective sets of triode rectifiers are sequentially gated at the AC power frequency, as of 60 Hertz, with 120° phase shift between each of the output power buses.

As an alternative, the gun **12** may be gated at the 60 Hertz power frequency and the three sets of output triode rectifiers synchronized with the 60 Hertz pulses of the beam.

An advantage to the high velocity electron beam transmission system of FIG. **16** is that the self magnetic field of the beam almost completely overcomes the repulsive space charge forces generated within the beam.

As an alternative to varying the beam current in the system of FIG. **16**, for matching the power delivered to the load to the power demanded by the load, the beam current is maintained constant and the number of resonators **74** employed for accelerating the beam varied in accordance with the output power demanded by the load.

Power is tapped off the beam intermediate the transmitting location **14** and the receiving location **16** by providing an output resonator **79** coupled in wave energy exchanging relation to the RF modulated beam and excited by the beam. As with the output resonators **79**, the RF power extracted via the cavity **79** is rectified via rectifier **81** and fed to a second load **80**. The load **80** may comprise an inverter **24** for providing three phase output power or three sets of rectifiers may be employed which are sequentially switched into a primary winding of a three phase transformer for providing inversion of the power to the load.

The intermediate output power tap comprising the resonator **79**, rectifier **81**, and load **80** is also utilized with any of the other DC transmission systems such as **11**, **42**, or FIG. **9**, by pulse modulating the beam at the resonant frequency of the cavity **79** without the necessity of the accelerating and decelerating RF structures **73** and **83**.

Referring now to FIGS. **17–19**, a number of circuits are shown for controlling the beam at the transmitting end **14** to insure that the electrons collected by the collector **17** strike the collector at nearly zero velocity so that no large amount of power is dissipated in the collector **17** (i.e. the system efficiency will be high). This zero velocity condition is realized when the cathode potential $V_k = V_2 = I_b R_L$, where V_c is the collector potential, I_b is the electron beam current, and R_L is the load resistance presented to the collector **17**.

There are two ways of accomplishing this end. First, both V_k and I_b are adjusted simultaneously so that $V_k = v_c$. Secondly the beam current I_b is adjusted to be equal to V_k/R_L by sensing the collector voltage V_c and setting the current I_b so that V_c equals V_k.

All of the above methods rely upon a comparison circuit for comparing V_c and V_k to derive the error control signal. The comparison circuit comprises an analog summing amplifier or a combination of analog-to-digital converters and digital summing logic of the type shown in FIG. **19**. More particularly, with regard to FIG. **19**, the collector voltage V_c is fed to a first analog-to-digital converter **91** to derive a first digital output proportional to V_c. The cathode potential V_k is applied to a second analog-to-digital converter **92** to derive a second digital output proportional to V_k. The two digital output are applied to a logic subtractor **93** for substraction therein to derive the error signal in the form of a digital output which is thence fed to a digital-to-analog converter **94** to derive an analog control signal (error signal).

The error signal, either analog or digital, which is proportional to the difference between the cathode potential V_k and collector potential V_c controls the system parameter selected for control.

Referring now to FIG. **17**, there is shown a control circuit for matching the cathode potential V_k to the collector potential V_c. In the circuit of FIG. **17** the cathode potential V_k is varied to be equal to the collector potential V_c while allowing the beam current to vary with variations in the cathode potential. The beam current I_b will vary as a function of the cathode potential V_k according to the relation: $I_b = KV_k^{3/2}$ where K is the beam perveance.

In the variable voltage cathode power supply **38**, the difference signal coming from the comparison circuitry **28** is used to vary the mechanical position of a variable mutual inductance transformer, such as an Inductrol, therein for varying the output potential V_k. As an alternative, the error signal derived from the output of the comparison circuit **28** is utilized as the input signal to a phase control regulator incorporated in the variable voltage power supply **38** for varying V_k.

Referring now to FIG. **18**, there is shown the second method for matching the cathode potential V_k to the collector potential V_c. The difference signal from the output of the comparison circuit **28** is amplified and applied to the control electrode **29** in the proper phase to reduce the difference signal to zero. In this case, the beam perveance K will vary up to some value which is dependent upon the system voltage (a constant), and the maximum system current. The beam focus system, such as the quadrupole, is designed to handle such a range of perveance.

