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(54) **POWER CONVERTER**

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(57) **ABSTRACT**

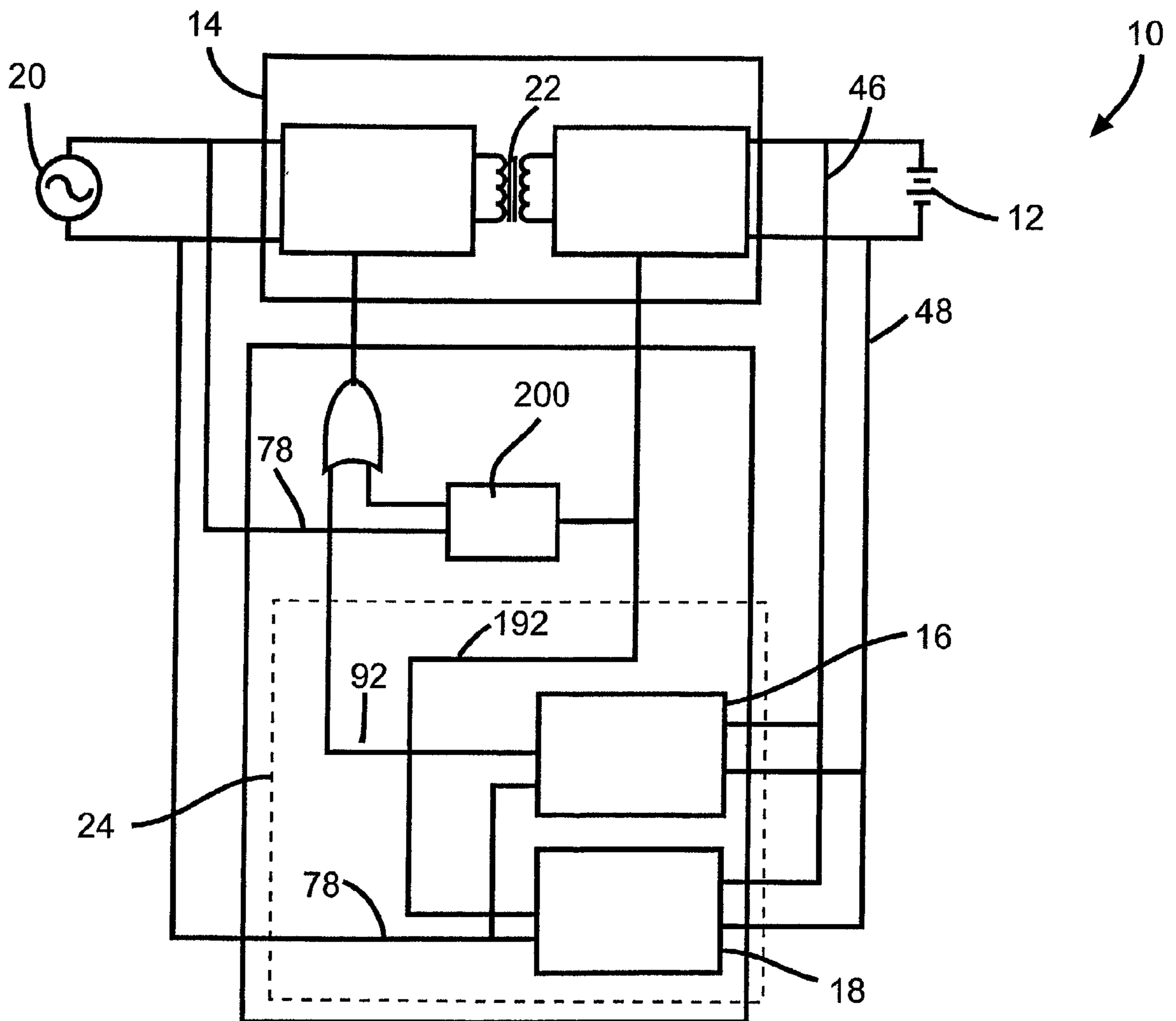
The present invention relates to a bi-directional AC/DC converter having (i) a power stage, (ii) a sourcing control circuit and (iii) a recuperation control circuit. The converter operates with a Power Factor Correction in both directions, i.e. when transferring energy from the AC mains into the DC load as well as when it is transferring energy from an active DC load into the AC mains. Smooth transition between sourcing and recuperation is possible by allowing an active load to control the output voltage until the correct control circuit begins regulation.

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(22) Filed: **Dec. 1, 2000**

Related U.S. Application Data

(63) Non-provisional of provisional application No. 60/168,571, filed on Dec. 2, 1999.



