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(54) **Title**: APPLICATION OF PIEZO TECHNOLOGY TO CONVERT ALTERNATING CURRENT (AC) LINE POWER TO ISOLATED DIRECT CURRENT (DC) POWER IN HIGH EXTERNAL MAGNETIC FIELDS

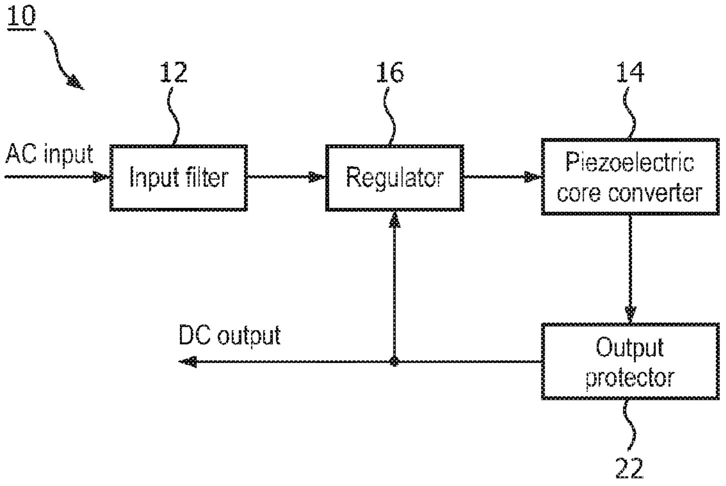

FIG. 1

(57) **Abstract**: A system (10) and a method (200) supply power in high external magnetic fields. Alternating current (AC) line power is converted (202) to isolated power using one or more piezoelectric transformers (18). The flow of AC line power to the piezoelectric transformers (18) is regulated (204) to maintain the isolated power at a predetermined voltage.

Application Of Piezo Technology To Convert Alternating Current (Ac) Line Power To Isolated Direct Current (Dc) Power In High External Magnetic Fields

The present application relates generally to power supplies. It finds particular application in conjunction alternating current (AC)/direct current (DC) power adapters for medical devices used in high external magnetic fields, and will be described with particular reference thereto. However, it is to be understood that it also finds application in other usage scenarios, and is not necessarily limited to the aforementioned application.

Traditional methods of converting AC line power to isolated DC power involve the use of ferrous, electromagnetic transformers and inductors. When an AC/DC power adapter employing such methods is used in high external magnetic fields, such as in the magnet room of a magnetic resonance imaging (MRI) facility, the power adapter must usually be positioned and mechanically secured at a safe distance from the magnet. Without securing the power adapter at a safe distance, the electromagnetic transformer and inductors can saturate from the high external magnetic field. This can cause the power adapter to lose its ability to convert power, overheat, or be damaged. Further, electromagnetic transformers have a significant magnetic attraction and without securing the power adapter at a safe distance, the power adapter can create a safety hazard by becoming a projectile.

A challenge with securing the power adapter away from the magnet is that often times a device powered by the power adapter needs to be used in close proximity to the magnet. Typically, this challenge is addressed by providing power via a long cable extending from the power adapter to the device, or by providing power from batteries local to the device and merely using the power adapter to charge the batteries. However, employing a long cable reduces portability and can pose a safety risk to both the device and users of the device since the users can trip over the cable. Further, batteries are limited in the amount of power that can be provided and have a useful life much shorter than the device itself.

Other less common methods of converting AC line power to isolated DC power involve the use of piezoelectric transformers, as described in U.S. Patent No. 2,830,274 to Rosen et al. The piezoelectric methods are commonly used in AC/DC power adapters used to develop high AC voltages required for florescent backlight tubes used in displays, such as laptop displays. Further, the piezoelectric methods are commonly used in micro power energy harvesting to power remote sensors. More recently, the piezoelectric methods have been deployed in low power AC/DC adapters for notebook computers due to reduced size and weight. Challenges with power adapters employing the piezoelectric methods are that these adapters fail to provide sufficient power for medical applications. Further, such power adapters fail to generate an isolated low voltage DC output sufficient for medical applications and are only available for a single AC line voltage, most typically the relatively low AC line voltage of the United Sates.

The present application provides a new and improved system and method which overcome these problems and others.

In accordance with one aspect, a power supply for supplying power in high external magnetic fields is provided. The power supply includes one or more piezoelectric transformers converting alternating current (AC) line power to isolated power. The power supply further includes one or more regulator modules at least one of regulating the flow of AC line power to the piezoelectric transformers and regulating the flow of isolated power from the piezoelectric transformers to maintain a constant output voltage regardless of the AC line power.

In accordance with another aspect, a method for supplying power in high external magnetic fields. The method includes converting alternating current (AC) line power to isolated power using one or more piezoelectric transformers. The method further includes regulating the flow of AC line power to the piezoelectric transformers to maintain the isolated power at a predetermined voltage.

In accordance with another aspect, a power supply for supplying power in high external magnetic fields is provided. The power supply includes a piezoelectric core converter module configured for converting alternating current (AC) line power to isolated power using one or more piezoelectric transformers. The power supply further includes a regulator module configured for regulating the flow of AC line power to the piezoelectric core converter module to maintain the isolated power at a predetermined voltage.

One advantage resides in eliminating magnetic immunity issues.

Another advantage resides in eliminating projectile risks.

Another advantage resides in an alternating current (AC)/direct current (DC) power adapter integral with the device being powered.

Another advantage resides in support for the wide range of worldwide AC line voltages and frequencies.

Another advantage resides in closer positioning to a magnet producing high external magnetic fields.

Another advantage resides in improved portability.

Still further advantages of the present invention will be appreciated to those of ordinary skill in the art upon reading and understand the following detailed description.

The invention may take form in various components and arrangements of components, and in various steps and arrangements of steps. The drawings are only for purposes of illustrating the preferred embodiments and are not to be construed as limiting the invention.

FIGURE 1 illustrates a power adapter employing one or more piezoelectric transformers and a feedback loop for regulating the output of the power adapter.

FIGURE 2 illustrates a more specific embodiment of the power adapter of FIGURE 1.

FIGURE 3 illustrates a graph of voltage gain of a piezoelectric transformer as a function of frequency.

FIGURE 4A illustrates circuits for the input filter and the input pre-regulator modules of FIGURE 2.

FIGURE 4B illustrates circuits for the bias pre-regulator and the bias regulator modules of FIGURE 2.

FIGURE 4C illustrates circuits for the H-bridge and the piezoelectric transformer modules of FIGURE 2.

FIGURE 4D illustrates circuits for the microcontroller module of FIGURE 2.

FIGURE 4E illustrates circuits for the output rectifier, the over voltage protector, and the error amplifier modules of FIGURE 2.

FIGURE 4F illustrates circuits for the opto-isolator and the over current protector modules of FIGURE 2.

FIGURE 5 illustrates an alternative embodiment of the power adapter of FIGURE 1 without the feedback loop for regulating the output of the power adapter.

FIGURE 6A illustrates a circuit for the input filter module and a part of a circuit for the pre-regulation module of FIGURE 5.

FIGURE 6B illustrates a part of a circuit for the pre-regulation module of FIGURE 5.

FIGURE 6C illustrates a circuit for the piezoelectric core converter module of FIGURE 5.

FIGURE 6D illustrates circuits for the output protector and the post regulator modules of FIGURE 5.

FIGURE 7 illustrates a magnetic resonance imaging (MRI) system with a power adapter employing one or more piezoelectric transformers positioned proximate a main magnet.

FIGURE 8 illustrates a method for supplying power in high external magnetic fields using piezoelectric transformers.

The present application provides an improved approach for converting alternating current (AC) line power to medically isolated direct current (DC) power useful for powering medical devices without the use of electromagnetic components, such as electromagnetic transformers and inductors. Instead of using electromagnetic components for power conversion, the improved approach employs one or more piezoelectric transformers. By eliminating electromagnetic components, the improved approach can achieve isolated power conversion that is immune to high magnetic fields, such as those generated by the main magnetic of a magnetic resonance imaging (MRI) system.

To provide a DC output at increased power and voltage levels, such as those useful for many medical devices needed in proximity to the main magnetic of a MRI system, the number of piezoelectric transformers can be increased. Even more, to allow power conversion operation over the full range of worldwide AC line voltages and frequencies, conversion using the piezoelectric transformers can be regulated by, for example, a microcontroller.

With reference to FIGURE 1, an AC/DC power adapter **10** for use in high external magnetic fields is provided. As used herein, a high external magnetic field is a magnetic field above 2000 gauss (G). An input filter module **12** receives AC power from an external source, such as a power grid or generator, over an AC power line and filters the received AC power. The input filter module **12** filters the received AC power to remove noise, such as radio frequency interference. Additionally, or alternatively, the input filter **12** filters the received AC power to protect the power adapter **10** from power surges, brown outs, and other atypical conditions associated with the AC power line. The voltage and the frequency of the AC power line can span the full range of worldwide AC line voltages and frequencies. For example, the voltage of the AC power line can range from 90-250 volts (V), and the frequency of the AC power line can range from 50-60 hertz (Hz).

The filtered power passes from the input filter module **12** to a piezoelectric core converter module **14** through a regulator module **16**, which regulates the flow of filtered power to the piezoelectric core converter module **14**. The piezoelectric core converter module **14** employs one or more piezoelectric transformers **18** (see FIGURE 4C) to convert the regulated, filtered power from the regulator module **16** to an isolated DC power output. A piezoelectric transformer converts input electrical energy to mechanical energy and then converts that mechanical energy back to output electrical energy that is galvanically and therefore safely isolated from the input electrical energy. To increase the power and voltage levels of the DC power output, the number of piezoelectric transformers can be increased and arranged in parallel.

The regulator module **16** regulates the flow of filtered power to the piezoelectric core converter module **14** to maintain the DC power output at a constant, predetermined voltage, regardless of the voltage and the frequency of the AC power line, using feedback from the DC power output. The regulator module **16** can further regulate the flow of filtered power to protect the piezoelectric transformers **18** from overheating, power spikes and brown outs on the AC power line, and overloading. Suitably, a microcontroller **20** (see FIGURE 4D) of the regulator module **16** manages the regulation of the filtered power.

The DC power output from the piezoelectric core converter module **14** is passed to an external load through an output protector module **22**. The external load can, for example, be a medical device. Examples of medical devices include patient monitors, displays, entertainment devices, infusion pumps, injectors, motors, anesthesia workstations, cameras, battery chargers, and communication devices. The output protector module **22** ensures that the voltage and/or current of the DC power output do not exceed predefined limits. This advantageously protects both the power adapter **10** and the external load.

Those skilled in the art should appreciate that even though the input filter module **12** and the output protector module **22** were illustrated and described in connection with FIGURE 1, those modules **12, 22** are not required for proper operation of the power adapter **10**. Hence, in some instances, the power adapter **10** is without the input filter module **12** and/or the output protector module **22**.

With reference to FIGURE 2, a more specific embodiment of the power adapter **10** described in FIGURE 1 is provided. The correspondences with the modules **12, 14, 16, 22** of FIGURE 1 are shown in dash boxes. As above, the input filter module **12** receives AC power from the external source. The filtered power is provided to an input pre-regulator module **24**, which converts the filtered power to a regulated, DC power output. The input pre-regulator module **24** suitably converts the filtered power to the regulated, DC power output by rectifying the filtered power. Therefore, the voltage of the regulated, DC power output is typically dependent upon the received AC power. In the United States of America, for example, the regulated, DC power output is about 125 volts (V). The regulated, DC power out is provided to a microcontroller module **26** and an H-bridge module **28**. The input pre-regulator module **24** further provides filtered power to a bias pre-regulator module **30**, which prepares the filtered power for use by a bias regulator module **32**.