In a further variation of the control system of FIG. **18** the peak current of the beam I_b is maintained constant while the average current is varied in accordance with the error signal derived from the comparison circuit **28**. The average current is varied by creating (in a pulse modulator **96**) a repetitive rectangular pulse signal applied to the control grid **29**. The duty factor of the repetitive pulse is varied by the output of the comparison circuit **28** in such a manner that the difference between the collector potential V_c and the cathode voltage V_k

tends toward zero. When this control variation is used, there must be enough capacitance in the collector circuit **17** and the repetition frequency of the current pulse is high enough so that the collector voltage V_c does not follow the rapid variations of the beam current I_b. The pulsed version of the control system of FIG. **18** imposes the most easily met requirements on the beam focus system. Also, the method of FIG. **18** (whether or not pulsed) is the most suitable when it is desired to deliver a varying amount of power to the receiving end **16** at a constant collector voltage such as would exist in the typical power system.

What is claimed is:

1. In an electron beam power transmission system for transmitting electrical power from a transmitting location to a receiving location remote from the transmitting location:

elongated evacuated envelope means extending from the transmitting location to a geographically removed receiving location;

transmitter means at the transmitting location for formng, accelerating, and projecting electrons over an elongated beam path extending within and along said evacuated envelope from the transmitting location to the receiving location; and

transmitter means at the transmitting location for accelerating and projecting electrons through said evacuated envelope means from the transmitting location to the receiving location;

receiver means at the receiving location for collecting the electrons and converting the kinetic energy thereof to electical power for application to a power load;

said transmitted means including first and second electron guns having first and second cathode emitters respectively for emitting electrons and first and second apertured anode electrodes respectively for drawing first and second streams of emitted electrons from said first and second cathode emitters to form respective first and second electron beams;

first and second converging evacuated envelope portions opening into a common portion of said elongated envelope means which extends from the transmitting location to the receiving location, said first and second convergent envelope portions being disposed to receive said first and second electron beams from said first and second electron guns, respectively, and to direct said respective beams via convergent first and second beam paths into a common beam path within said common portion of said elongated envelope means, and first and second beam focus means for focusing said first and second beams into said first and second convergent beam paths within said first and second envelope portions, respectively.

2. The apparatus of claim **1** wherein said means for supplying and applying the alternating potentials between said cathodes and anodes of said first and second guns includes, a transformer, and wherein said inductive means is a secondary winding means of said transformer having a centertap, and wherein said first and second anodes are connected to said centertap of said secondary transformer winding mean.

3. The apparatus of claim **1** wherein said means for supplying and applying the alternating potentials between said cathodes and anodes of said guns includes, a transformer having a core with primary and secondary windings thereon, said secondary windings including first and second secondary windings connected for applying said first and second alternating potentials to said respective first and second guns in the 180° out of phase relation, and wherein said first and second secondary windings are balanced and bucking wound on said transformer core as connected for conduction of cathode current drawn from said respective secondary windings by each of said first and second guns.

4. In a power transmission system for transmitting electrical power from a transmitting location to a remote receiving location;

elongated evacuated envelope means extending from the transmitting location to the receiving location geographically removed from the transmitting location;

elongated evacuated envelope means extending from the transmitting location to a geographically removed receiving location;

transmitter means at the transmitting location for forming, accelerating and projecting electrons over an elongated beam path extending within and along said evacuated envelope from the transmitting location to the receiving location; and

receiver means at the receiving location for collecting the electrons of the beam and for converting the kinetic energy of the beam to electrical power for application to a power load;

said transmitter means including an electron gun having a cathode emitter for emitting electrons and an apertured anode electrode for drawing a stream of electrons through said envelope means;

inductive means connected between said cathode emitter and said anode electrode for supplying and applying an alternating potential between said cathode emitter and said anode electrode for causing said gun to produce an electron beam from said gun during only every other half-cycle of the applied alternating potential;

control electrode means interposed between said cathode and anode means for controlling the flow of beam current from said gun during each beam forming half-cycle of the applied alternating potential; and

means for supplying and applying a control potential to said control electrode for limiting the flow of beam current from said gun to less than the full half-cycle of the applied alternating potential.

5. The apparatus of claim **4** wherein said first and second beam focus means each includes at least a quadrupole magnetic beam focusing structure.

