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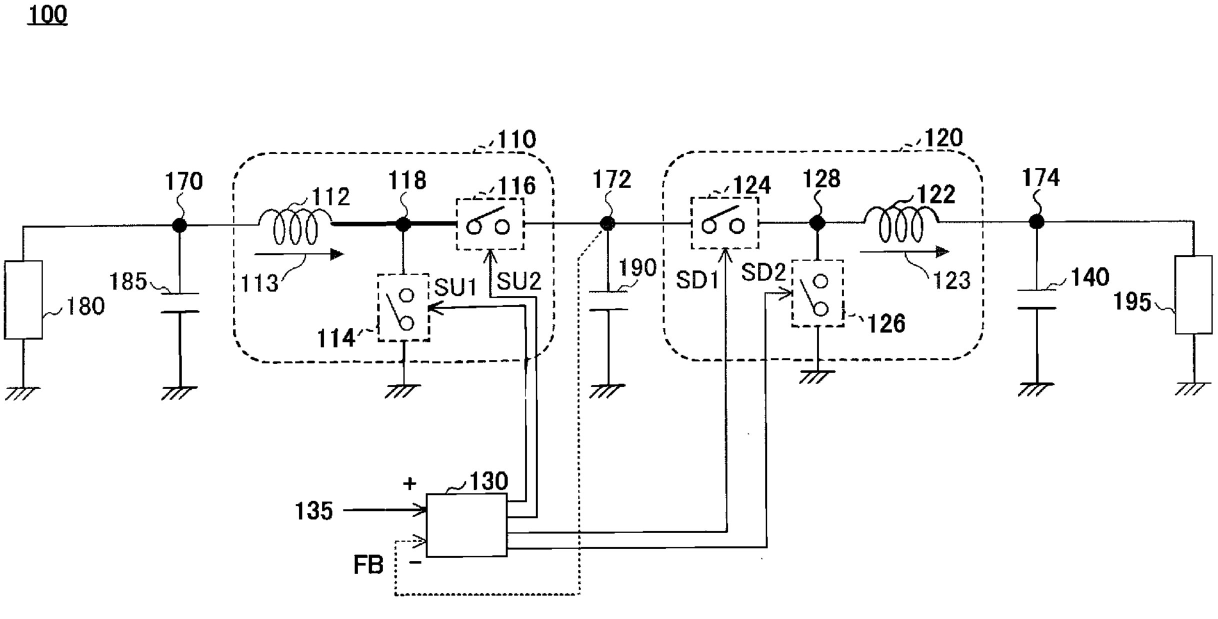

Fig. 1

(57) **Abstract:** An embodiment of the present disclosure provides a driving circuit for driving a capacitive load, such as a piezoelectric MEMS sound transducer. The driving circuit includes a step-up circuit configured to increase a load voltage across the capacitive load, a step-down circuit configured to decrease the load voltage, and a controller configured to receive an input signal and control the step-up circuit and the step-down circuit such that the load voltage is an amplified version of the input signal. The driving circuit further includes an energy storage configured to store electric energy discharged from the capacitive load. The step-up circuit is electrically connected between a power supply and the capacitive load, and the step-down circuit is electrically connected between the capacitive load and the energy storage. The energy storage is separated from the power supply.

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DRIVING CIRCUIT AND METHOD FOR DRIVING CAPACITIVE LOAD, AND SPEAKER DEVICE AND ELECTRONIC DEVICE INCLUDING DRIVING CIRCUIT

TECHNICAL FIELD

[0001] The present disclosure relates generally to a driving circuit, and more particularly to a driving circuit for driving a capacitive load.

BACKGROUND

[0002] Recently, in the field of audio mobile applications, such as smart phones, tablets, and wearable devices, piezoelectric Micro Electro Mechanical System (MEMS) sound transducers are becoming an important technology for speaker devices, including earphones, headphones, and the like. At least one piezoelectric MEMS sound transducer is used to drive a diaphragm of the speaker device. Compared to conventional transducers such as electro-dynamic sound transducers, piezoelectric MEMS sound transducers have small unit size and allow for precise vibration control, which can lead to system miniaturization and high sound quality.