The bias regulator module **32** receives prepared, filtered power from the bias pre-regulator module **30** and converts the power to a first regulated, DC power output and a second regulated, DC power outputs. The first regulated, DC power output has a voltage sufficient to power the microcontroller module **26**, such as 3.3V, and the second regulated, DC power output has a voltage sufficient to power the H-bridge module **28**, such as 15V. In some instances, the first and the second regulated, DC power outputs can be one and the same depending upon the power requirements of the H-bridge module **28** and the microcontroller module **26**.

The H-bridge module **28** receives the second regulated, DC power output from the bias regulator module **32**, which is used to power the H-bridge module **28**. Further, the H-bridge module **28** receives the regulated, DC power output from the input pre-regulator module **24** and generates a high frequency pulse train from the regulated, DC power output of the input pre-regulator module **24**. The high frequency pulse train is duty cycle controlled in accordance with a control signal from the microcontroller module **26** to generate a constant root mean square (RMS) voltage. This advantageously removes the large variations in voltages from worldwide AC line power. The high frequency pulse train is provided to a piezoelectric transformer module **34**.

The piezoelectric transformer module **34** includes an air core inductor **36** (see FIGURE 4C) receiving the high frequency pulse train. The air core inductor **36** resonates with the input capacitance of one or more piezoelectric transformers **18** (see FIGURE 4C) of the piezoelectric transformer module **34**, thus generating a sinusoidal input to the piezoelectric transformers **18** at a frequency just above the mechanical resonance of the piezoelectric transformers **18**. An air core inductor advantageously avoids saturation of the inductor in the presence of high magnetic fields. Further, the sine wave of the sinusoidal input minimizes other harmonics that create heat in the piezoelectric transformers **18** without contributing to power conversion. Even more, the sine wave of the sinusoidal input also helps to significantly reduce radiated emissions, which can create image artifacts in an MRI, and to reduce the dv/dt stress on the piezoelectric transformers **18**.

The piezoelectric transformers **18** convert the electrical energy of the sinusoidal input to mechanical vibrations, which are in turn converted to electrical energy in the form of an isolated, lower voltage sinusoid at the output of the piezoelectric transformers **18**. The output sinusoid is rectified by an output rectifier module **38** to form a DC power output that is safely isolated from the AC power line. The isolated DC power output then passes through an over voltage protector module **40** and an over current protector module **42** to ensure the voltage and current of the DC power output stay within predefined limits.

The microcontroller module **26** receives the first regulated, DC power output from the bias regulator module **32**, which is used to power the microcontroller module **26**. A microcontroller **20** (see FIGURE 4D) of the microcontroller module **26** monitors the isolated DC power output via an opto-isolator module **44**. In that regard, an error amplifier module **46** determines the difference between the isolated DC power output and the expected DC power output. The difference is then provided to the microcontroller **20** through the opto-isolator module **44**. Based on the difference signal, the microcontroller **20** adjusts the frequency of the pulse train in order to regulate the voltage of the DC power output to a constant DC voltage regardless of output load variations. This pulse frequency regulation makes use of the voltage gain properties of the piezoelectric transformers **18**. FIGURE 3 illustrates a graph of voltage gain of a piezoelectric transformer (output voltage/input voltage) as a function of frequency (kilohertz (kHz)).

The microcontroller **20** can further monitor the temperature of the piezoelectric transformers **18** using a signal indicator of temperature received from the piezoelectric transformer module **34** and/or a signal indicative of the voltage of the AC power line received from the input pre-regulator module **24**. Based on the temperature signal and/or the power line signal, the microcontroller **20** can take action to protect the piezoelectric transformers **18** from AC line brown outs or surges, output overloads, overheating, and so on by, for example, disabling the external load.

With reference to FIGURES 4A-4F, a more specific embodiment of the power adapter **10** described in FIGURE 2 is provided. The correspondences with the modules **12,**

24-34, 38-46 of FIGURE 2 are shown in dashed boxes. As seen, each of the modules **12, 24-34, 38-46** corresponds to an electrical circuit. FIGURE 4A illustrates a circuit for the input filter module **12**, and a circuit for the input pre-regulator module **24**. FIGURE 4B illustrates a circuit for the bias pre-regulator module **30**, and a circuit for the bias regulator module **32**. FIGURE 4C illustrates a circuit for the H-bridge module **28**, and a circuit for the piezoelectric transformer module **34**. The circuit for the piezoelectric transformer module **34** illustrates the interconnection of the air inductor **36** and the piezoelectric transformers **18**. FIGURE 4D illustrates a circuit for the microcontroller module **26**, the circuit including the microcontroller **20**. FIGURE 4E illustrates a circuit for the output rectifier module **38**, a circuit for the over voltage protector module **40**, and a circuit for the error amplifier module. FIGURE 4F illustrates a circuit for the opto-isolator module **44**, and a circuit for the over current protector module **42**.

The embodiment of the power adapter **10** described in FIGURES 4A-F was experimentally tested in both at 1.5 Tesla (T) and a 3.0T MRI environment. During testing, it was found that the power adapter **10** was capable of operating in magnetic fields of at least 3T and with an output power in excess of 50 watts (W). Even more, it was found that the power adapter **10** did not cause any image artifacts to appear on 1.5T MRIs or 3T MRIs. Moreover, the power adapter **10** had negligible magnetic pull in the presence of a 3T MRI magnet. The power adapter **10** was able to sit unassisted in the bore of the 3T magnet. Further, no effects on the operation of the power adapter **10** from the magnetic field were observed in any orientation. The power adapter **10** operated successfully all the way into the bore of the 3T magnet.

With reference to FIGURE 5, an alternative embodiment of the AC/DC power adapter **10** described in FIGURE 1 is illustrated. The input filter module **12** and the output protector module **22** remain as described above. Similarly, the piezoelectric core converter module **14** remains as described above except that it outputs an isolated AC power output. However, in contrast to having a single regulator module **30** with feedback, as described in connection with FIGURE 1, this embodiment of the power adapter **10** includes a pre-regulator module **48** and a post-regulator module **50**.

The pre-regulator module **48** regulates the flow of filtered power to the piezoelectric core converter module **14** to maintain the frequency and voltage of the filtered power provided to the piezoelectric core converter module **14** at predetermined levels, regardless of the voltage and the frequency of the AC power line. Suitably, the filtered power provided to the piezoelectric core converter is sinusoidal with a frequency just above the mechanical resonance of the piezoelectric transformers **18**. The post-regulator module **50** regulates the flow of isolated AC power from the piezoelectric core converter module **14** and converts the isolated AC power to an isolated DC power output. In that regard, the post-regulator module **50** maintain the DC power output at a constant, predetermined voltage, regardless of the voltage of the isolated AC power output by the piezoelectric core converter module **14**.

With reference to FIGURES 6A-4D, a more specific embodiment of the power adapter **10** described in FIGURE 5 is provided. The correspondences with the modules **12, 14, 22, 48, 50** of FIGURE 5 are shown in dashed boxes. As seen, each of the modules **12, 14, 22, 48, 50** corresponds to an electrical circuit. FIGURE 6A illustrates a circuit for the input filter module **12**, and a part of a circuit for the pre-regulation module **48**. FIGURE 6B illustrates a part of a circuit for the pre-regulation module **48**. FIGURE 6C illustrates a circuit for the piezoelectric core converter module **14**. The circuit for the piezoelectric core converter module **14** illustrates the interconnection of the air inductor **36** and the piezoelectric transformers **18**. Further, the circuit for the piezoelectric core converter module **14** illustrates the parallel connection of multiple piezoelectric transformers **18** to increase the power output of the power adapter **10**. FIGURE 6D illustrates a circuit for the output protector module **22**, and a circuit for the post regulator module **50**.

With reference to FIGURE 7, an MRI system **100** within which a device **101** employing the power adapter **10** can be employed is provided. The device **101** is suitably a medical device, such as the illustrated patient monitor. The MRI system **100** uses magnetic resonance (MR) to generate one or more diagnostic images of a target volume of a patient **102**. The system **100** includes a scanner **104** defining an imaging (or scan) volume **106** sized to accommodate the target volume. A patient support can be employed to support the patient **102** and to position the target volume near the isocenter of the imaging volume **106**.

The scanner **104** includes a main magnet **108** that creates a strong, static B_0 magnetic field extending through the imaging volume **106**. The main magnet **108** typically employs superconducting coils to create the static B_0 magnetic field. However, the main magnet **108** can also employ permanent or resistive magnets. Insofar as superconducting coils are employed, the main magnet **108** includes a cooling system, such as a liquid helium cooled cryostat, for the superconducting coils. The strength of the static B_0 magnetic field is commonly one of 0.23T, 0.5T, 1.5T, 3T, 7T, and so on in the imaging volume **106**, but other strengths are contemplated.

A gradient controller **110** of the scanner **104** is controlled to superimpose magnetic field gradients, such as x, y and z gradients, on the static B_0 magnetic field in the imaging volume **106** using a plurality of magnetic field gradient coils **112** of the scanner **104**. The magnetic field gradients spatially encode magnetic spins within the imaging volume **106**. Typically, the plurality of magnetic field gradient coils **112** include three separate magnetic field gradient coils spatially encoding in three orthogonal spatial directions.

Further, one or more transmitters **114**, such as a transceiver, are controlled to transmit B_1 resonance excitation and manipulation radiofrequency (RF) pulses into the imaging volume **106** with one or more transmit coil arrays, such as a whole body coil **116** and/or a surface coil **118**, of the scanner **104**. The B_1 pulses are typically of short duration and, when taken together with the magnetic field gradients, achieve a selected manipulation of magnetic resonance. For example, the B_1 pulses excite the hydrogen dipoles to resonance and the magnetic field gradients encode spatial information in the frequency and phase of the resonance signal. By adjusting the RF frequencies, resonance can be excited in other dipoles, such as phosphorous, which tend to concentrate in known tissues, such as bones.

A sequence controller **120** controls the gradient controller **110** and/or the transmitters **114** according to imaging sequences to produce spatially encoded MR signals within the imaging volume **106**. An imaging sequence defines a sequence of B_1 pulses and/or magnetic field gradients. Further, the imaging sequences can be received from a device or system being remote or local to the sequence controller, such as a sequence memory **122**.

One or more receivers **124**, such as a transceiver, receive the spatially encoded magnetic resonance signals from the imaging volume **106** and demodulate the received spatially encoded magnetic resonance signals to MR data sets. The MR data sets include, for example, k-space data trajectories. To receive the spatially encoded magnetic resonance signals, the receivers **124** use one or more receive coil arrays, such as the whole body coil **116** and/or the surface coil **118**, of the scanner **104**. The receivers **124** typically store the MR data sets in a data memory **126**.

A reconstruction processor **128** reconstructs the MR data sets into MR images or maps of the imaging volume **106**. This includes, for each MR signal captured by the MR data sets, spatially decoding the spatial encoding by the magnetic field gradients to ascertain a property of the MR signal from each spatial region, such as a pixel or voxel. The intensity or magnitude of the MR signal is commonly ascertained, but other properties related to phase, relaxation time, magnetization transfer, and the like can also be ascertained. The MR images or maps are typically stored in an image memory **130**.

A main controller **132** controls the reconstruction processor **128** and the sequence controller **120** to generate one or more diagnostic images of the target volume using one or more scans of the target volume. For each scan, the target vessel is positioned within the imaging volume **106**. For example, the patient **102** is positioned on the patient support. The surface coil **118** is then positioned on the patient **102** and the patient support moves the target volume into the imaging volume **106**. The size of the imaging volume **106** can vary between scans.

Once the target volume is positioned within the imaging volume **106**, the main controller **132** controls the sequence controller **120** according to scan parameters, such as number of slices, and provides the sequence controller **120** with an imaging sequence. The imaging sequence can, for example, be stored in the sequence memory **122**. As noted above, an imaging sequence defines a sequence of B_1 pulses and/or magnetic field gradients that produce spatially encoded MR signals from the imaging volume **106**. Further, the main controller **132** can control the receivers **124** according to scan parameters. For example, the main controller **132** can adjust the gain of the receivers **124**.