6. In an electron beam power transmission system for transmitting electrical power from a transmitting location to a receiving location remote from the transmitting location;

receiver means at the receiving location for collecting the electrons of the beam and for converting the kinetic energy of the beam to electrical power for application to a power load;

said transmitter means including first and second electron guns having first and second cathode emitters respectively for emitting electrons and first and second apertured anode electrodes respectively for drawing first and second streams of emitted electrons from said first and second cathode emitters to form respective first and second electron beams;

means for supplying and applying an alternating potential between said cathode emitter and said anode electrode of each of said first and second guns in 1802 out of phase relation such that the potential of said first cathode of said first gun is negative relative to the potential of said first anode electrode when the potential of said second cathode of said second gun is positive relative to the potential of said second anode electrode and vice versa;

said means for supplying and applying the alternating potential to said first and second guns including an inductive means connected between said first and second cathode emitters, and said first and second anodes being connected to said inductive means intermediate said connections of said first and second cathode emitters.

7. The apparatus of claim 1 wherein said control potential supplying and applying means supplies and applies a control potential of a value and waveform such as to limit conduction of beam current to that portion of the cycle of applied alternating potential corresponding to a beam current of not less than $I_{max}/6$, where I_{max} is the peak beam current during the beam conductive half-cycle of the applied alternating potential.

8. In a power transmission system for transmitting electrical power from a transmitting location to a remote receiving location:

elongated evacuated envelope means extending from the transmitting location to the geographically removed receiving location;

transmitter means at the transmitting location for accelerating and projecting electrons through said evacuated envelope means from the transmitting location to the receiving location;

receiver means at the receiving location for collecting the electrons and for converting the kinetic energy thereof to electrical power for application to a power load;

said receiver means including first and second electron collectors for collecting the electrons, electrical insulator means for insulating said first and second collectors from said evacuated envelope means to permit independent potentials to be established on said collectors relative to said envelope means, means for causing electrons to be collected in an alternating sequence in said first and second electron collectors, in 180° phase relation at the fundamental frequency of a power frequency for the electrical power to be delivered to the load first and second bucking would balanced inductive winding means connected to said first and second collectors for flow of collected beam current therethrough in 180° out of phase relation at the power frequency.

9. The apparatus of claim **8**, wherein said receiver means includes, an output power transformer means and said first and second inductive winding means comprises primary winding means of said transformer.

10. The apparatus of claim **8** wherein the power transmission system is a three phase system and said receiver means includes an output power transformer means, said first and second inductive winding means comprises primary winding means of said transformer, and wherein said transformer includes secondary winding means, said secondary winding means being connected in a delta configuration.

11. The apparatus of claim **8** including first and second series resonant circuits connected in shunt with respective ones of said first and second winding means, said series tuned circuits each being resonant for an odd harmonic of the power frequency.

12. The apparatus of claim **11** wherein said series tuned circuits are each resonant at the fifth harmonic of the power frequency.

13. In a power transmission system for transmitting electrical power from a transmitting location to a receiving location remote from said transmitting location:

elongated evacuated envelope means extending from the transmitting location to the receiving location geographically removed from the transmitting location;

transmitter means at the transmitting, location for accelerating and projecting electrons through said evacuated envelope means from the transmitting location to the receiving location;

receiver means at the receiving location for collecting the electrons and for converting the kinetic energy thereof to electrical power for application to a power load;

said transmitter means including an electron gun having a cathode emitter for emitting electrons and an apertured anode for drawing the stream of electrons from said cathode emitter;

inductive means connected between said cathode emitter and said anode electrode for supplying and applying an alternating potential between said cathode emitter and said anode electrode at a power frequency for causing said gun to produce an electron beam from said gun during only every other half-cycle of the applied alternating potential;

control electrode means interposed between said cathode emitter and said anode electrode means for controlling the flow of beam current from said gun during the beam conductive half-cycle of the applied alternating potential; and

means for supplying and applying a train of control potential pulses to said control electrode for shaping the flow of beam current from said gun during the beam conductive half-cycle of the applied alternating potential to suppress at least one odd order harmonic of the power frequency of the collected beam current.

14. The apparatus of claim **13** wherein said control potential is shaped by said supplying means to provide a beam conductive phase angle to suppress the odd order harmonics of the beam current.