[0003] Some piezoelectric MEMS sound transducers require a high voltage input signal (e.g. peak-to-peak voltage of 30 V, i.e., 30 Vpp), which is higher than supply voltage from a power supply, in order to generate a sufficient sound pressure level. Also, the input signal may need to carry a DC offset voltage. Such a signal is not convenient for a mobile device having a limited capacity of battery. In addition, the piezoelectric MEMS sound transducer includes a piezoelectric layer disposed between top and bottom electrodes, and thus, can be modeled as a capacitive load (namely, a capacitor) in an equivalent circuit. Accordingly, when the piezoelectric MEMS sound transducer is driven to vibrate the diaphragm for emitting sound into air, charging and discharging operation is repeatedly performed. However, most of electric energy transferred to the piezoelectric MEMS sound transducer is not converted into acoustic energy, but is drained to the ground. In other words, most of the electric energy does not contribute to sound emission and a large apparent power is wastefully delivered to the piezoelectric MEMS sound transducer. Also, this large apparent power can lead to a large apparent current flowing through a peripheral circuit, such as an amplifier, thereby creating large power loss. As such, it may be desirable to implement an energy recovery function or operation in the driving circuit so as to reuse the electric energy transferred to the capacitive load for low power operation in mobile applications. Some solutions for energy recovery have been proposed, however, known solutions have their respective drawbacks.

[0004] Therefore, an improved solution for energy recovery operation from such a capacitive load is still desired.

SUMMARY

[0005] An object of embodiments of the present disclosure is to provide a driving circuit and a method for driving a capacitive load to effectively implement energy recovery operation from the capacitive load. The embodiments of the present disclosure further provide a speaker device including such a driving circuit, and an electronic device including such a speaker device.

[0006] According to a first aspect, a driving circuit for driving a capacitive load is provided. The driving circuit includes a step-up circuit configured to increase a load voltage across the capacitive load, a step-down circuit configured to decrease the load voltage, and a controller configured to receive an input signal and control the step-up circuit and the step-down circuit such that the load voltage is an amplified version of the input signal. The driving circuit further includes an energy storage configured to store electric energy discharged from the capacitive load. The step-up circuit is electrically connected between a power supply and the capacitive load, and the step-down circuit is electrically connected between the capacitive load and the energy storage. The energy storage is separated from the power supply. In other words, the energy storage is not electrically connected to the power supply.

[0007] The energy storage separated from the power supply can store electric energy discharged from the capacitive load to implement energy recovery operation, without affecting supply voltage from the power supply.

[0008] In a possible implementation of the first aspect, the energy storage may be configured to supply electric energy to at least one other device or system separated from the driving circuit. Accordingly, the electric energy stored in the energy storage may be reused for the at least one other device or system.

[0009] In a possible implementation of the first aspect, the driving circuit may further include a selector switch having two input terminals and one output terminal, one of the two input terminals being connected to the power supply, the other one of the two input terminals being connected to the energy storage, and the output terminal being connected to the step-up circuit. The selector switch may be controlled such that either the power supply or the energy storage supplies electric energy to the step-up circuit. In this manner, the electric energy stored in the energy storage may be reused for the driving circuit itself.

[0010] In a possible implementation of the first aspect, the driving circuit may further include a sensing block configured to sense electric energy stored in the energy storage and control the selector switch depending on the sensed electric energy. The sensing block may be separated from the controller or integrated into the controller. In this manner, the selector switch can be controlled depending on an actual amount of the electric energy stored in the energy storage.

[0011] In a possible implementation of the first aspect, the sensing block may be further configured to compare the sensed electric energy with a reference value, and in response to the sensed electric energy being greater than or equal to the reference value, control the selector switch such that the energy storage supplies electric energy to the step-up circuit. In this manner, the electric energy stored in the energy storage can be reused for the driving circuit, only if the stored energy is sufficient for driving the capacitive load. Also, by properly setting the reference value, more efficient energy recovery operation can be achieved.

[0012] In a possible implementation of the first aspect, the driving circuit may further include an accumulation block configured to monitor the input signal and/or control signals provided from the controller to the step-up circuit and the step-down circuit to estimate electric energy stored in the energy storage. The accumulation block may be further configured to control the selector switch depending on the estimated electric energy. The accumulation block may be separated from the controller or integrated into the controller. In this manner, the selector switch can be controlled without sensing an actual amount of the electric energy stored in the energy storage 140.