The main controller **132** can carry out the foregoing functionality by software, hardware or both. Where the main controller **132** employs software, the main controller **132** includes at least one processor executing the software. The software is suitably stored on a program memory **134**, which can be local or remote from the main controller **42**. Further, the main controller **132** can be managed by a user using a graphical user interface presented to the user by way of a display device **136** and a user input device **138**. The user can, for example, initiate imaging, display images, manipulate images, etc.

Notwithstanding that the reconstruction processor **128** and the sequence controller **120** were illustrated as external to the main controller **132**, it is to be appreciated that one or both of these components can be integrated with the main controller **132** as software, hardware or a combination of both. For example, the reconstruction processor **128** can be integrated with the main controller **132** as a software module executing on the at least one processor of the main controller **132**.

With reference to FIGURE 8, a method **200** for supplying power in external magnetic fields according to the above discussion is provided. The method **200** is performed by a power supply, such as the AC/DC power adapter **10**, in a high external magnetic field. A high external magnetic field is typically a magnetic field greater than 2000 G. Such magnetic fields are common proximate (e.g., within a few feet) of a main magnetic **108** of a magnetic resonance imaging MRI system **100**.

The method **200** includes converting **202** alternating current AC line power to isolated power using one or more piezoelectric transformers **18**. This is carried out by the piezoelectric core converter module **14**. The isolated power can be DC or AC (compare FIGURE 1 and FIGURE 5). When the isolated power is DC power, it is typically provided to an external load **101** without further conversion and/or regulation. Otherwise, additional conversion and/or regulation are often needed for the external load **101**. The converting typically includes generating a sinusoidal input to the piezoelectric transformers **18** at a frequency above the mechanical resonance of the piezoelectric transformers **18** by an air core inductor **36**.

The flow of AC line power to the piezoelectric transformers **18** is regulated **204** to maintain the isolated power at a predetermined voltage (RMS voltage when the isolated power is AC). This is carried out by the regulator module **16** or the pre-regulator module **48** depending upon the number of regulation stages. The regulating can include receiving measurements of the isolated power and regulating the flow of AC line power to piezoelectric transformers **18** based on the received measurements. Further, the regulating can include converting the AC line power to a pulse train and controlling a duty cycle of the pulse train to maintain the isolated power at the predetermined voltage. Even more, the regulating can include monitoring the temperature of the piezoelectric transformers **18** and/or monitoring the AC line power. Based on the monitoring, the piezoelectric transformers **18** can be protected from damage by, for example, disconnecting external loads and/or the power line power from the piezoelectric transformers **18.**

In some instances, as described in FIGURE 5, the flow of the isolated power to an external load **101** can be regulated **206** after the conversion. This is carried out by the post-regulator module **50**. Typically, the post-regulation includes converting the isolated power, which is typically AC, to isolated DC power sufficient for powering the external load **101**. Regardless of the voltage of the isolated power, the isolated DC power remains constant. Hence, in embodiments including post-regulation, there are two stages of regulation: a pre-regulation stage and a post-regulation stage.

As used herein, a memory includes any device or system storing data, such as a random access memory (RAM) or a read-only memory (ROM). Further, as used herein, a processor includes any device or system processing input device to produce output data, such as a microprocessor, a microcontroller, a graphic processing unit (GPU), an application-specific integrated circuit (ASIC), an FPGA, and the like; a controller includes any device or system controlling another device or system; a user input device includes any device, such as a mouse or keyboard, allowing a user of the user input device to provide input to another device or system; and a display device includes any device for displaying data, such as a liquid crystal display (LCD) or a light emitting diode (LED) display.

The invention has been described with reference to the preferred embodiments. Modifications and alterations may occur to others upon reading and understanding the preceding detailed description. For example, while the foregoing discussion focused on an AC/DC power adapter, those skilled in the art will appreciate that the piezoelectric transformers can be applied to other types of power supplies. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

CLAIMS:

1. A power supply **(10)** for supplying power in high external magnetic fields, the power supply **(10)** comprising:

a piezoelectric core converter module **(14)** configured for converting alternating current (AC) line power to isolated power using one or more piezoelectric transformers **(18)**; and

a regulator module **(16, 48)** configured for regulating the flow of AC line power to the piezoelectric core converter module **(14)** to maintain the isolated power at a predetermined voltage.

2. The power supply **(10)** according to claim 1, wherein the isolated power is isolated direct current (DC) power, the isolated DC power provided to an external load **(101)**.

3. The power supply **(10)** according to either one of claims 1 and 2, wherein the regulator module **(16, 48)** is further configured for:

receiving measurements of the isolated power; and

regulating the flow of AC line power to the piezoelectric core converter module **(14)** based on the received measurements.

4. The power supply **(10)** according to any one of claims 1-3, wherein the piezoelectric core converter module **(14)** includes an air core inductor **(36)** configured for generating a sinusoidal input to the piezoelectric transformers **(18)** at a frequency above the mechanical resonance of the piezoelectric transformers **(18)**.

5. The power supply **(10)** according to any one of claims 1-4, wherein the one or more piezoelectric transformers **(18)** includes a plurality of piezoelectric transformers connected in parallel to increase power output of the power supply **(10)**.

6. The power supply **(10)** according to any one of claims 1-5, wherein the regulator module **(16, 18)** is further configured for:

converting the AC line power to a pulse train; and

controlling a duty cycle of the pulse train to maintain the isolated power at the predetermined voltage.

7. The power supply **(10)** according to any one of claims 1-6, wherein the regulator module **(16, 48)** includes a microcontroller **(20)** regulating the flow of AC line power to the piezoelectric core converter module **(14)**.

8. The power supply **(10)** according to any one of claims 1-7, wherein the regulator module **(16, 48)** is further configured for:

monitoring the temperature of the piezoelectric transformers **(18)** and/or monitoring the AC line power; and

protecting the piezoelectric transformers **(18)** from damage based on the monitoring.

9. The power supply **(10)** according to any one of claims 1-8, wherein the regulator module **(16, 48)** is a pre-regulator module **(48)**, and wherein the power supply **(10)** further includes:

a post-regulator module **(50)** configured for:

regulating the flow of the isolated power to an external load **(101)**; and

converting the isolated power to isolated DC power.

10. The power supply **(10)** according to any one of claims 1-9, wherein the high magnetic field is greater than 2000 gauss (G).

11. A medical system **(100)** comprising:

a magnetic resonance imaging (MRI) scanner **(104)** including a main magnetic **(108)** which generates a high external magnetic field; and

the power supply **(10)** according to any one of claims 1-10 positioned proximate to the main magnetic **(108)** and providing power to an external load **(101)**.

12. A method **(200)** for supplying power in high external magnetic fields, the method **(200)** comprising:

converting **(202)** alternating current (AC) line power to isolated power using one or more piezoelectric transformers **(18)**; and regulating **(204)** the flow of AC line power to the piezoelectric transformers **(18)** to maintain the isolated power at a predetermined voltage.

13. The method **(200)** according to claim 12, wherein the isolated power is isolated direct current (DC) power, the isolated DC power provided to an external load **(101)**.

14. The method **(200)** according to either one of claims 12 and 13, wherein the regulating **(204)** includes:

receiving measurements of the isolated power; and

regulating the flow of AC line power to piezoelectric transformers **(18)** based on the received measurements.

15. The method **(200)** according to any one of claims 12-14, wherein the converting **(202)** includes:

generating a sinusoidal input to the piezoelectric transformers **(18)** at a frequency above the mechanical resonance of the piezoelectric transformers **(18)** by an air core inductor **(36)**.

16. The method **(200)** according to any one of claims 12-15, wherein the regulating **(204)** includes:

converting the AC line power to a pulse train; and

controlling a duty cycle of the pulse train to maintain the isolated power at the predetermined voltage.

17. The method **(200)** according to any one of claims 12-16, wherein the regulating **(204)** includes:

monitoring the temperature of the piezoelectric transformers **(18)** and/or monitoring the AC line power; and

protecting the piezoelectric transformers **(18)** from damage based on the monitoring.

18. The method **(200)** according to any one of claims 12-17, further including:

regulating **(206)** the flow of the isolated power to an external load **(101)**, the regulating **(206)** includes converting the isolated power to isolated DC power.

19. The method **(200)** according to any one of claims 12-18, further including:

positioning the piezoelectric transformers **(18)** proximate a main magnetic **(108)** of a magnetic resonance imaging (MRI) system **(100)**, the main magnet **(108)** generating the high external magnetic fields.

20. A power supply **(10)** for supplying power in high external magnetic fields, the power supply **(10)** comprising:

one or more piezoelectric transformers **(18)** converting alternating current (AC) line power to isolated power;

one or more regulator modules **(16, 48, 50)** at least one of regulating the flow of AC line power to the piezoelectric transformers **(18)** and regulating the flow of isolated power from the piezoelectric transformers **(18)** to maintain a constant output voltage regardless of the AC line power.

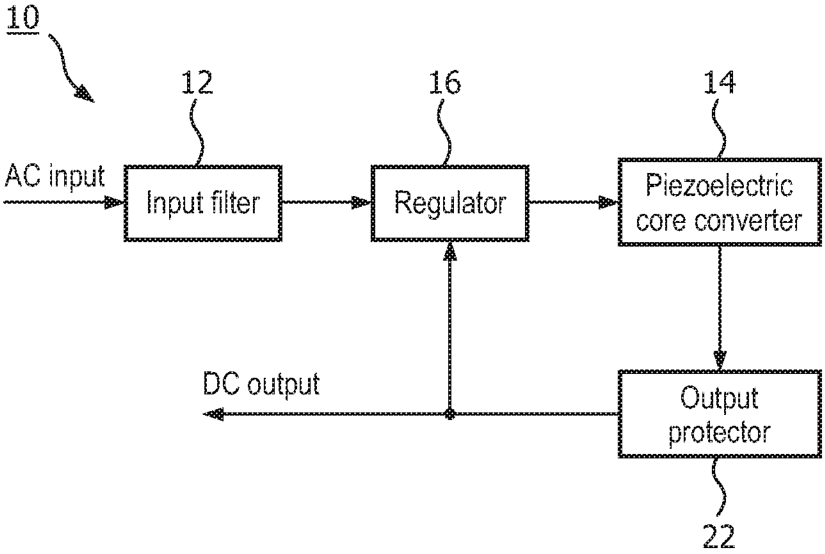
10
12
16
14
AC input
Input filter
Regulator
Piezoelectric core converter
DC output
Output protector
22

FIG. 1

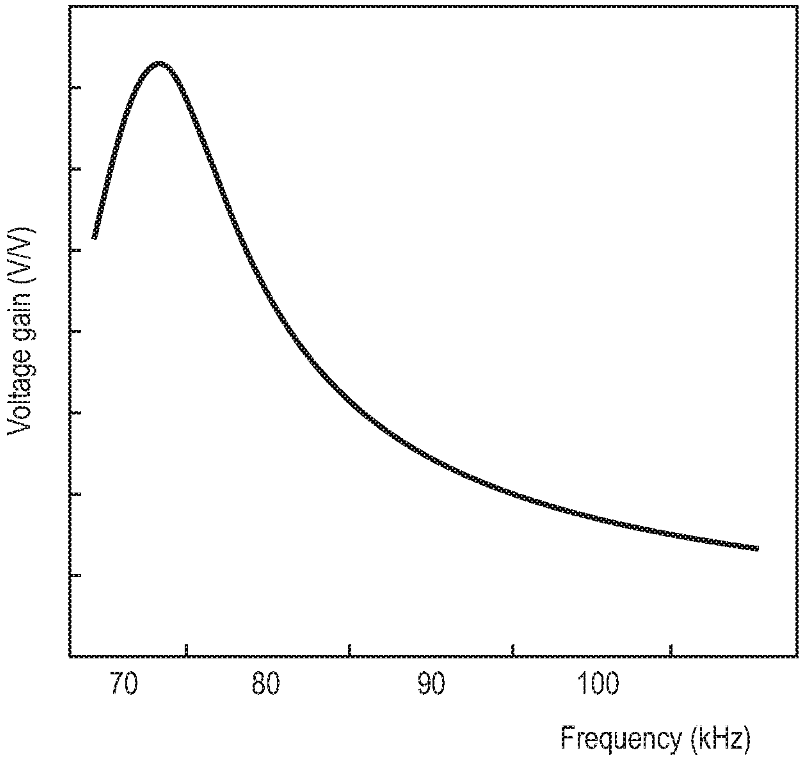
Voltage gain (V/V)
70
80
90
100
Frequency (kHz)