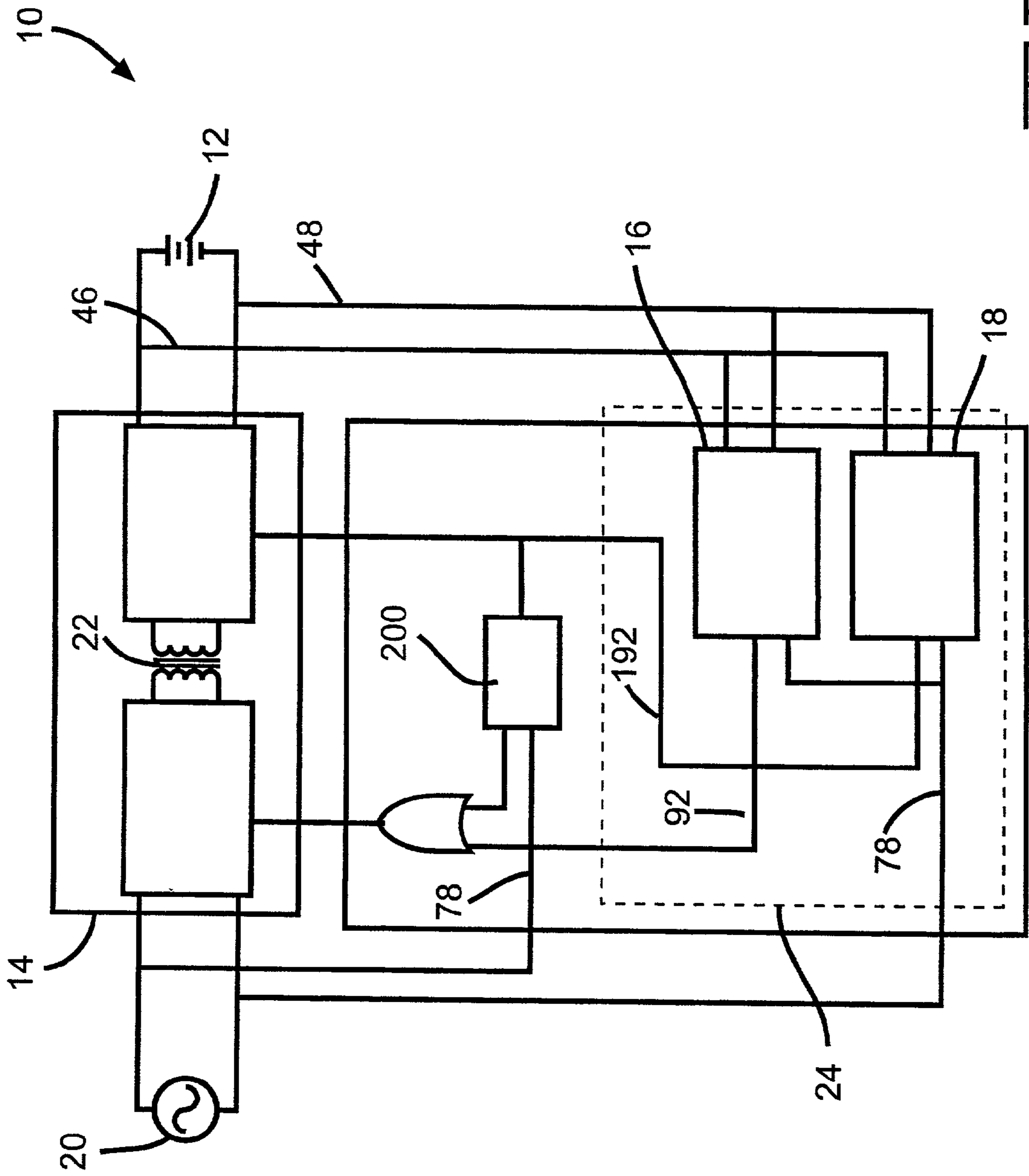


FIG. 1

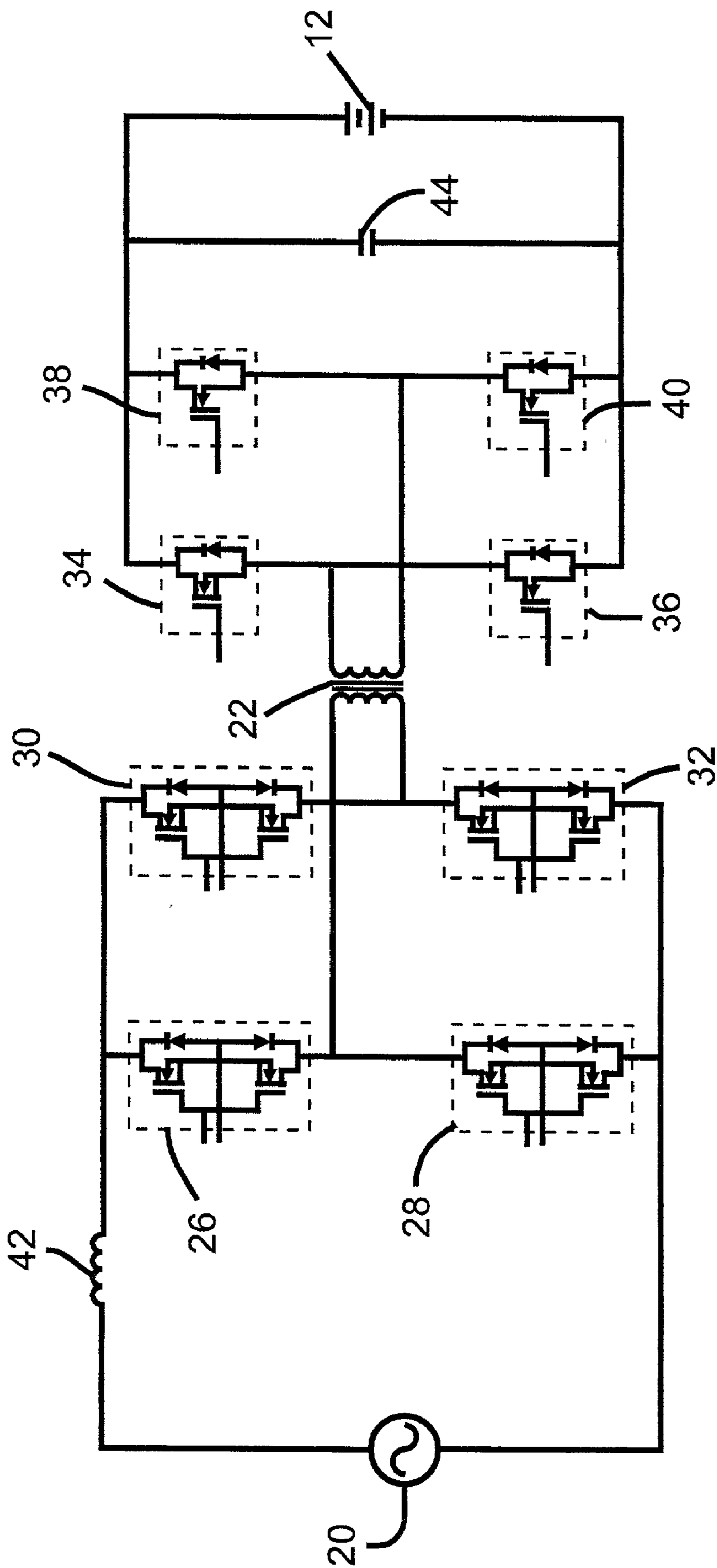


FIG. 2

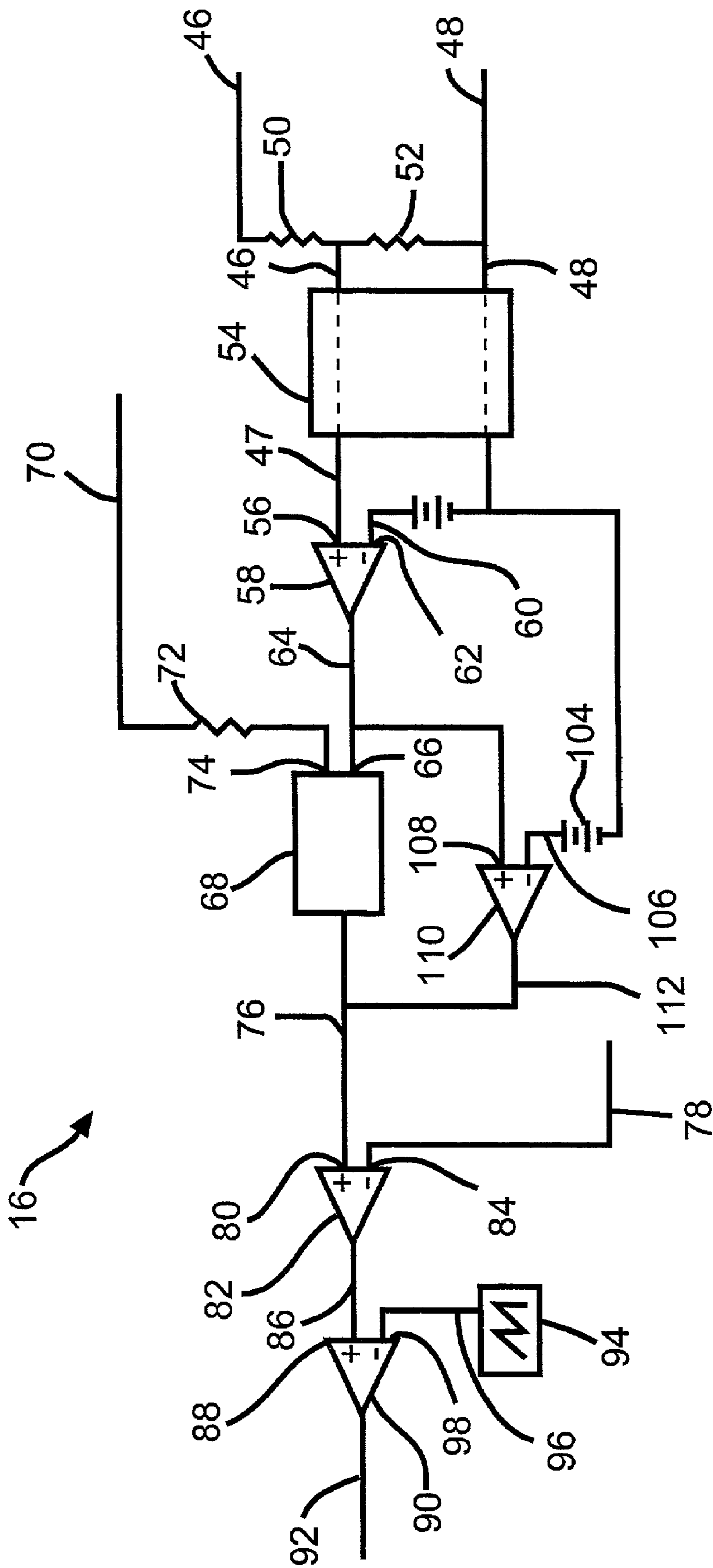


FIG. 3

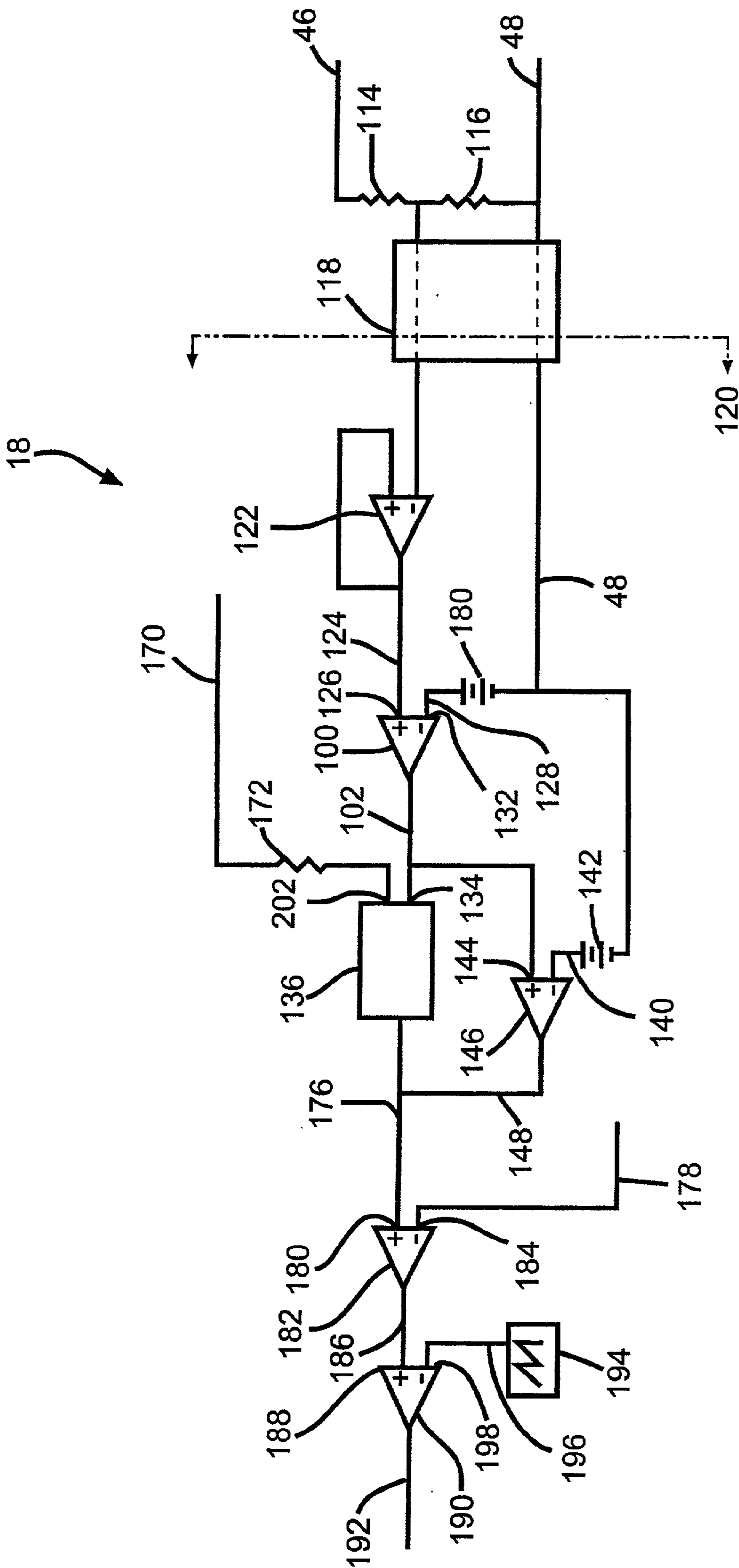


FIG. 4

COMPONENT

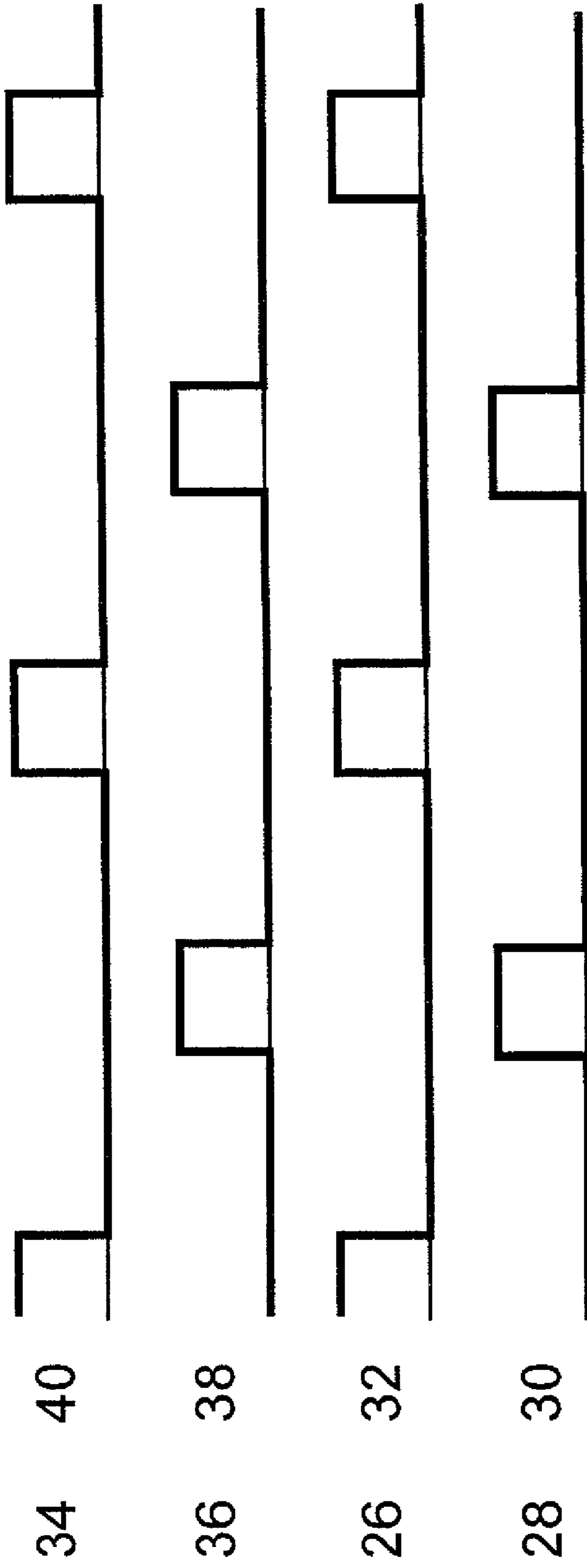


FIG. 5

COMPONENT

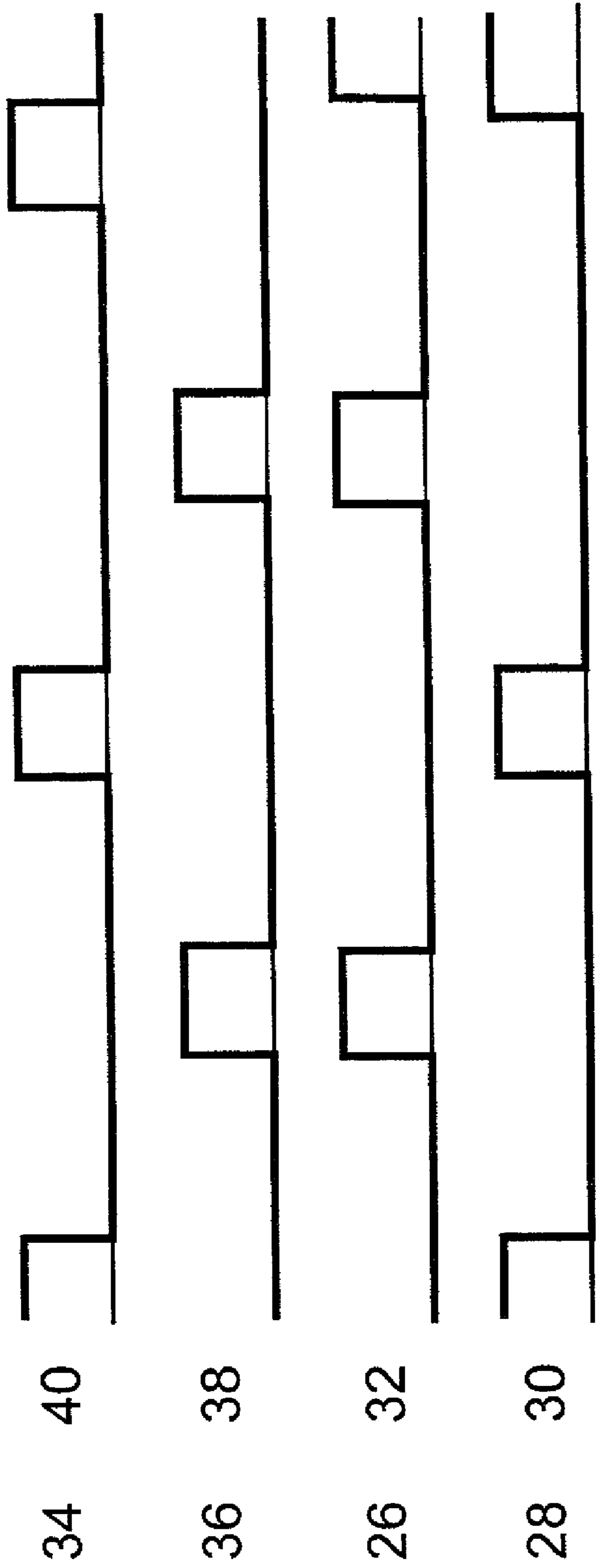


FIG. 6

POWER CONVERTER

CLAIM OF PRIORITY

[0001] This non-provisional patent application claims priority to U.S. provisional patent application Ser. No. 60/168,571, filed on Dec. 2, 1999.

FIELD OF THE INVENTION

[0002] The present invention relates, in general, to power conversion and, more specifically, to a bi-directional AC/DC converter and a method of operation of the converter.

BACKGROUND OF THE INVENTION

[0003] Applicants are unfamiliar with any AC/DC power supply converter that provide the following characteristics:

[0004] 1. Provide galvanic isolation between input and output sides of the converter unit;

[0005] 2. Be able to work with an active load (a load that can sink or source energy, such as battery, for instance), by sourcing energy into the load or sinking energy generated by the load;

[0006] 3. Recycle energy when working with an active load by returning the energy into the electrical main of the unit; and