[0013] In a possible implementation of the first aspect, the accumulation block may be further configured to compare the estimated electric energy with a reference value, and in response to the estimated electric energy being greater than or equal to the reference value, control the selector switch such that the energy storage supplies electric energy to the step-up circuit. In this manner, the electric energy stored in the energy storage can be reused for the driving circuit, only if the stored energy is sufficient for driving the capacitive load. Also, by properly setting the reference value, a more efficient energy recovery operation can be achieved.

[0014] In a possible implementation of the first aspect, the amplified version of the input signal may be a linearly-amplified version of the input signal. This may be advantageous in many applications. For example, if the driving circuit receives an audio signal as the input signal and drives a piezoelectric MEMS sound transducer according to the audio signal, the linear amplification of the audio signal can reduce acoustic distortion, leading to high quality sound.

[0015] In a possible implementation of the first aspect, the controller may be further configured to receive or detect a value indicative of the load voltage as a feedback input. The use of such a feedback input may allow for minimizing an error in the load voltage.

[0016] In a possible implementation of the first aspect, the step-up circuit may include a first inductor having one end connected to the power supply, a first switch connected between the other end of the first inductor and a ground, and a second switch connected between the other end of the first inductor and the capacitive load. Also, the step-down circuit may include a second inductor having one end connected to the energy storage, a third switch connected between the other end of the second inductor and the capacitive load, and a fourth switch connected between the other end of the second inductor and the ground. Then, the controller may control the first, second, third, and fourth switches based on the input signal. In this manner, the driving circuit can provide the capacitive load with a higher voltage than the voltage supplied from the power supply. In addition, the driving circuit can transfer electric energy from the capacitive load to the energy storage without requiring any complicated circuit.

[0017] In a possible implementation of the first aspect, the step-up circuit may include a first inductor having one end connected to the power supply, a first switch connected between the other end of the first inductor and a ground, and a first diode having an anode connected to the other end of the first inductor and a cathode connected to the capacitive load. Also, the step-down circuit may include a second inductor having one end connected to the energy storage, a second switch connected between the other end of the second inductor and the capacitive load, and a second diode having an anode connected to the ground and a cathode connected to the other end of the second inductor. Then, the controller may control the first and second switches based on the input signal. In this manner, control of the driving circuit can be further simplified.

[0018] According to a second aspect, a method for driving a capacitive load is provided. The method includes a step of receiving an input signal and a step of controlling a load voltage across the capacitive load such that the load voltage is an amplified version of the input signal. The step of controlling the load voltage includes charging the capacitive load by supplying electric energy from a power supply to the capacitive load through a step-up circuit, and discharging the capacitive load by transferring electric energy from the capacitive load to an energy storage through a step-down circuit. The energy storage is separated from the power supply.

[0019] In a possible implementation of the second aspect, the method may further include a step of switching a selector switch such that either the power supply or the energy storage supplies electric energy to the capacitive load through the step-up circuit.

[0020] In a possible implementation of the second aspect, the method may further include a step of sensing electric energy stored in the energy storage, and the step of switching the selector switch may include controlling the selector switch depending on the sensed electric energy. In another possible implementation of the second aspect, the method may further include a step of monitoring the input signal and/or control signals provided to the step-up circuit and the step-down circuit to estimate electric energy stored in the energy storage, and the step of switching the selector switch may include controlling the selector switch depending on the estimated electric energy.

[0021] The second aspect and possible implementations thereof can have the same advantages as described in connection with the first aspect.

[0022] According to a third aspect, a speaker device is provided. The speaker device includes a piezoelectric MEMS sound transducer. The speaker device also includes a circuit configured to receive an input signal and electric power and drive the piezoelectric MEMS sound transducer as a capacitive load. The circuit includes the driving circuit of any one of the first aspect or possible implementations of the first aspect.

[0023] According to a fourth aspect, an electronic device including the speaker device of the third aspect is provided. The electronic device also includes a processor configured to provide the input signal to the speaker device and a battery configured to supply the electric power to the speaker device.

[0024] The third and fourth aspects can have the same advantages as described in connection with the first aspect.