FIG. 3

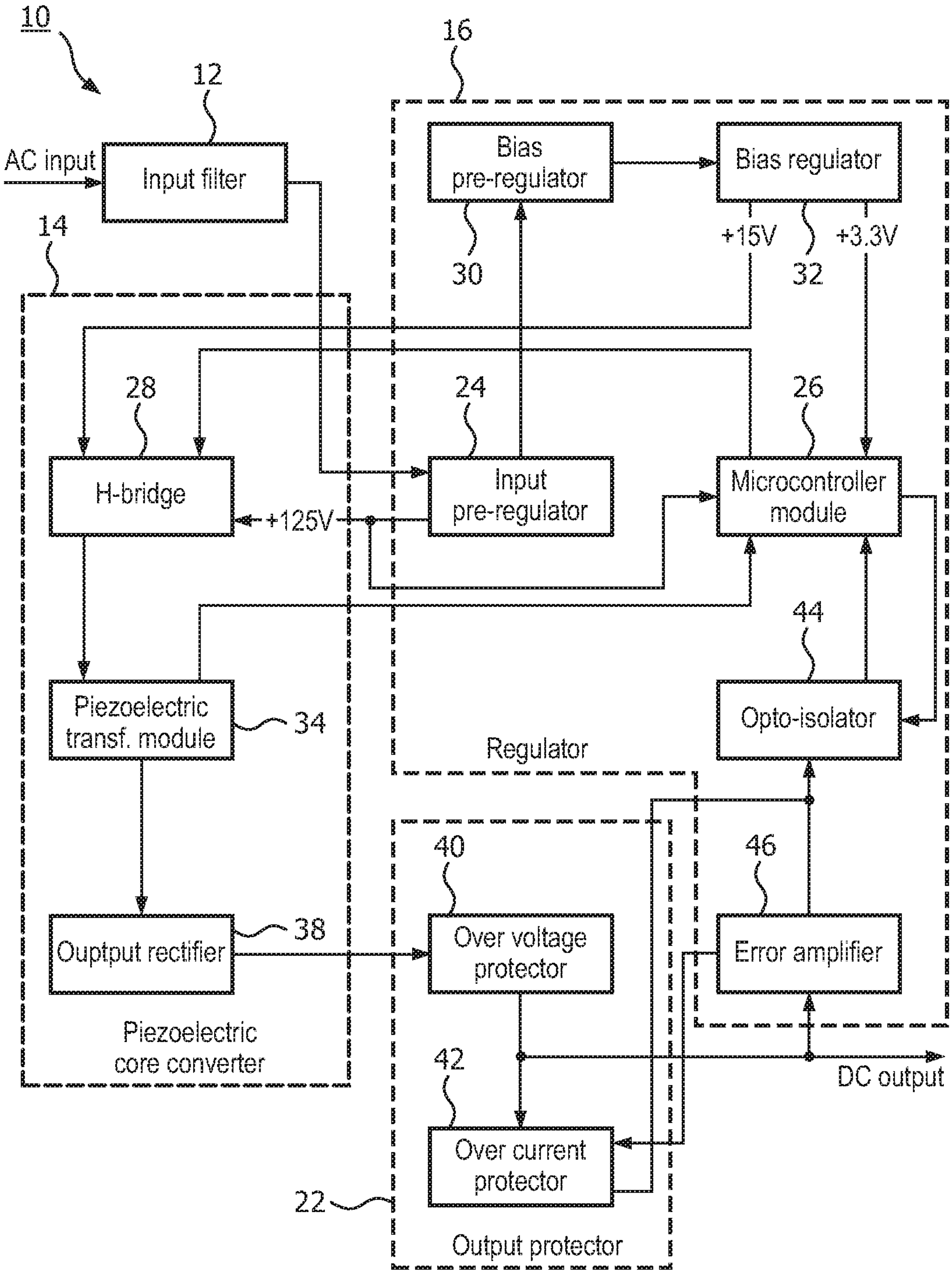
10
12
AC input
Input filter
16
Bias
pre-regulator
Bias regulator
30
+15V
32
+3.3V
14
28
24
26
H-bridge
Input
pre-regulator
Microcontroller
module
+125V
44
Piezoelectric
transf. module
34
Opto-isolator
Regulator
40
46
Ouptput rectifier
38
Over voltage
protector
Error amplifier
Piezoelectric
core converter
42
DC output
Over current
protector
22
Output protector

FIG. 2

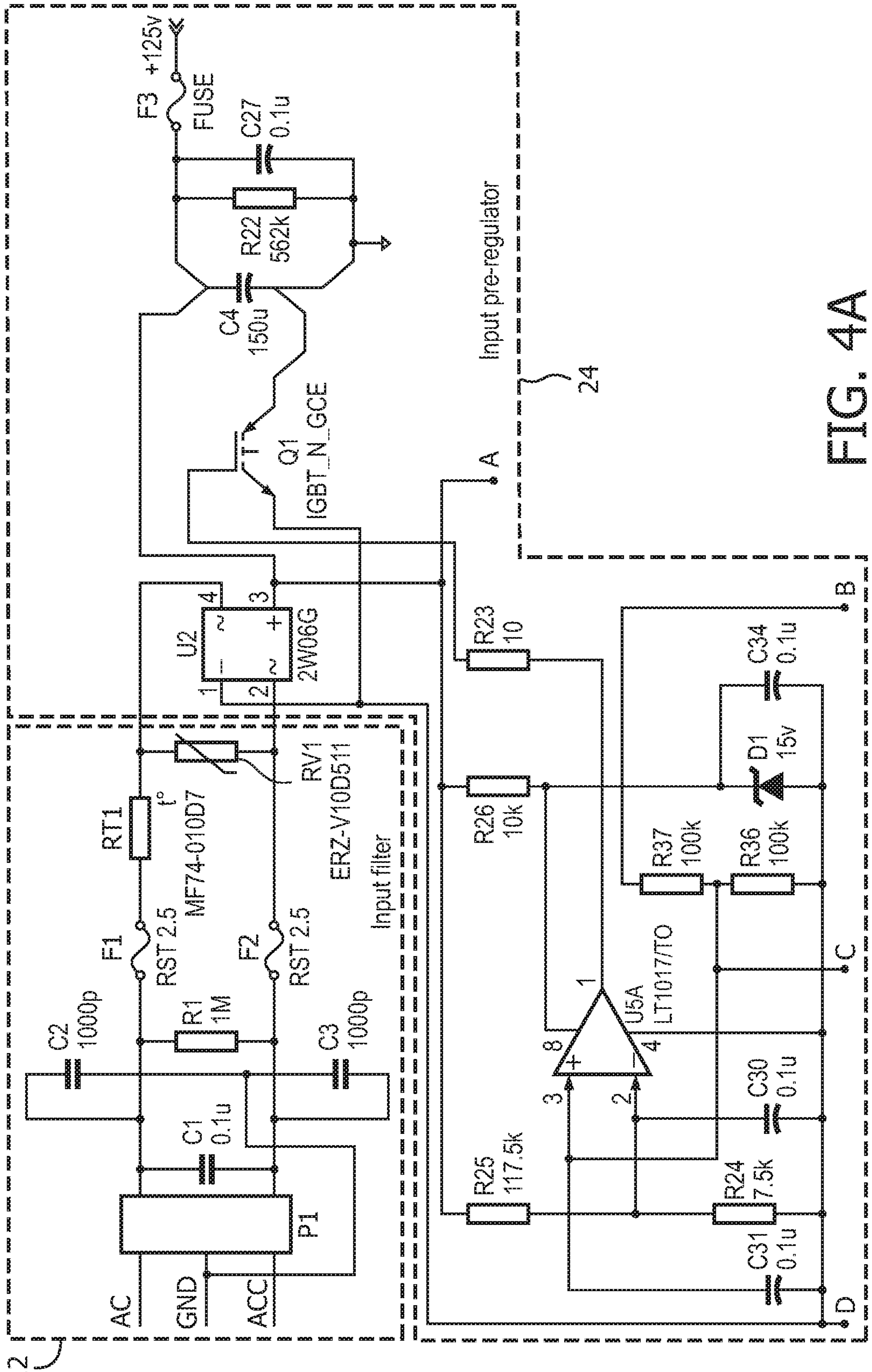
12
AC
GND
ACC
P1
C1
0.1u
C2
1000p
C3
1000p
R1
1M
F1
RST 2.5
F2
RST 2.5
RT1
t°
MF74-010D7
RV1
ERZ-V10D511
Input filter
U2
2W06G
1
2
3
4
~
~
+
−
F3
+125v
FUSE
C27
0.1u
R22
562k
C4
150u
Q1
IGBT_N_GCE
A
Input pre-regulator
24
B
R23
10
C34
0.1u
D1
15v
R26
10k
R37
100k
R36
100k
C
U5A
LT1017/TO
1
8
3
2
4
+
−
C30
0.1u
R25
117.5k
R24
7.5k
C31
0.1u
D