[0007] 4. Provide Power Factor Correction for the line current, regardless if the energy is taken from the mains or recycled into the mains.

[0008] Different variations of isolated converters that provide Power Factor Correction have been described in Hirachi et al.'s article entitled *Switched-Mode PFC Rectifier with High Frequency Transformer Link for High-Power Density Single Phase UPS*, Proceedings of the PESC Conference, June 1997, p. 290-96; Cho et al.'s article entitled *Zero-Voltage-Transition Isolated PWM Boost Converter for Single Stage Power Factor Correction*, Proceedings of the APEC conference, March 1997, p. 471-76; and Dalal's article *400 W Single-Stage Current-Fed Isolated Boost Converter with PFC*, Unitrode Power Supply Seminar 1999-00 Series, Manual SLUP002, p. 3.1-3.24. These articles disclose a process to integrate a Power Factor Correction circuit with a DC/DC converter stage to obtain circuits simpler than classic, two-stage approaches (a PFC regulator and DC/DC converter as a separate, basically independent units).

[0009] In particular, the Hirachi et al. reference presents an isolated AC/DC/AC converter for use in uninterruptible power systems. Comparison between conventional circuit configurations, which are based on non-isolated boost topologies and proposed solutions, which is basically an isolated boost converter, with a diode bridge and a separate MOSFET bridge on the primary side and a rectifier bridge on the secondary side.

[0010] Cho et al. disclose an isolated boost converter consisting of a diode rectifier bridge and a MOSFET bridge on the primary side and a diode bridge of the secondary side with additional circuitry located also on the secondary side, for minimizing switching loss in the AC/DC converter.

[0011] Dalal suggest a current fed isolated AC/DC converter topology based on the push-pull converter and typically consisting of a bridge rectifier on the input, center-

tapped transformer and two MOSFET switches on the primary side and a diode rectifier bridge on the secondary side of the unit.

[0012] However, these articles do not disclose a system that can (1) be able to work with an active load (a load that can sink or source energy, such as battery, for instance), by sourcing energy into the load or sinking energy generated by the load; (2) recycle energy when working with an active load by returning it into the mains; or (3) provide Power Factor Correction for the line current, regardless if the energy is taken from the mains or recycled into the mains.

[0013] Furthermore, several solutions for non-isolated topologies (Wang et al. in the article entitled *Some Novel Four-Quadrant DC-DC Converters*, Proceeding of the PESC Conference, June 1998, p. 1775-82;) and an isolated topologies (Reimann et al.'s article entitled *A Novel Control Principle of Bi-Directional DC-Dc Power Conversion*, Proceedings of the PESC Conference, June 1997, p. 978-84; and Huang et al.'s article entitled *Novel Current Mode Bi-directional High-Frequency Link DC/AC Converter for UPS*, Proceedings of the PESC Conference, June 1998, p. 1867-71) capable of transferring energy from the DC source to the DC or AC load and also in the opposite direction (bi-directional power flow) have been presented. The topologies disclosed in those article do not disclose systems capable of (1) recycling energy when working with an active load by returning it into the mains; or (2) providing Power Factor Correction for the line current, regardless if the energy is taken from the mains or recycled into the mains. Moreover, the Wang et al. reference fails to disclose a method for providing galvanic isolation between input and output sides of the unit.