BRIEF DESCRIPTION OF DRAWINGS

[0025] FIG. 1 is a schematic circuit diagram of a driving circuit for driving a capacitive load according to a first embodiment of the present disclosure.

[0026] FIG. 2 is a schematic circuit diagram of a driving circuit for driving a capacitive load according to a second embodiment of the present disclosure.

[0027] FIG. 3 is a schematic circuit diagram of a driving circuit for driving a capacitive load according to a third embodiment of the present disclosure.

[0028] FIG. 4 is a schematic circuit diagram of a driving circuit for driving a capacitive load according to a fourth embodiment of the present disclosure.

[0029] FIG. 5 is a schematic circuit diagram of a driving circuit for driving a capacitive load according to a fifth embodiment of the present disclosure.

[0030] FIG. 6 is a flowchart of a method for driving a capacitive load according to an embodiment of the present disclosure.

[0031] FIG. 7 is a schematic diagram of a speaker device according to an embodiment of the present disclosure.

[0032] FIG. 8 is a schematic diagram of an electronic device according to an embodiment of the present disclosure.

[0033] Throughout the drawings, same or similar elements are indicated by same or similar reference numerals.

DESCRIPTION OF EMBODIMENTS

[0034] To enable any person skilled in the art to better understand objectives, features, and advantages of embodiments of the present disclosure, the following further describes the technical solutions in preferable embodiments of the present disclosure in detail with reference to the accompanying drawings.

[0035] In the present disclosure, the terms “include”, “comprise”, “have” and any other variants mean to cover the non-exclusive inclusion, for example, a process, method, circuit, device, or system that includes a list of steps or elements is not necessarily limited to those steps or elements, but may include other steps or elements not expressly listed or inherent to such a process, method, circuit, device, or system. Moreover, the articles “a” and “an” as used in the present disclosure are intended to include one or more items, and may be used interchangeably with “one or more”.

[0036] FIG. 1 is a schematic circuit diagram of a driving circuit 100 for driving a capacitive load 190 according to a first embodiment of the present disclosure. The driving circuit 100 includes a step-up circuit 110, a step-down circuit 120, a controller 130, and an energy storage 140.

[0037] The driving circuit 100 has a power supply node 170, an output node 172, and an energy recovery node 174, to which a power supply 180, the capacitive load 190, and the energy storage 140 are connected, respectively. In this manner, the step-up circuit 110 is electrically connected between the power supply 180 and the capacitive load 190 and the step-down circuit 120 is electrically connected between the capacitive load 190 and the energy storage 140.

[0038] The step-up circuit 110 is configured to increase a load voltage across the capacitive load 190, that is, the voltage at the output node 172. The step-down circuit 120 is configured to decrease the load voltage across the capacitive load 190. The controller 130 is configured to receive an input signal 135 and control the step-up circuit 110 and the step-down circuit 120 such that the load voltage is an amplified version of the input signal 135. In other words, the driving circuit 100 can function as an amplifier configured to receive the input signal 135, amplify it to an amplified voltage, and output the amplified voltage at the output node 172. In some implementation, the driving circuit 100 is configured to linearly amplify the input signal 135 and output a linearly-amplified version of the input signal 135 to the capacitive load 190. Details of constitutions and operations of these components 110, 120 and 130 will be described below.

[0039] The power supply 180 can be a battery, such as a Li-ion battery or the like. Alternatively, the power supply 180 may be another type of DC source, such as a super capacitor or a rectifier. The power supply 180 may include an internal or external capacitor 185. It can be understood that the capacitor 185 can be regarded as a part of the power supply 180.

[0040] The capacitive load 190 is an object to be driven by the driving circuit 100. As an example, the capacitive load 190 can be a piezoelectric MEMS transducer used for a speaker device. In this case, the controller 130 receives an audio signal as the input signal 135 from an audio circuit (not shown) and controls the step-up circuit 110 and the step-down circuit 120 to provide the piezoelectric MEMS transducer 190 with an amplified audio signal. It should be noted, however, that the capacitive load 190 may be another type of capacitive load, such as a MEMS ultrasonic transducer, an ultrasonic motor, or the like.