FIG. 4A

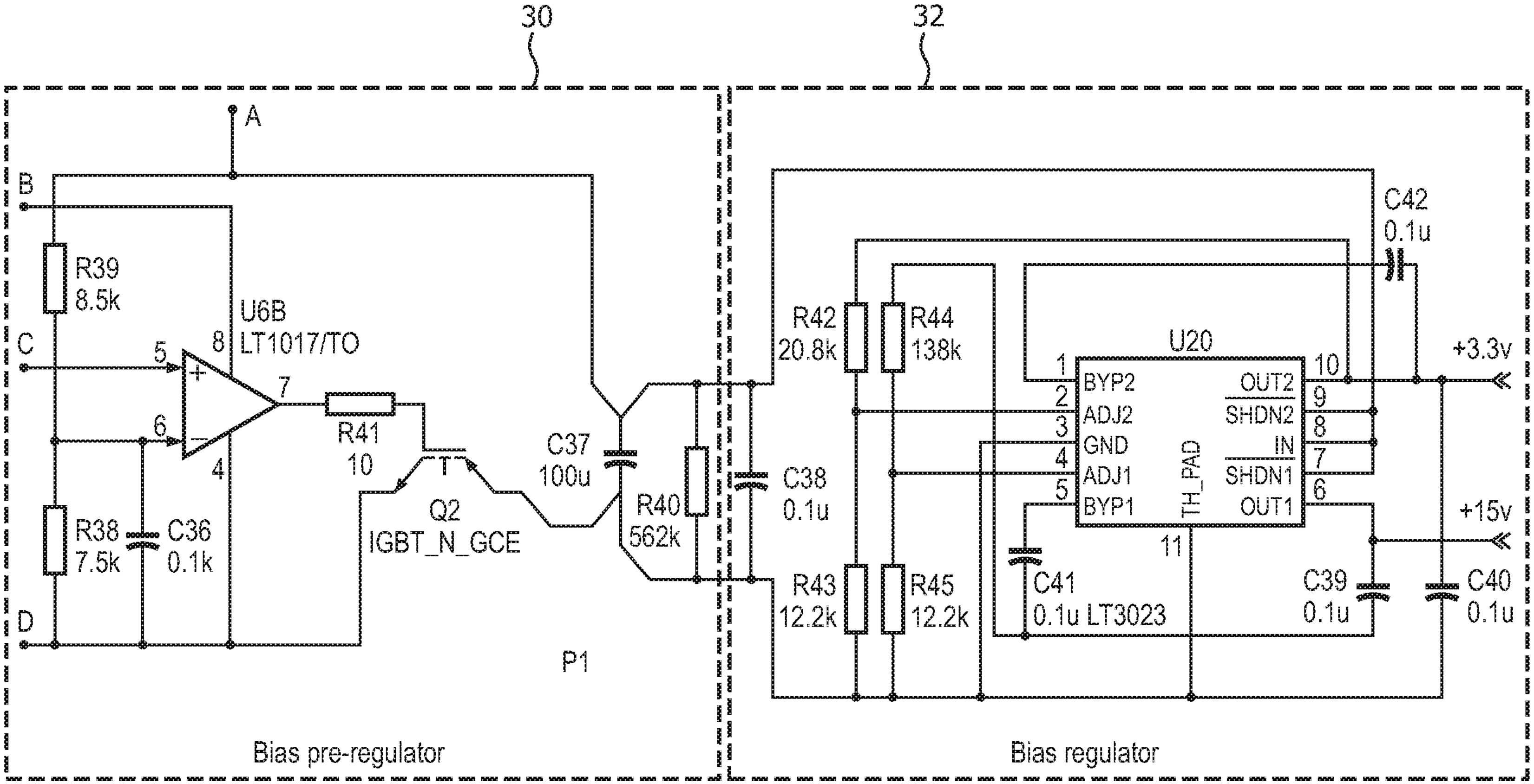
30
32
A
B
C
D
R39
8.5k
R38
7.5k
C36
0.1k
U6B
LT1017/TO
5
6
7
8
4
+
−
R41
10
Q2
IGBT_N_GCE
C37
100u
R40
562k
P1
C38
0.1u
R42
20.8k
R44
138k
R43
12.2k
R45
12.2k
U20
BYP2
ADJ2
GND
ADJ1
BYP1
TH_PAD
OUT2
SHDN2
IN
SHDN1
OUT1
1
2
3
4
5
6
7
8
9
10
11
C41
0.1u LT3023
C42
0.1u
+3.3v
+15v
C39
0.1u
C40
0.1u
Bias pre-regulator
Bias regulator

FIG. 4B

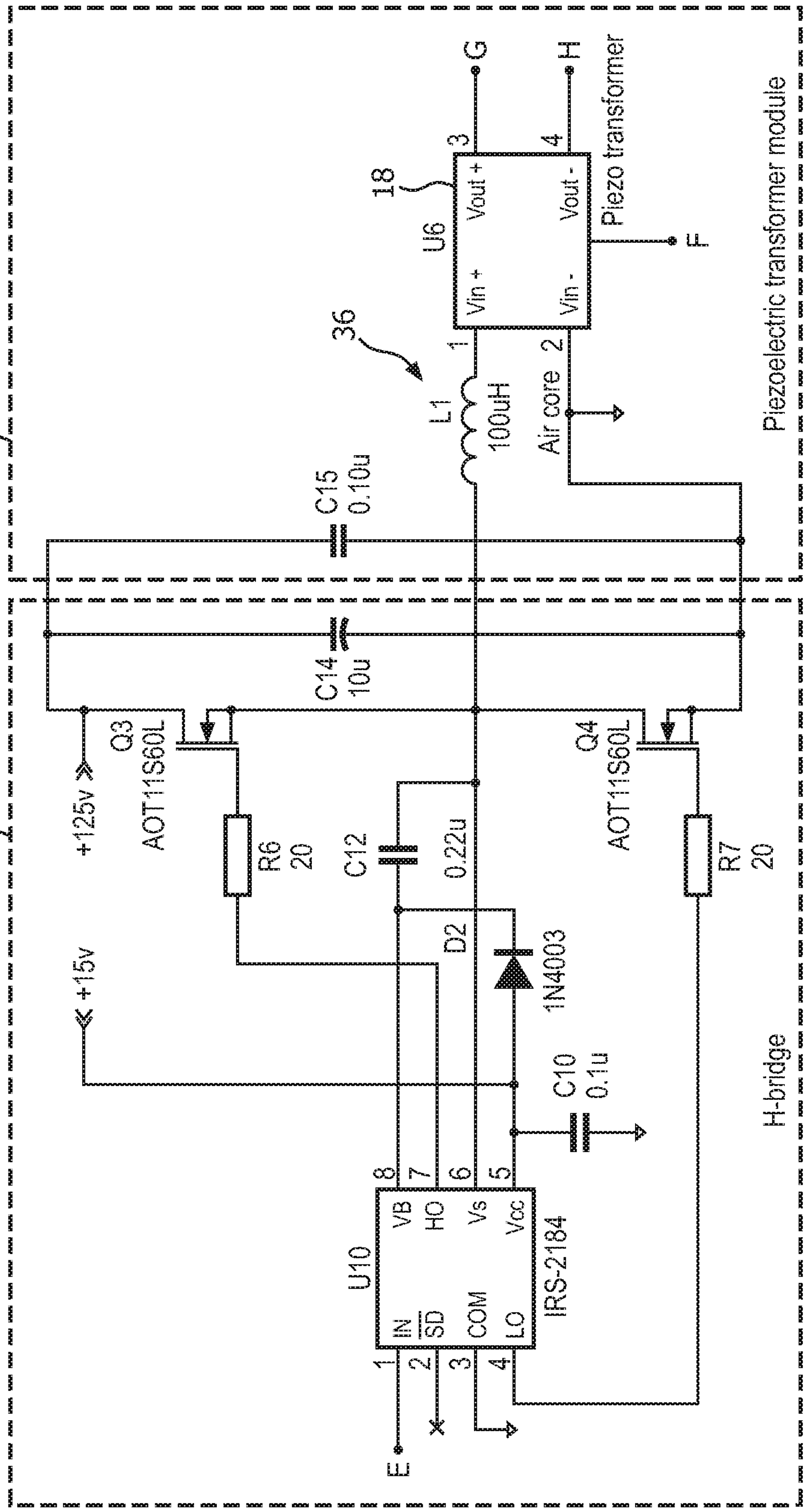
34
28
G
H
Piezo transformer
Piezoelectric transformer module
18
U6
Vin +
Vin -
Vout +
Vout -
3
4
1
2
F
36
L1
100uH
Air core
C15
0.10u
C14
10u
+125v
Q3
AOT11S60L
Q4
AOT11S60L
R6
20
R7
20
C12
0.22u
D2
1N4003
+15v
C10
0.1u
U10
IRS-2184
VB
HO
Vs
Vcc
IN
SD
COM
LO
8
7
6
5
1
2
3
4
E
H-bridge

FIG. 4C

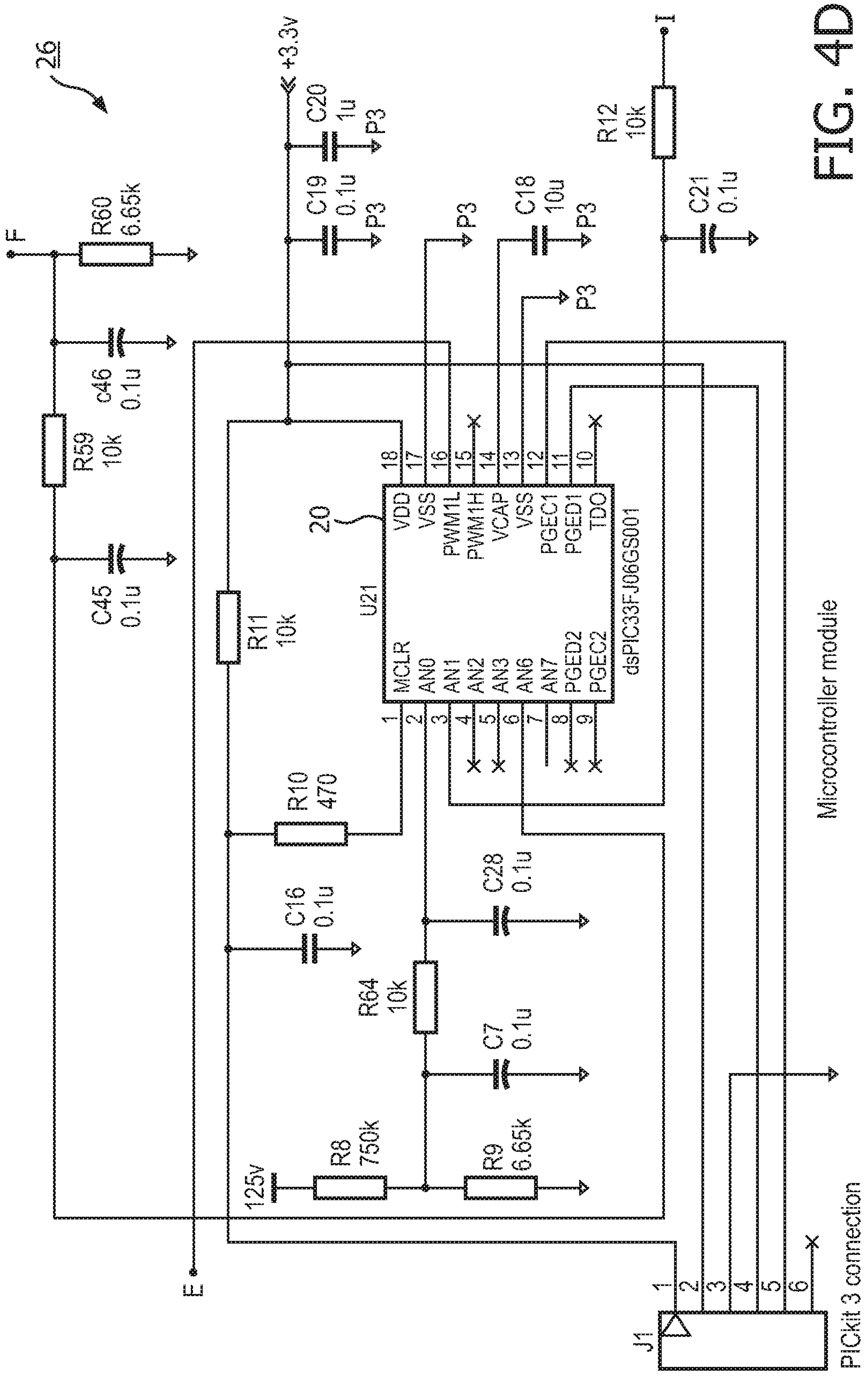
26
+3.3v
C20
1u
P3
C19
0.1u
P3
P3
C18
10u
P3
P3
R12
10k
I
C21
0.1u
F
R60
6.65k
c46
0.1u
R59
10k
C45
0.1u
20
U21
18 VDD
17 VSS
16 PWM1L
15 PWM1H
14 VCAP
13 VSS
12 PGEC1
11 PGED1
10 TDO
1 MCLR
2 AN0
3 AN1
4 AN2
5 AN3
6 AN6
7 AN7
8 PGED2
9 PGEC2
dsPIC33FJ06GS001
R11
10k
R10
470
C16
0.1u
C28
0.1u
R64
10k
C7
0.1u
125v
R8
750k
R9
6.65k
E
Microcontroller module
J1
1
2
3
4
5
6
PICkit 3 connection