15. In a power transmission system for transmitting electrical power from a transmitting location to a remote receiving location:

elongated evacuated envelope means extending from the transmitting location to the receiving location geographically removed from the transmitting location;

transmitter means at the transmitting location for accelerating and projecting electrons through said evacuated envelope means from the transmitting location to the receiving location;

receiver means at the receiving location for collecting the electrons and for converting the kinetic energy thereof to electrical power for application to a power load;

said receiver means including electron collector means for collecting the electrons, electrical insulator means for insulating said collector means from said evacuated envelope to permit independent potentials to be established on said collector means relative to said envelope, means for causing electrons to be collected in a sequence of pulses of beam current in said collector means, output transformer means coupled to said collector means for supplying a current to the power load in response to collected beam current, said transformer means including a primary winding means connected to said collector means for conduction of collected beam current therethrough;

means for sensing an output proportional to the collected beam current, means for sensing an output proportional to the collector potential;

means for comparing the phase of the collected current signal with the phase of the collector voltage signal to derive a power factor load correction signal; and

means connected to the secondary of said power transformer means for controlling the power factor of the current delivered to the load in response to the error signal derived from said comparator means, whereby the phase of the collected beam current is brought into coincidence with the phase of the collector potential established on said beam collector means.

* * * * *

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,916,246 Dated October 28, 1975

Inventor(s) Donald Henry Preist Page 1 of 4

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 17 (Claim 1) delete lines 26-29.

Column 17 (Claim 1) line 34, change "transmitted" to -- transmitter --.

Column 17 (Claim 1) delete lines 41-55 and substitute --

> means for supplying and applying an alternating potential between said cathode emitter and said anode electrode of each of said first and second guns in 180° out of phase relation such that the potential of said first cathode of said first gun is negative relative to the potential of said first anode electrode when the potential of said second cathode of said second gun is positive relative to the potential of said second anode electrode and vice versa;

Signed and Sealed this

Twenty-second Day of February 1977

[SEAL]

Attest:

RUTH C. MASON
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents and Trademarks

said means for supplying and applying the alternating potential to said first and second guns including an inductive means connected between said first and second cathode emitters, and said first and second anodes being connected to said inductive means intermediate said connections of said first and second cathode emitters.--

Column 18 (Claim 4) delete lines 17-48 and substitute --

transmitter means at the transmitting location for accelerating and projecting electrons through said evacuated envelope means from the transmitting location to the receiving location;
receiver means at the receiving location for collecting the electrons and converting the kinetic energy thereof to electrical power for application to a power load; said transmitted means including first and second electron guns having first and second cathode emitters respectively for emitting electrons and first and second apertured anode electrodes respectively for drawing first and second streams of emitted electrons from said first and second cathode emitters to form respective first and second electron beams;
first and second converging evacuated envelope portions opening into a common portion of said elongated envelope means which extends from the transmitting location to the receiving location, said first and second convergent envelope portions being disposed to receive said first and second electron beams from said first and second electron guns, respectively, and to direct said respective beams via convergent first and second beam paths into a common beam path within said common portion of said elongated envelope means, and first and second beam focus means for focusing said first and second beams into said first and second convergent beam paths within said first and second envelope portions, respectively.--

Donald Henry Preist

Column 18 (Claim 6) delete lines 56-66 and substitute --

elongated evacuated envelope means extending from the transmitting location to the receiving location geographically removed from the transmitting location;
transmitter means at the transmitting, location for accelerating and projecting electrons through said evacuated envelope means from the transmitting location to the receiving location;
receiver means at the receiving location for collecting the electrons and for converting the kinetic energy thereof to electrical power for application to a power load;
said transmitter means including an electron gun having a cathode emitter for emitting electrons and an apertured anode for drawing the stream of electrons from said cathode emitter;
inductive means connected between said cathode emitter and said anode electrode for supplying and applying an alternating potential between said cathode emitter and said anode electrode at a power frequency for causing said gun to produce an electron beam from said gun during only every other half-cycle of the applied alternating potential;
control electrode means interposed between said cathode emitter and said anode electrode means for controlling the flow of beam current from said gun during the beam conductive half-cycle of the applied alternating potential; and
means for supplying and applying a train of control potential pulses to said control electrode for shaping the flow of beam current from said gun during the beam conductive half-cycle of the applied alternating potential to suppress at least one odd order harmonic of the power frequency of the collected beam current.--

Column 19 (Claim 6) delete lines 1-16.

Column 19 (Claim 7) line 17 delete "1" and insert --6--.

Column 20 (Claim 13) line 17 delete "," comma.