[0041] The energy storage 140 is configured to store electric energy discharged from the capacitive load 190. The energy storage 140 may be a capacitor and is so illustrated in the entire drawings, although it is not limited thereto. As an example, the energy storage 140 may have a capacitance in a range of 1 to 10 μF. However, the capacitance of the energy storage 140 may be determined depending on a specific application and/or implementation. The energy recovery node 174, to which the energy storage 140 is connected, may be additionally connected to an external circuit, device, or system 195 (hereinafter referred to as “other circuit” 195), which is separated from the driving circuit 100. For example, the other circuit 195 may be a peripheral circuit for the driving circuit 100, a microphone circuit, an RF circuit, or the like.

[0042] The energy storage 140 can be configured to supply the electric energy stored therein to the other circuit 195. The energy storage 140 is separated from the power supply 180 (which may include the capacitor 185). In other words, the energy storage 140 is not electrically connected to the power supply 180. Therefore, the energy storage 140 can work as an additional power supply separated from the power supply 180.

[0043] Now, still referring to FIG. 1, constitutions and operations of the step-up circuit 110, the step-down circuit 120, and the controller 130 are described.

[0044] The step-up circuit 110 may include a first inductor 112, a first switch 114, and a second switch 116. As shown in FIG.1, the first inductor 112 has one end connected to the power supply 180 and the other end that forms a node 118, to which both the first switch 114 and the second switch 116 are connected. The node 118 may be herein referred to as “first inductor terminal” 118. The first switch 114 is connected between the first inductor terminal 118 and the ground. The second switch 116 is connected between the first inductor terminal 118 and the output node 172, to which the capacitive load 190 is connected. The first switch 114 and the second switch 116 are controlled (namely, opened and closed) by step-up control signals SU1 and SU2, respectively, provided by the controller 130.

[0045] The step-up circuit 110 can take three states according to open/close states of the first and second switches 114 and 116. The three states include a first operational state, a second operational state, and a non-operational state.

[0046] In the first operational state where the first switch 114 is closed and the second switch 116 is opened, the first inductor terminal 118 is short-circuited to the ground. Consequently, electric energy transfers from the power supply 180 to the first inductor 112 and a current 113 (also referred to as “first inductor current” 113) flowing through the first inductor 112 increases. The first operational state is followed by the second operational state.

[0047] In the second operational state where the first switch 114 is opened and the second switch 116 is closed, the electric energy transfers from the first inductor 112 to the capacitive load 190, as the first inductor current 113 flows into the capacitive load 190. Consequently, the first inductor current 113 decreases and the load voltage at the output node 172 increases. In this manner, through the first and second operational states, including state transition therebetween, electric energy is transferred from the power supply 180 to the capacitive load 190 and the load voltage is increased. The first and second operational states can be repeated so as to reach a target load voltage, which is based on the input signal 135. Then, the step-up circuit 110 transitions to the non-operational state.

[0048] In the non-operational state where the first switch 114 and the second switch 116 are both opened, electric energy does not transfer between the power supply 180 and the capacitive load 190.

[0049] It can be understood that the first switch 114 and the second switch 116 should not be closed concurrently. If the first switch 114 and the second switch 116 were closed concurrently, electric energy stored in the capacitive load 190 would erroneously flow off to the ground via these switches. Therefore, the controller 130 is designed so as to avoid this condition.

[0050] The step-down circuit 120 may include a second inductor 122, a third switch 124, and a fourth switch 126. As shown in FIG.1, the second inductor 122 has one end connected to the energy storage 140 and the other end that forms a node 128, to which both the third switch 124 and the fourth switch 126 are connected. The node 128 may be herein referred to as “second inductor terminal” 128. The third switch 124 is connected between the second inductor terminal 128 and the output node 172, to which the capacitive load 190 is connected. The fourth switch 126 is connected between the second inductor terminal 128 and the ground. The third switch 124 and the fourth switch 126 are controlled (namely, opened and closed) by step-down control signals SD1 and SD2, respectively, provided by the controller 130.

[0051] The step-down circuit 120 can take three states according to open/close states of the third and fourth switches 124 and 126. These three states include a third operational state, a fourth operational state, and a non-operational state.

[0052] In the third operational state where the first switch 124 is closed and the fourth switch 126 is opened, electric energy transfers from the capacitive load 190 to the second inductor 122 so that electrical potential at the second inductor terminal 128 becomes the same as that at the output node 172. Consequently, a current 123 (also referred to as “second inductor current” 123) flowing through the second inductor 122 increases and the load voltage decreases. The third operational state is followed by the fourth operational state.