FIG. 4D

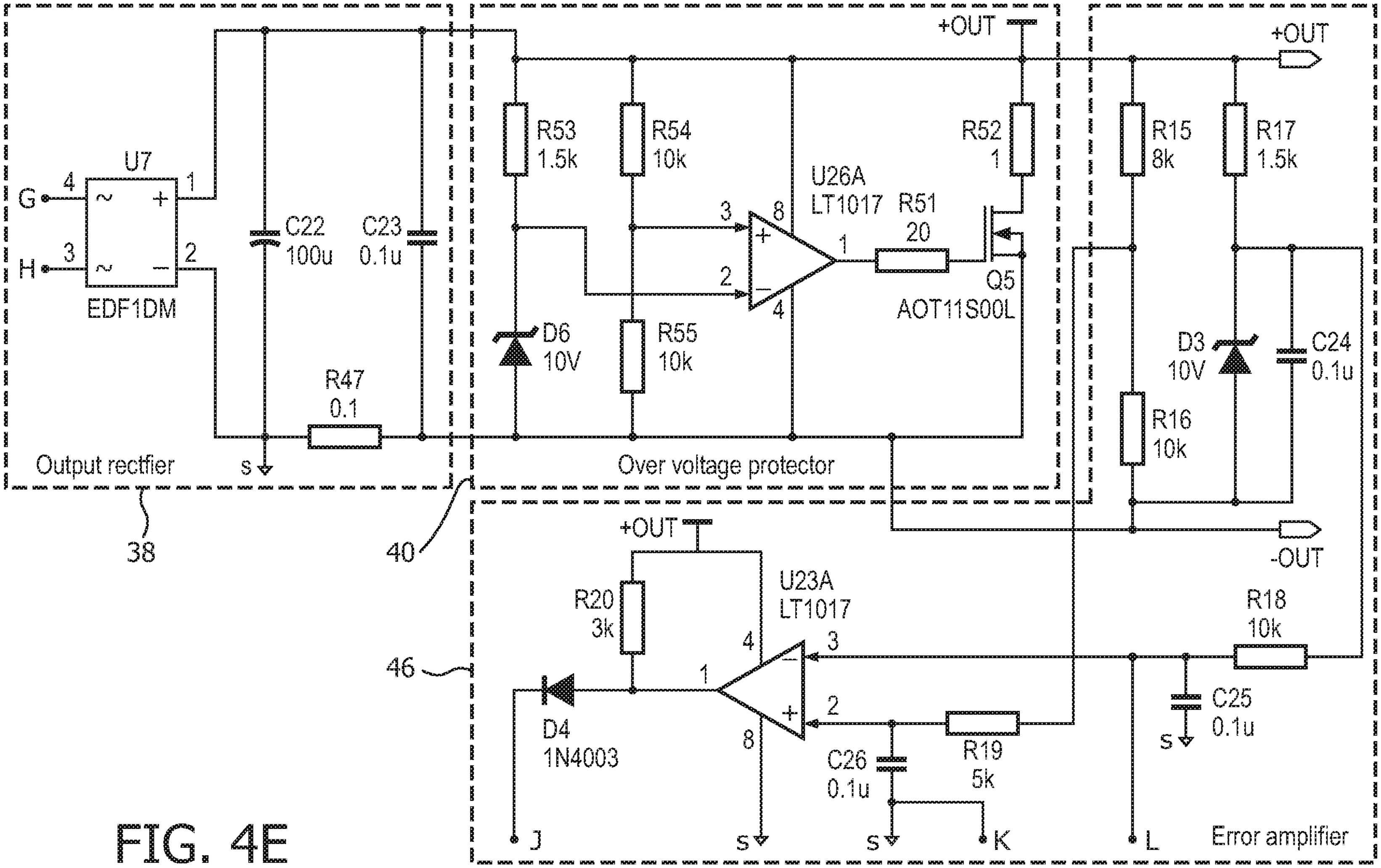
G
H
4
3
U7
~
~
+
−
1
2
EDF1DM
C22
100u
C23
0.1u
R47
0.1
s
Output rectfier
38
40
R53
1.5k
R54
10k
D6
10V
R55
10k
3
2
8
4
+
−
U26A
LT1017
1
R51
20
+OUT
R52
1
Q5
AOT11S00L
Over voltage protector
+OUT
R15
8k
R17
1.5k
D3
10V
C24
0.1u
R16
10k
-OUT
46
+OUT
R20
3k
U23A
LT1017
4
3
2
1
8
D4
1N4003
R18
10k
C25
0.1u
s
C26
0.1u
R19
5k
J
s
s
K
L
Error amplifier

FIG. 4E

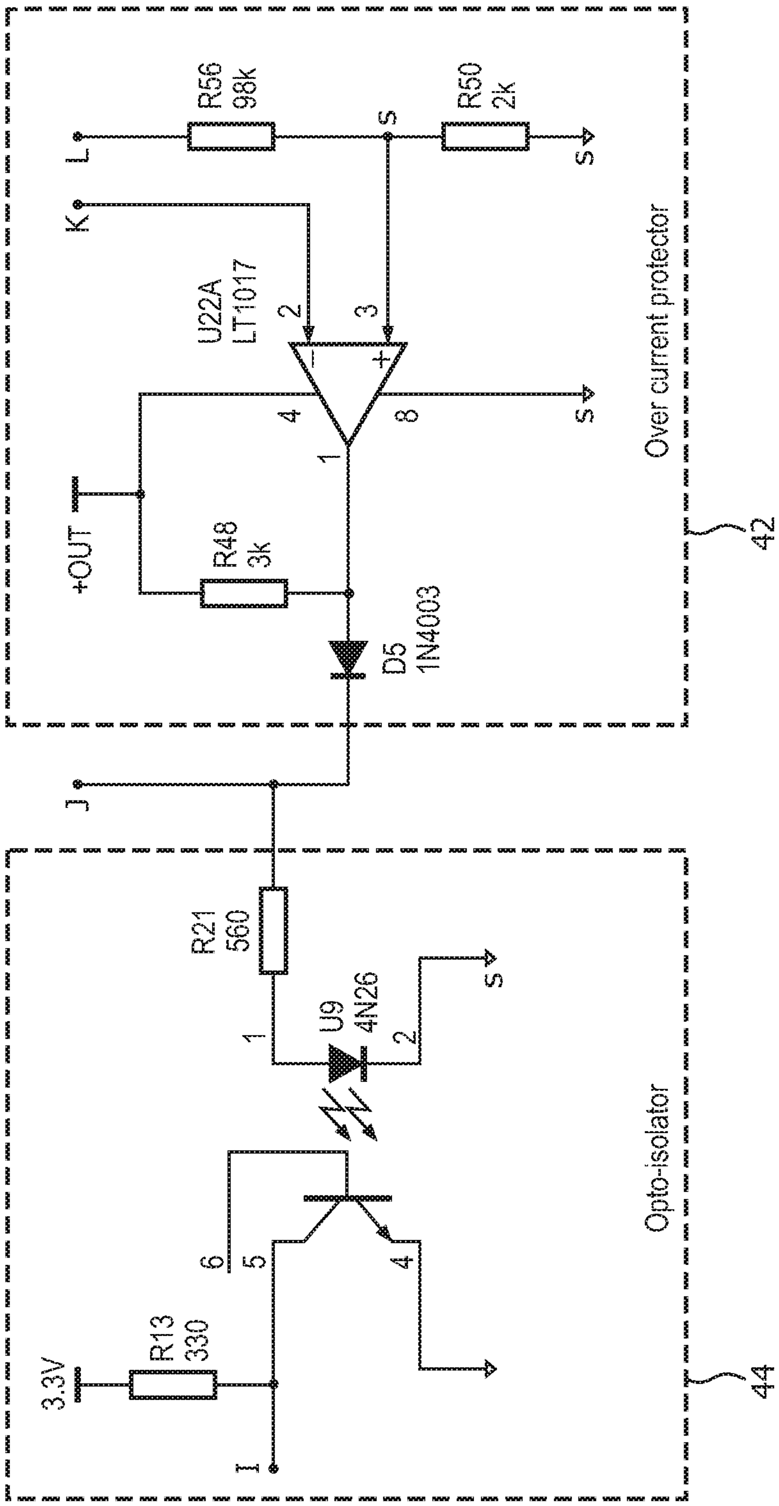
L
R56
98k
s
R50
2k
s
K
U22A
LT1017
2
3
−
+
4
8
1
s
+OUT
R48
3k
D5
1N4003
Over current protector
42
J
R21
560
U9
4N26
1
2
s
6
5
4
3.3V
R13
330
I
Opto-isolator
44

FIG. 4F

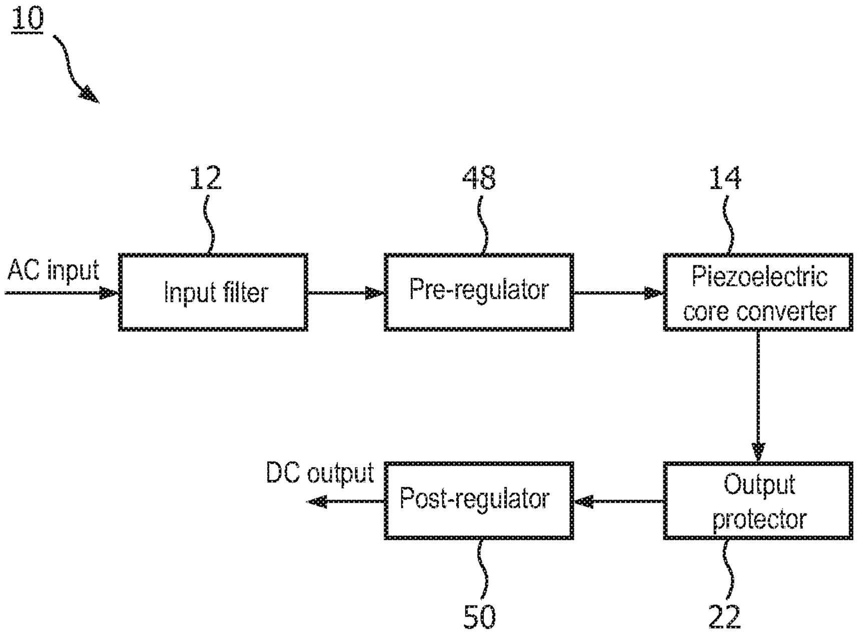
10
12
48
14
AC input
Input filter
Pre-regulator
Piezoelectric core converter
DC output
Post-regulator
Output protector
50
22