[0014] In particular, Wang et al. disclose a family of four topologies capable of operating in all four quadrants. This is a family of non-isolated converters, operating from a DC source and capable of generating both positive and negative polarity of output voltages, in addition to positive and negative output current, as may be directed by the load.

[0015] Reimann et al. suggest an isolated DC/DC converter topology capable of controlling energy flow in both directions—from source to load and from load side to the source side of the unit. It is basically an isolated boost topology consisting of two bridges, one on the primary side and the other on the secondary side, each having four quasi-bidirectional switches.

[0016] Also, there are products on the market (such as BOP series from KEPCO, Inc.) which are capable of controlling active loads. These products, made by the applicant, lack the ability to (1) recycle energy when working with an active load by returning it into the mains; or (2) provide Power Factor Correction for the line current, regardless if the energy is taken from the mains or recycled into the mains.

[0017] Work described in Hui et al.'s article entitled *A Bi-Directional AC-DC Power Converter with Power Factor Correction* (Proceedings of the PESC Conference, June 1998, p. 1323-29) presents a non-isolated topology providing a bidirectional link between AC line and DC source capable of recycling the energy, but it does not provide galvanic isolation between input and output.

[0018] As in inventor's knowledge, there has not been unit presented so far that can simultaneously satisfy the follow-

ing requirements: (1) providing galvanic isolation between input and output sides of the converter unit; (2) be able to work with an active load (a load that can sink or source energy, such as battery, for instance), by sourcing energy into the load or sinking energy generated by the load; (3) recycle energy when working with an active load by returning the energy into the electrical main of the unit; and (4) provide Power Factor Correction for the line current, regardless if the energy is taken from the mains or recycled into the mains.

BRIEF SUMMARY OF THE INVENTION

[0019] An isolated, bi-directional AC/DC converter with Power Factor Correction function and capability to recuperate energy into the mains has been invented. It consists of a power stage and a control section. The power stage processes raw power from electrical mains to the power required by the load. The power stage also processes the power generated by an active load and delivers the energy to the mains during the recuperation phase. The power stage has an input filter inductor, at least four bidirectional switches that form a bridge configuration on the primary side of an isolation transformer, the isolation transformer, at least four quasi-bidirectional switches that form a bridge on the secondary side of the isolation transformer and an output filter capacitor.

[0020] The control section of the unit regulates the current on the primary side and voltage on the secondary side. The function of the control circuit is to satisfy load requirements and provide Power Factor Correction. The control section has two distinctive parts. The first part controls the unit when the power is being delivered to the load (sourcing). The second part controls the unit when an active load is present and the power gets recycled into the mains (recuperation). Each part of the control section is in control only when needed, which is ensured by utilizing a circuitry that automatically disables itself when conditions for each part to take over are met.

[0021] The present invention is capable of satisfying all four requirements of (1) providing galvanic isolation between input and output sides of the converter unit; (2) be able to work with an active load (a load that can sink or source energy, such as battery, for instance), by sourcing energy into the load or sinking energy generated by the load; (3) recycle energy when working with an active load by returning the energy into the electrical main of the unit; and (4) provide Power Factor Correction for the line current, regardless if the energy is taken from the mains or recycled into the mains. The output voltage in the present invention effectively has two levels, one during sourcing, and the other, slightly higher one, during recuperation.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] FIG. 1 presents the global block schematic of the invention;

[0023] FIG. 2 shows the schematics of the power stage, with all the primary and secondary switches, input inductor and output capacitor;

[0024] FIG. 3 illustrates a schematic of the sourcing control circuit;

[0025] FIG. 4 illustrates a schematic of the recuperation control circuit;

[0026] FIG. 5 shows driving signals for the main and secondary switches during recuperation for positive half-period of the input line voltage; and

[0027] FIG. 6 shows driving signals for the main and secondary switches during recuperation for negative half-period of the input line voltage.

DETAILED DESCRIPTION OF THE INVENTION

[0028] The present invention solves the above-discussed deficiencies of the prior art. The present invention provides a power converter system **10** capable of sourcing power to a load and also capable of recuperating power from an active load **12** (such as battery, for instance) into at least one source of electrical power (hereinafter the "mains"). The system **10** uses a bidirectional power circuit section **14** and at least two control sections **16, 18**. The first control section **16** controls the unit **10** during sourcing of the energy. And the second control section controls the unit **10** during recuperation. A global block-schematic depicting the major components of the system **10** are shown in FIG. 1. In FIG. 1, the system **10** has mains **20**, the active load **12**, power transformer **22** acting as an isolation element, and a control section **24**.

[0029] Power section **14** is presented in greater detail in FIG. 2. First, second, third and fourth bidirectional switches, **26, 28, 30, 32**, respectively, are located on the primary side of the isolation transformer **22**. In contrast, first, second, third and fourth quasi-bidirectional switches, **34, 36, 38, and 40**, respectively, are located on the secondary side of the transformer **22**. A first inductor **42** is the input inductor, and an output filter capacitor **44** is shown. The power section **14** illustrated in FIG. 2 is just one embodiment known to those of ordinary skill in the art, since variations of this circuit have been presented in the prior art.

[0030] The sourcing control circuit **16**, as shown in FIG. 3, is a basic building block of the power factor regulator circuits **10**. As such, circuit **16** has also been presented in the prior art. However, its use in the present invention, in conjunction with the recuperation control circuit **18** (shown in FIG. 4) are, as in inventor's opinion, unique and at least one inventive step of the present invention.