[0053] In the fourth operational state where the third switch 124 is opened and the fourth switch 126 is closed, the electric energy accumulated in the second inductor supplies a current to the energy storage 140 through the fourth switch 126. In this manner, through the third and fourth operational states, including state transition therebetween, electric energy is transferred from the capacitive load 190 to the energy storage 140 and the load voltage is decreased. In other words, the electric energy discharged from the capacitive load 190 can be transferred to the energy storage 140 for energy recovery. The third and fourth operational states can be repeated so as to reach a target load voltage, which is based on the input signal 135. Then, the step-down circuit 120 transitions to the non-operational state.

[0054] In the non-operational state of the step-down circuit 120 where the third switch 124 and the fourth switch 126 are both opened, electric energy does not transfer between the capacitive load 190 and the energy storage 140.

[0055] It can be understood that the third switch 124 and the fourth switch 126 should not be closed concurrently. If the third switch 124 and the fourth switch 126 were closed concurrently, electric energy stored in the capacitive load 190 would erroneously flow off to the ground via these switches. Therefore, the controller 130 is designed so as to avoid this condition.

[0056] In order to implement the foregoing operations of the step-up circuit 110 and the step-down circuit 120, the controller 130 is configured to generate the step-up and step-down control signals SU1, SU2, SD1, and SD2 based on the input signal 135. In general, the controller 130 can utilize a pulse width modulation (PWM) scheme to generate the control signals SU1, SU2, SD1, and SD2.

[0057] Preferably, the controller 130 is configured to receive or detect a value indicative of the load voltage as a feedback input FB, as shown by a dotted line in FIG. 1. The controller 130 can compare the feedback input FB with a target load voltage, which may be an amplified version of the input signal 135. When the feedback input FB is lower than the target load voltage, the controller 130 generates the step-up control signals SU1 and SU2 to operate the step-up circuit 110 as described above, thereby charging the capacitive load 190. When the feedback input FB is higher than the target load voltage, the controller 130 generates the step-down control signals SD1 and SD2 to operate the step-down circuit 120 as described above, thereby discharging the capacitive load 190 and transferring the discharged energy to the energy storage 140. The use of the feedback input FB allows for minimizing an error in the load voltage. As an example, audio signal 135 can be linearly amplified and acoustic distortion can be reduced, leading to high quality sound.

[0058] The technical solution for energy recovery operation disclosed herein can provide several advantages as described below.

[0059] 1. The step-up circuit 110 can act as a boost circuit to generate a high voltage (e.g., over 30 Vpp) from a low voltage supplied from the power supply 180, without any additional power supply circuit or special power supply. As an example, any waveform having a voltage up to 30 Vpp or more can be generated from DC 3.7 V, which may be supplied by a single cell Li-ion battery. Such a high voltage can effectively drive the capacitive load, for example, a piezoelectric MEMS sound transducer.

[0060] 2. The energy stored in the capacitive load 190 can be transferred to the energy storage 140 without requiring any complicated circuit and/or control. If an additional circuit is required, for example, for a polarity switching, level shifting, or electrical isolation, it may involve complicated control, as well as, additional energy consumption and footprint.

[0061] 3. The energy stored in the capacitive load 190 can be recovered without affecting the supply voltage from the power supply 180.

[0062] In this regard, some known solutions suggest transferring the energy stored in the capacitive load back to the power supply, by providing a recycling path between the capacitive load and the power supply. However, in actual applications, the energy flowing back into the power supply can generate ripple noise or the like onto the supply voltage. The ripple noise on the supplied voltage can cause a serious problem in high performance audio applications or in operation of other components connected to the power supply.