FIG. 5

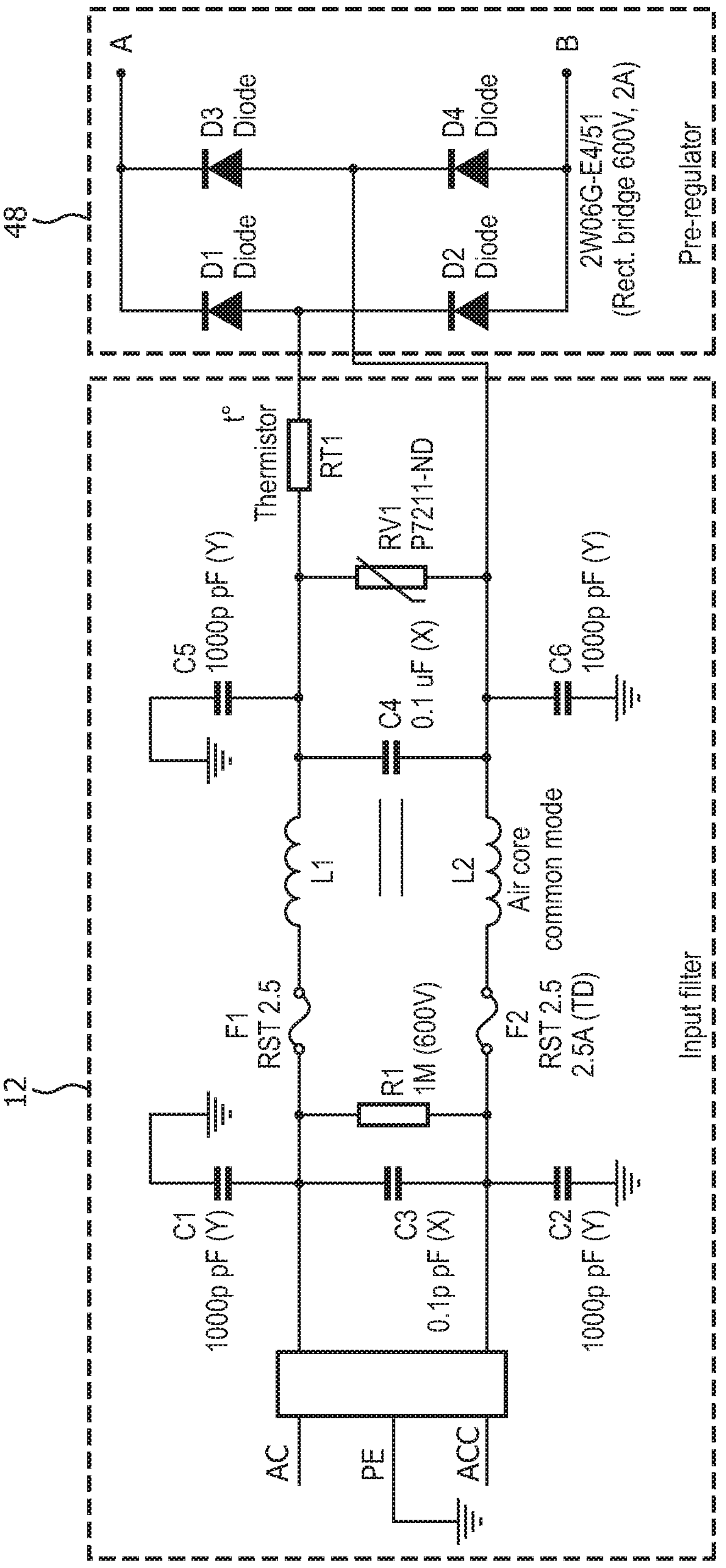
48
A
D3
Diode
D1
Diode
D4
Diode
D2
Diode
B
2W06G-E4/51
(Rect. bridge 600V, 2A)
Pre-regulator
12
t°
Thermistor
RT1
RV1
P7211-ND
C5
1000p pF (Y)
C4
0.1 uF (X)
C6
1000p pF (Y)
L1
L2
Air core
common mode
F1
RST 2.5
F2
RST 2.5
2.5A (TD)
R1
1M (600V)
C1
1000p pF (Y)
C3
0.1p pF (X)
C2
1000p pF (Y)
Input filter
AC
PE
ACC

FIG. 6A

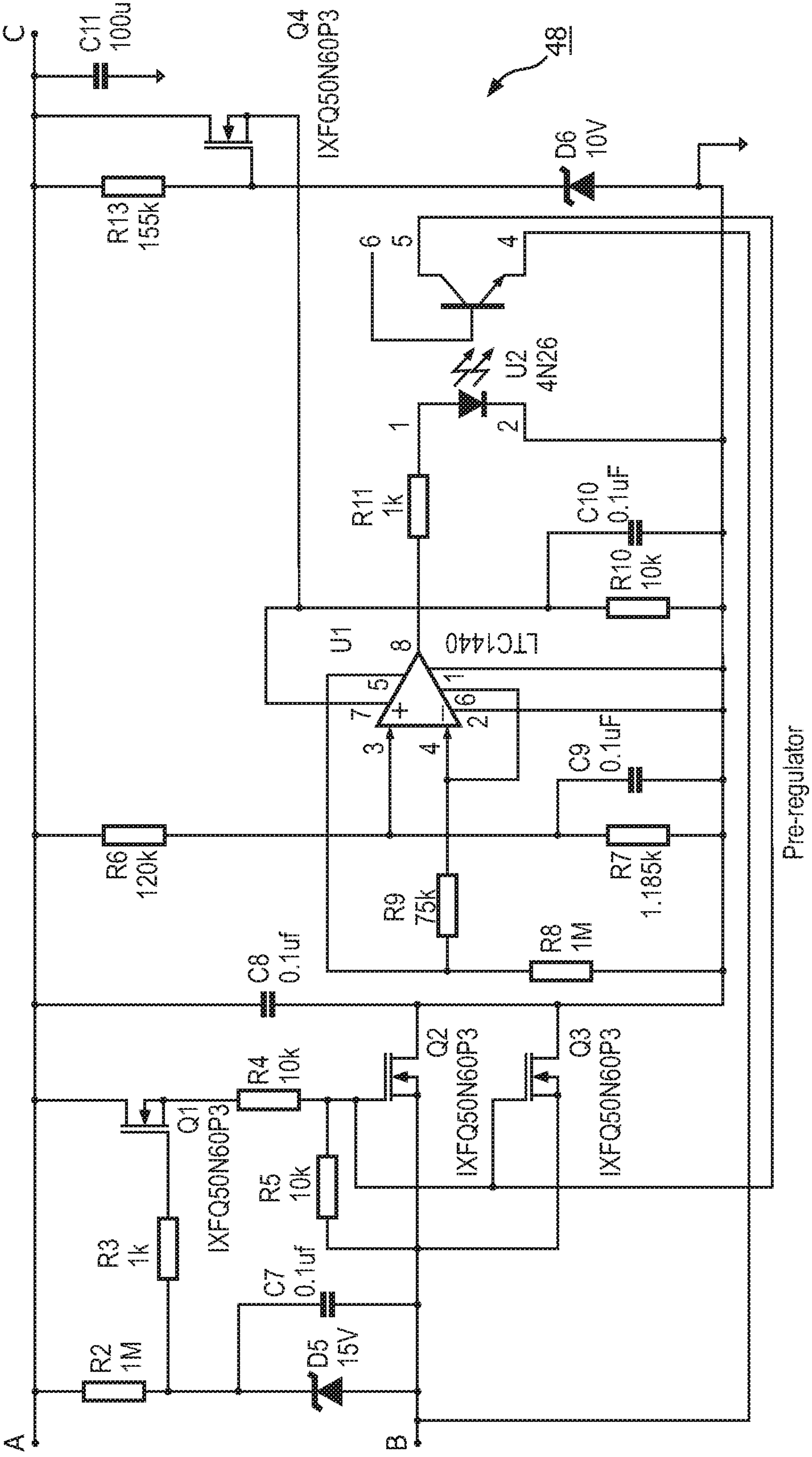
A
B
C
C11
100uF
Q4
IXFQ50N60P3
48
R13
155k
D6
10V
6
5
4
U2
4N26
1
2
R11
1k
C10
0.1uF
R10
10k
U1
LTC1440
8
5
7
6
1
2
3
4
+
−
C9
0.1uF
R6
120k
R7
1.185k
R9
75k
R8
1M
C8
0.1uf
Pre-regulator
Q1
IXFQ50N60P3
R4
10k
Q2
IXFQ50N60P3
Q3
IXFQ50N60P3
R5
10k
R3
1k
C7
0.1uf
R2
1M
D5
15V

FIG. 6B

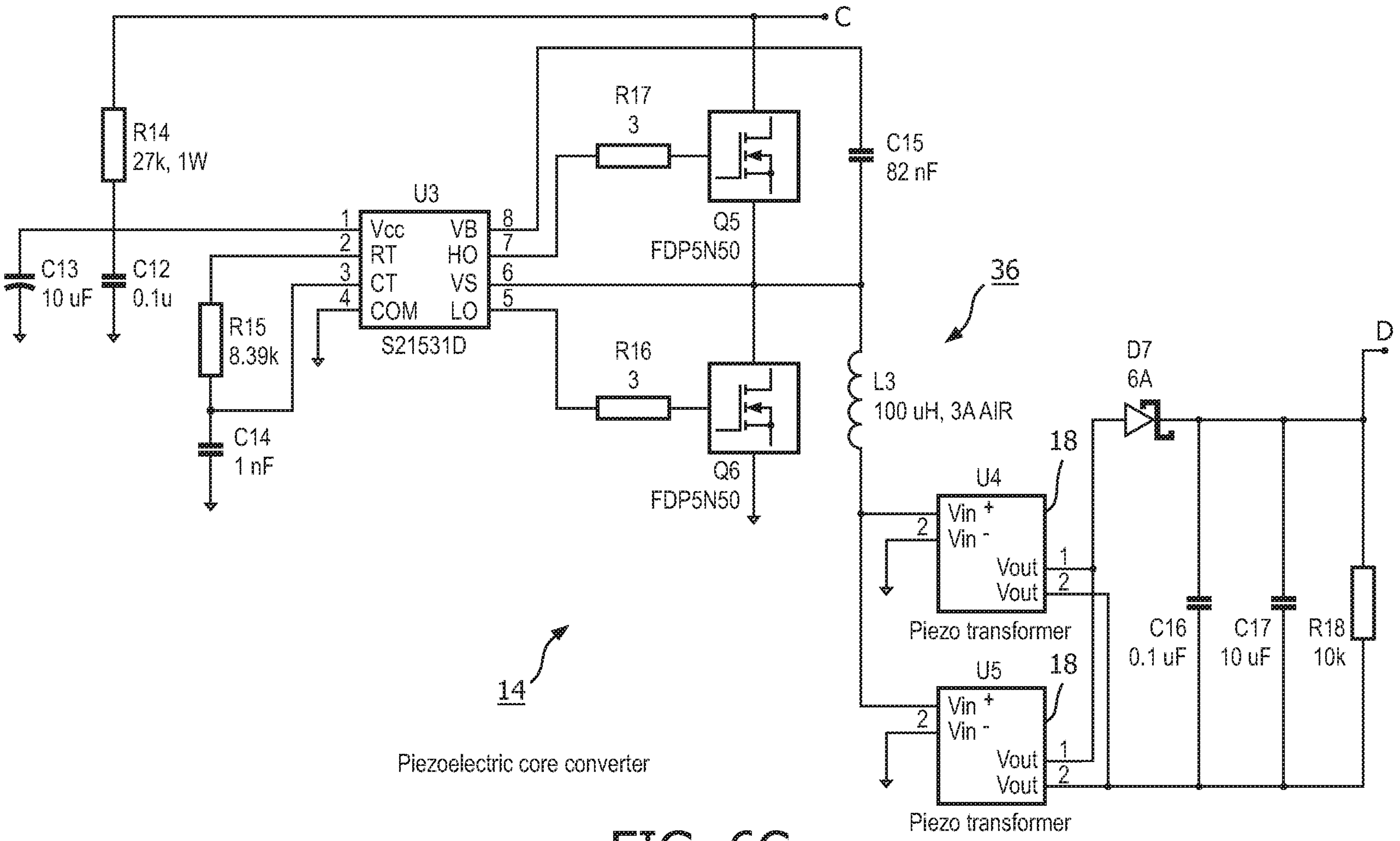
C
R14
27k, 1W
C13
10 uF
C12
0.1u
U3
1
2
3
4
Vcc
RT
CT
COM
VB
HO
VS
LO
8
7
6
5
S21531D
R15
8.39k
C14
1 nF
R17
3
R16
3
Q5
FDP5N50
Q6
FDP5N50
C15
82 nF
36
L3
100 uH, 3A AIR
D7
6A
D
18
U4
Vin +
Vin -
Vout
Vout
2
1
2
Piezo transformer
18
U5
Vin +
Vin -
Vout
Vout
2
1
2
Piezo transformer
C16
0.1 uF
C17
10 uF
R18
10k
14
Piezoelectric core converter