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 3,916,246 Page 1 of 6

DATED : October 28, 1975

INVENTOR(S) : DONALD HENRY PREIST

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 17, (Claim 1), delete lines 14 through 55 and substitute

1. In an electron beam power transmission system for transmitting electrical power from a transmitting location to a receiving location remote from the transmitting location:

elongated evacuated envelope means extending from the transmitting location to a geographically removed receiving location;

transmitter means at the transmitting location for forming, accelerating, and projecting electrons over an elongated beam path extending within and along said evacuated envelope from the transmitting location to the receiving location; and

receiver means at the receiving location for collecting the electrons of the beam and for converting the kinetic energy of the beam to electrical power for application to a power load;

said transmitter means including first and second electron guns having first and second cathode emitters respectively for emitting electrons and first and second apertured anode electrodes respectively for drawing first and second streams of emitted electrons from said first and second cathode emitters to form respective first and second electron beams;

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 3,916,246

DATED : October 28, 1975

INVENTOR(S) : DONALD HENRY PREIST

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

means for supplying and applying an alternating potential between said cathode emitter and said anode electrode of each of said first and second guns in 180° out of phase relation such that the potential of said first cathode of said first gun is negative relative to the potential of said first anode electrode when the potential of said second cathode of said second gun is positive relative to the potential of said second anode electrode and vice versa;

said means for supplying and applying the alternating potential to said first and second guns including an inductive means connected between said first and second cathode emitters, and said first and second anodes being connected to said inductive means intermediate said connections of said first and second cathode emitters.

Column 18, (Claim 4) delete lines 10 through 48 and substitute 4. In an electron beam power transmission system for transmitting mitting electrical power from a transmitting location to a receiving location remote from the transmitting location;

elongated evacuated envelope means extending from the transmitting location to a geographically removed receiving location;

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

Page 3 of 6

PATENT NO. : 3,916,246
DATED : October 28, 1975
INVENTOR(S) : DONALD HENRY PREIST

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

transmitter means at the transmitting location for forming, accelerating and projecting electrons over an elongated beam path extending within and along said evacuated envelope from the transmitting location to the receiving location; and

receiver means at the receiving location for collecting the electrons of the beam and for converting the kinetic energy of the beam to electrical power for application to a power load;

said transmitter means including an electron gun having a cathode emitter for emitting electrons and an apertured anode electrode for drawing a stream of electrons through said envelope means;

inductive means connected between said cathode emitter and said anode electrode supplying and applying an alternating potential between said cathode emitter and said anode electrode for causing said gun to produce an electron beam from said gun during only every other half-cycle of the applied alternating potential;

control electrode means interposed between said cathode and anode means for controlling the flow of beam current from said gun during each beam forming half-cycle of the applied alternating potential; and

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 3,916,246
DATED : October 28, 1975
INVENTOR(S) : DONALD HENRY PREIST

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

means for supplying and applying a control potential to said control electrode for limiting the flow of beam current from said gun to less than the full half-cycle of the applied alternating potential.

Column 18, (claim 6), delete lines 52 through 66; Column 19, claim 6, delete lines 1 through 16, and substitute

6. In a power transmission system for transmitting electrical power from a transmitting location to a remote receiving location:

elongated evacuated envelope means extending from the transmitting location to the receiving location geographically removed from the transmitting location;

transmitter means at the transmitting location for accelerating and projecting electrons through said evacuated envelope means from the transmitting location to the receiving location;

receiver means at the receiving location for collecting the electrons and converting the kinetic energy thereof to electrical power for application to a power load;

said transmitter means including first and second

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 3,916,246

DATED : October 28, 1975

INVENTOR(S) : DONALD HENRY PREIST

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

electron guns having first and second cathode emitters respectively for emitting electrons and first and second apertured anode electrodes respectively for drawing first and second streams of emitted electrons from said first and second cathode emitters to form respective first and second electron beams;

first and second converging evacuated envelope portions opening into a common portion of said elongated envelope means which extends from the transmitting location to the receiving location, said first and second convergent envelope portions being disposed to receive said first and second electron beams from said first and second electron guns, respectively, and to direct said respective beams via convergent first and second beam paths into a common beam path within said common portion of said elongated envelope means, and first and second beam focus means for focusing said first and second beams into said first and second convergent beam paths within said first and second envelope portions, respectively.

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

Page 6 of 6

PATENT NO. : 3,916,246

DATED : October 28, 1975

INVENTOR(S) : DONALD HENRY PREIST

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 19, claim 7, line 17, delete "1" and insert "6".

Column 20, claim 13, line 17, delete "," .

This certificate supersedes Certificate of Correction issued February 22, 1977.

Signed and Sealed this

Tenth **Day of** *April 1979*

[SEAL]

Attest:

RUTH C. MASON
Attesting Officer

DONALD W. BANNER
Commissioner of Patents and Trademarks