[0031] Sourcing

[0032] The sourcing control circuit **16** (FIG. 3) operates in a controlled manner. An output voltage **46** (positive), **48** (return) is reduced to a lower value by first and second voltage dividers **50, 52**. The output voltage **46, 48** is then transferred across an isolation barrier **54** to the primary side of the unit. The isolation barrier **54** can be any conventional component such as an optocoupler or high frequency pulse transformer. From the isolation barrier **54**, the output voltage **46** is brought to a negative (inverting) input **56** of a first voltage amplifier **58**. A first voltage reference signal **60** connects to a positive (non-inverting) input **62** of the amplifier **58**. The first voltage reference **60** together with first and second voltage dividers **50, 52** determine the output voltage **46, 48** of the unit **10**.

[0033] The first voltage amplifier **58** generates a first output signal **64** that represents an amplified difference between the actual output voltage, **46, 48** (reduced by first and second voltage dividers **50, 52**) and a given reference signal **60**—the voltage error signal (VES) **64**. A first input **66**

of a multiplier **68** receives the first output signal **64**. While a second input **74** of the multiplier **68** receives an input voltage signal **70** that is transferred to a current by a third resistor **72**. This signal represents the template signal for the input current **78** of the unit **10**.

[0034] The multiplication component **68** generates a current reference signal **76**, which an input current **78** will follow, that is always in phase with the input voltage **70**, and that has the same shape. Thereby, the unit **10** provides a high power factor (Power Factor Corrected operation). The current reference signal **76** is further used as a reference signal at the positive input **80** of the current amplifier **82**, where it gets compared to the actual, measured input current **78** that is brought to a negative input **84** of the amplifier **82**. An output of the current amplifier **82** is the current error signal **86**, and the signal **86** is fed to one input **88** of a Pulse Width Modulated comparator **90** to generate a Pulse Width Modulated signal **92**. A separate oscillator **94** generates a sawtooth signal **96** which is received by a second input **98** of the comparator **90**. The resulting PWM signal **92** has a pulse width which is proportional to the value of the current error signal.

[0035] The closed loop circuit of the unit **10** operates in such a way that if the output voltage **46, 48** increases for some reason, for example increased input voltage or reduced output load, then the output voltage signal **64** of the voltage amplifier **58** will go in the opposite direction. Multiplication of the voltage signal **64** and the input voltage signal **70** will, therefore, decrease the first multiplier **68** output signal **76** (assuming that AC mains input voltage is constant) and, consequently, the width of the PWM pulses **92** will also be reduced. These pulses **92** directly control the first, second, third and fourth bidirectional switches, **26, 28, 30, 32**. With this control, the pulses **92** reduce the input current **78** and, consequently the output voltage **46, 48**, effectively canceling increase in the voltage. If the output voltage **46, 48** decreases, the circuit **10** operates in opposite manner, thus increasing input current **78** and output voltage **46, 48**, again canceling any disturbances.

[0036] Transition from Sourcing to Recuperation

[0037] If an active load **12** is connected to the output of the unit **10** and the load **12** starts delivering energy into the unit **10**, the output voltage **46, 48** will start increasing. The sourcing control circuit **16** will try to lower the output voltage **46, 48**, as described above. Voltage error signal **64** will start decreasing. At some point the VES **64** will reach the level set by a second voltage reference signal **106** created by the second voltage reference **104**. When VES **64** becomes slightly lower than the second voltage reference signal **106** at one input **108** of a shut-down comparator **110**, the comparator's output signal **112** will become zero and it will pull down the multiplier's **68** output **76** disabling it effectively. At that instant the PWM pulses **92** will cease and the unit's **10** output voltage **46, 48** will be controlled by the active load **12** only.

[0038] Recuperation

[0039] With control circuits **16, 18** out of function, the output voltage **46** will continue increasing. The output voltage **46** is reduced by fourth and fifth voltage dividers **114, 116** in the recuperation control circuit **18** (FIG. 4). The output voltage **46** is then directed to a second isolation

barrier **118**, same type as described for the first isolation barrier **54**. On the primary side **120** of the isolation barrier **118**, the voltage **46** is fed to an inverting amplifier **122** with a gain of 1. The inverting amplifier **122** generates an inverting signal **124**. The inverting signal **124** is directed to a first input **126** of a voltage amplifier **100**. In the voltage amplifier **100**, the inverting signal **124** is compared to a third reference signal **128**. The third reference signal **128** is generated by reference voltage **130**. The voltage amplifier **100** receives the third reference signal through a second input **132**. The resulting signal of the voltage amplifier **100** is an amplifier signal **102**.

[0040] Amplifier signal **102** is transmitted to a first input **134** of a second multiplier **136**. The second multiplier **136** receives at a second input **202** an input voltage signal **170** that is transferred to a current by a third resistor **172**. This signal represents the template signal for the input current **178** of the unit **10**.

[0041] The multiplication component **136** generates a current reference signal **176**, which an input current **178** will follow, that is always in phase with the input voltage **170**, and that has the same shape. Thereby, the unit **10** provides a high power factor (Power Factor Corrected operation). The current reference signal **176** is further used as a reference signal at the positive input **180** of the current amplifier **182**, where it gets compared to the actual, measured input current **178** that is brought to a negative input **184** of the amplifier **182**. An output of the current amplifier **182** is the current error signal **186**, and the signal **186** is fed to one input **188** of a Pulse Width Modulated comparator **190** to generate a Pulse Width Modulated signal **192**. A separate oscillator **194** generates a sawtooth signal **196** which is received by a second input **198** of the comparator **190**. The resulting PWM signal **192** has a pulse width which is proportional to the value of the current error signal.