FIG. 6C

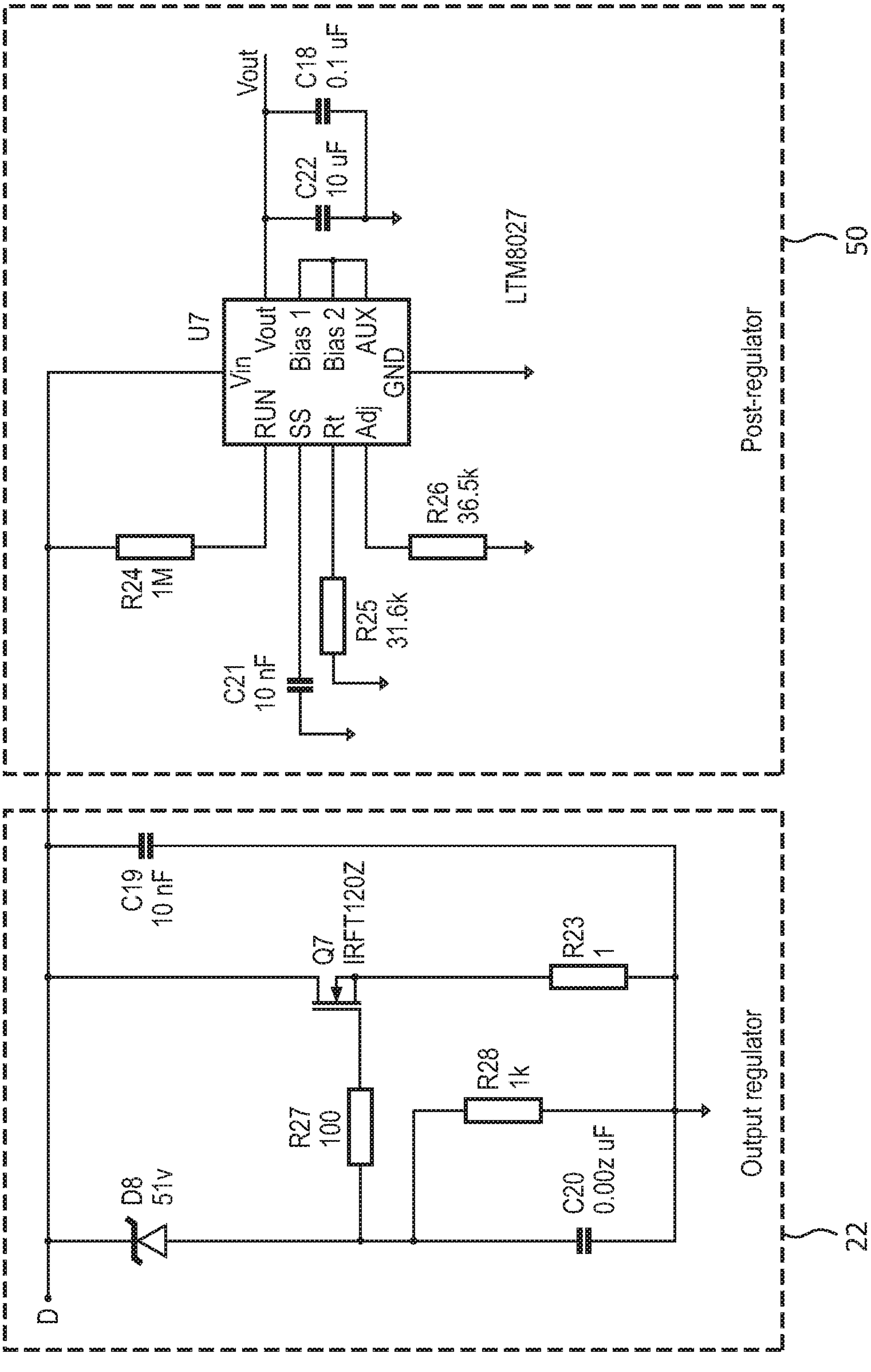
Vout
C18
0.1 uF
C22
10 uF
LTM8027
U7
Vin
Vout
Bias 1
Bias 2
AUX
RUN
SS
Rt
Adj
GND
R24
1M
R25
31.6k
R26
36.5k
C21
10 nF
Post-regulator
50
C19
10 nF
Q7
IRFT120Z
R23
1
R27
100
R28
1k
D8
51v
C20
0.00z uF
D
Output regulator
22

FIG. 6D

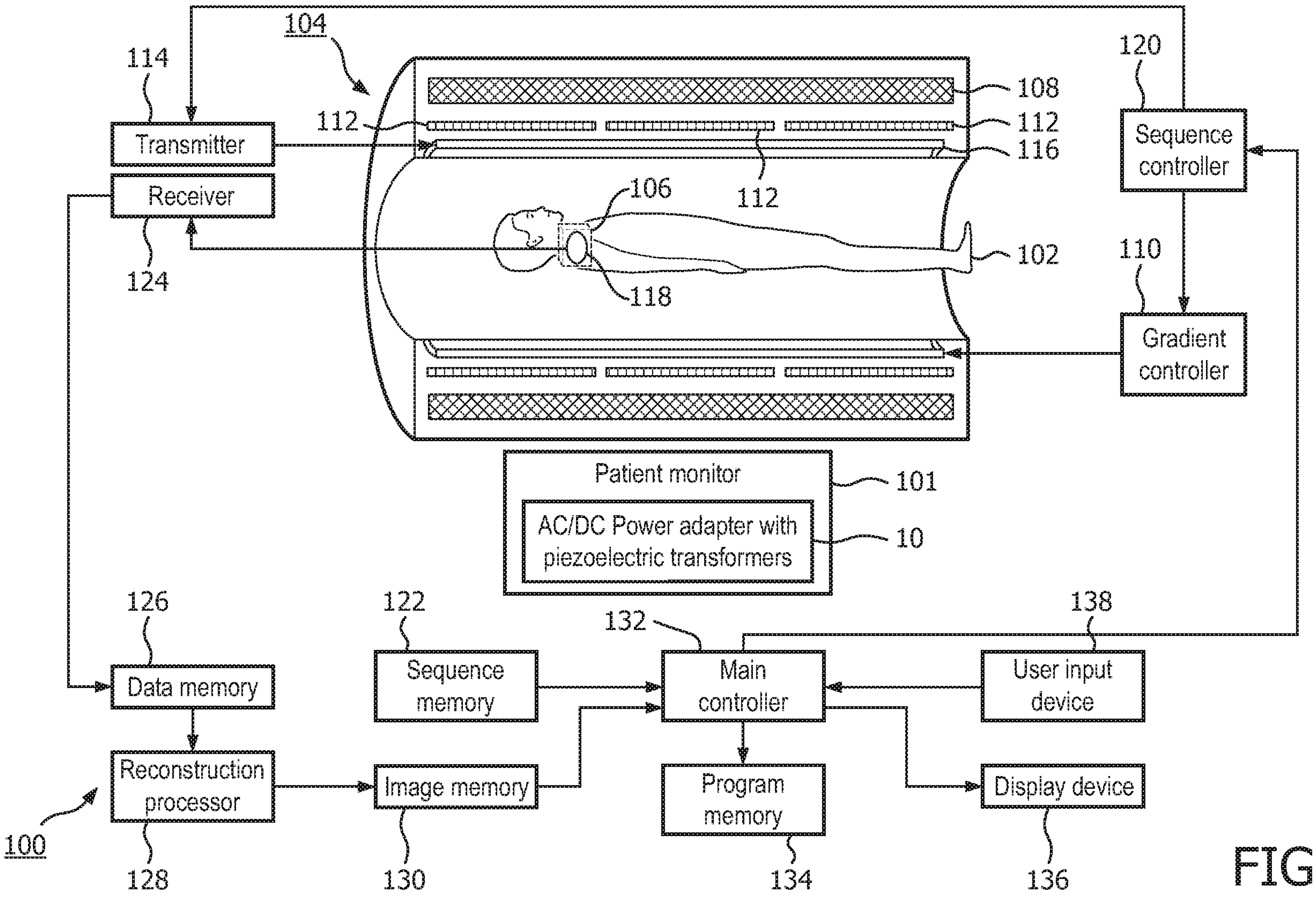
104
114
Transmitter
Receiver
124
112
108
112
116
112
106
118
102
120
Sequence controller
110
Gradient controller
Patient monitor
101
AC/DC Power adapter with piezoelectric transformers
10
126
Data memory
122
Sequence memory
132
Main controller
138
User input device
Reconstruction processor
Image memory
Program memory
Display device
100
128
130
134
136

FIG. 7

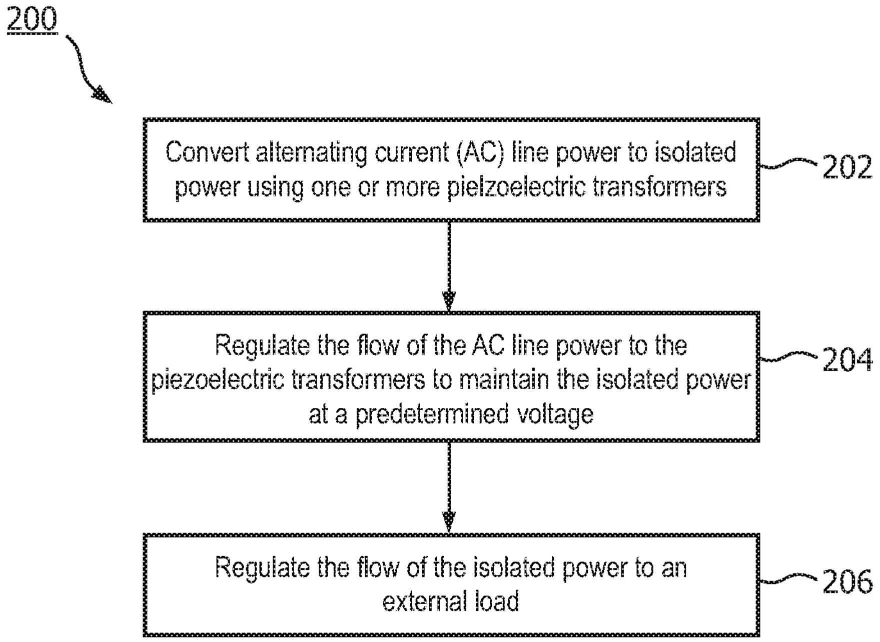
200
Convert alternating current (AC) line power to isolated power using one or more pielzoelectric transformers
202
Regulate the flow of the AC line power to the piezoelectric transformers to maintain the isolated power at a predetermined voltage
204
Regulate the flow of the isolated power to an external load
206

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2015/050085

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02M1/32 A61B5/055 H02M3/335 H02M1/44
ADD. H02M7/04 H02M1/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H02M A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	DE 10 2008 038989 A1 (SIEMENS AG [DE]) 8 October 2009 (2009-10-08) paragraph [0003] - paragraph [0007] paragraph [0012] - paragraph [0039] figures 1,2	1-4,6-20 5
X Y	JP 5 357033 B2 (TAIHEIYO CEMENT CORP) 4 December 2013 (2013-12-04) paragraph [0002] paragraph [0022] - paragraph [0028] paragraph [0035] paragraph [0040] paragraph [0046] - paragraph [0047] figure 1	1-4,6-20 5
Y	US 2005/285476 A1 (CHOU CHIN-WEN [TW] ET AL) 29 December 2005 (2005-12-29) the whole document	5

-/--

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search 20 April 2015	Date of mailing of the international search report 30/04/2015
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Lochhead, Steven

1

International application No
PCT/IB2015/050085

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 2003 348855 A (WEST ELECTRIC CO) 5 December 2003 (2003-12-05) paragraph [0014] -----	8,17
A	JP 2000 150190 A (MURATA MANUFACTURING CO) 30 May 2000 (2000-05-30) paragraph [0002] -----	8,17

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IB2015/050085

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
DE 102008038989 A1	08-10-2009	NONE	
JP 5357033 B2	04-12-2013	JP 5357033 B2	04-12-2013
		TW 200913450 A	16-03-2009
		WO 2009025129 A1	26-02-2009
US 2005285476 A1	29-12-2005	NONE	
JP 2003348855 A	05-12-2003	NONE	
JP 2000150190 A	30-05-2000	NONE	