[0042] When the output voltage **46, 48** increases, the voltage output **124** of the inverting amplifier **122** will decrease until it reaches a level set by the reference signal **128**. When it falls slightly below the reference signal **128** level, voltage error signal (VES) **102** at the output of the voltage amplifier **100** will increase. When the signal **102** goes above the level set by a fourth reference signal **140**, which is generated by reference voltage **142**, then shut-down comparator **144** will change the comparator output signal **146** from low to high and current reference signal **176** will not be tied to zero through diode **148** anymore. Thereby, the voltage amplifier's output **102**, multiplied by the input voltage signal **170** will result, similarly to the sourcing control circuit **16**, in increased width of the PWM pulses **192**. In difference to the sourcing control **16**, the recuperation control circuit **18** directly controls first, second, third and fourth quasi-bidirectional switches, **34, 36, 38, and 40**, with primary switches being indirectly controlled through a conventional synchronization circuit **200** (shown in FIG. 1). Returning to FIG. 4, the increased pulse width will, therefore, transfer more energy being taken from the active load **12**, which will decrease the output voltage **46, 48**, and keep it regulated. The Synchronization circuit **200**, used to drive secondary switches **34, 36, 38, and 40**, has two different patterns, one for positive half-period of the input voltage as shown in FIG. 5, and one for the negative half-period, as shown in FIG. 6.

[0043] If the active load **12** stops delivering energy into the unit **12**, output voltage **46, 48** will start decreasing, inverting amplifier's output voltage **124** will start increasing, voltage error signal **102** will start decreasing, and eventually it will reach the level of set forth by reference signal **140**, which will disable the current reference **176** and PWM signals **192** will cease. The output voltage **46, 48** will stay uncontrolled until it reaches the level of reference signal **60** (**FIG. 3**), at which point the sourcing control **16** will become active again and it will start regulating the output voltage **46, 48**.

[0044] While preferred embodiments of the present invention have been disclosed, it will be appreciated that it is not limited thereto but may be otherwise embodied with the scope of the following claims.

We claim:

1. A bidirectional AC/DC converter comprising a bidirectional power stage and a control circuit having a sourcing control section and a recuperation control section.

2. The bi-directional AC/DC converter of claim 1 is isolated.

3. The bi-directional AC/DC converter of claim 1 wherein the power stage processes raw power from electrical mains to the power required by a load.

4. The bi-directional AC/DC converter of claim 1 wherein the power stage processes energy generated by an active load and delivers the energy to the mains during a recuperation phase.

5. The bi-directional AC/DC converter of claim 1 wherein the power stage has an input filter inductor, at least four bidirectional switches that form a bridge configuration on the primary side of an isolation transformer, the isolation transformer, at least four quasi-bidirectional switches that form a bridge on the secondary side of the isolation transformer and an output filter capacitor.

6. The bidirectional AC/DC converter of claim 5 wherein the control circuit regulates the current on the primary side and voltage on the secondary side.

7. The bi-directional AC/DC converter of claim 1 wherein the control circuit satisfies load requirements and provide a Power Factor Correction.

8. The bi-directional AC/DC converter of claim 1 wherein the sourcing control section controls the converter when power is being delivered to a load.

9. The bi-directional AC/DC converter of claim 1 wherein the recuperation control section controls the converter when an active load is present and power gets recycled into electrical mains.

10. The bi-directional AC/DC converter of claim 1 wherein the recuperation control section and the sourcing control section each operates only when needed.

11. The bi-directional AC/DC converter of claim 10 wherein the recuperation control section and the sourcing control section each has circuitry that automatically disables each section when electrical circuit conditions are met.

12. The bi-directional AC/DC converter of claim 1 wherein the converter provides galvanic isolation between an input side and an output side of the converter unit.

13. The bi-directional AC/DC converter of claim 12 wherein the converter is able to work with an active load by sourcing energy into the load or sinking energy generated by the load.

14. The bi-directional AC/DC converter of claim 12 wherein the converter recycles energy when working with an active load by returning the energy into an electrical main.

15. The bi-directional AC/DC converter of claim 12 wherein the converter provides Power Factor Correction for a line current, regardless if the energy is taken from the mains or recycled into the mains.

16. The bi-directional AC/DC converter of claim 10 wherein the converter output voltage has two levels, the first output voltage level during sourcing, and the second output voltage level slightly higher than the first output voltage level during recuperation.

17. A method of automatic transition, in a bidirectional AC/DC converter having a bidirectional power stage and a control circuit having a sourcing control section and a recuperation control section, between the sourcing control section and the recuperation control section comprising the steps of:

allowing an output voltage to become controlled by an active load only, and

altering the output voltage to a higher or lower value to enable the control circuit to start regulating the output voltage.

18. The method of claim 17 is isolated.

19. The method of claim 17 wherein the power stage processes raw power from electrical mains to the power required by a load.

20. The method of claim 17 wherein the power stage processes energy generated by an active load and delivers the energy to the mains during a recuperation phase.

21. The method of claim 17 wherein the power stage has an input filter inductor, at least four bidirectional switches that form a bridge configuration on the primary side of an isolation transformer, the isolation transformer, at least four quasi-bidirectional switches that form a bridge on the secondary side of the isolation transformer and an output filter capacitor.

22. The method of claim 21 wherein the control circuit regulates the current on the primary side and voltage on the secondary side.

23. The method of claim 17 wherein the control circuit satisfies load requirements and provide a Power Factor Correction.

24. The method of claim 17 wherein the sourcing control section controls the converter when power is being delivered to a load.

25. The method of claim 17 wherein the recuperation control section controls the converter when an active load is present and power gets recycled into electrical mains.

26. The method of claim 17 wherein the recuperation control section and the sourcing control section each operates only when needed.

27. The method of claim 26 wherein the recuperation control section and the sourcing control section each has circuitry that automatically disables each section when electrical circuit conditions are met.

28. The method of claim 17 wherein the converter provides galvanic isolation between an input side and an output side of the converter unit.

29. The method of claim 17 wherein the converter is able to work with an active load by sourcing energy into the load or sinking energy generated by the load.

30. The method of claim 17 wherein the converter recycles energy when working with an active load by returning the energy into an electrical main.

31. The method of claim 17 wherein the converter provides Power Factor Correction for a line current, regardless

if the energy is taken from the mains or recycled into the mains.

32. The method of claim 26 wherein the converter output voltage has two levels, the first output voltage level during sourcing, and the second output voltage level slightly higher than the first output voltage level during recuperation.

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