[0063] Still considering the known solutions in which the energy discharged from the capacitive load is recycled by transferring it back to the power supply, the power supply is herein regarded as a capacitor (see the capacitor 185 in FIG. 1) for ease of description. When all energy stored in the load is discharged and then charged in the power supply capacitor, the following equation applies:

[0064] $C_L V_L^2/2$ (discharged energy) = $C_S V_{ripple}^2/2$ (charged energy for recycling)

where C_L is the capacitance of the load, V_L is the voltage on the load, C_S is the capacitance of the power supply capacitor, and V_{ripple} is amplitude of ripple voltage on the power supply capacitor. From this equation, the amplitude of ripple voltage is determined from the ratio of the capacitances, that is, C_L/C_S. If the load has a large capacitance, the power supply capacitor should also have a large capacitance. In other words, in order to effectively suppress the ripple noise, it is necessary to use a large power supply capacitor, which may prevent system miniaturization.

[0065] In contrast, the technical solution disclosed herein transfers the discharged energy from the capacitive load 190 to the energy storage 140 through the step-down circuit 120. As described above, the energy storage 140 is separated from the power supply 180. Accordingly, the supply voltage from the power supply 180 (and/or capacitor 185) is not affected by the energy recovery operation and is kept clean and constant without ripple noise or the like.

[0066] 4. As another advantage, the energy recovery operation can occur without substantial restrictions on conditions for operation. Since the energy storage 140 is separated from the power supply 180, the voltage across the energy storage 140 can take various values in a wide range, unlike in the known technical solutions as mentioned above. If the discharged energy is transferred back to the power supply, which has an approximately constant voltage, the energy recovery operation may be substantially limited to a certain range of the load voltage and stored energy may be dissipated when the load voltage is out of the range. Specifically, when the load voltage is lower than the power supply voltage, stored energy in the capacitive load may not be efficiently transferred to the power supply. In contrast, in the technical solution disclosed herein, the energy recovery operation can constantly occur in a wider range of the load voltage.

[0067] The first embodiment shown in FIG. 1 can be modified to constitute other embodiments, some of which are described below.

[0068] FIG. 2 is a schematic circuit diagram of a driving circuit 200 for driving a capacitive load according to a second embodiment of the present disclosure. The driving circuit 200 is the same as the driving circuit 100 according to the first embodiment, except that the step-up circuit 110, the step-down circuit 120, and the controller 130 are replaced with a step-up circuit 210, a step-down circuit 220, and a controller 230, respectively. The same components are given the same reference numerals and are not described again in detail.

[0069] More specifically, the step-up circuit 210 includes a first diode 216, in the place of the second switch 116 of the step-up circuit 110. Similarly, the step-down circuit 220 includes a second diode 226, in the place of the fourth switch 126 of the step-down circuit 120. In this case, the switch 114 in the step-up circuit 210 and the switch 124 in the step-down circuit 220 (which may be unchanged from the first switch 114 and the third switch 124 in the first embodiment) may be referred to as first and second switches 114 and 124, respectively. Correspondingly, the controller 230 is modified to provide a step-up control signal SU and a step-down control signal SD to the first switch 114 and the second switch 124, respectively.

[0070] The step-up circuit 210 can take a first operational state, a second operational state, and a non-operational state similar to those taken by the step-up circuit 110 in the first embodiment. Also, the step-down circuit 220 can take a third operational state, a fourth operational state, and a non-operational state similar to those taken by the step-down circuit 120 in the first embodiment.

[0071] In the first operational state, the step-up control signal SU is provided to the first switch 114 such that the first switch 114 is closed and thereby the first inductor terminal 118 is short-circuited to the ground. As described above with reference to the first embodiment, electric energy transfers from the power supply 180 to the first inductor 112 and the first inductor current 113 increases.

[0072] In the second operational state, the step-up control signal SU is disabled to open the first switch 114. Since the voltage at the first inductor terminal 118 becomes higher than the load voltage at the output node 172, the first diode 216 allows the first inductor current 113 to flow into the capacitive load 190. Consequently, the first inductor current 113 decreases and the load voltage increases. During the other states, the first diode 216 prevents conduction of electric current, since the first inductor terminal 118 has a lower voltage than the load voltage.

[0073] In the third operational state, the step-down control signal SD is provided to the second switch 124 such that the second switch 124 is closed. As described above with reference to the first embodiment, electric energy transfers from the capacitive load 190 to the second inductor 122 and the load voltage decreases.

[0074] In the fourth operational state, the step-down control signal SD is disabled to open the second switch 124. Since the voltage at the second inductor terminal 128 becomes lower than the ground level, the second diode 226 automatically passes the current to the energy storage 140 through the second inductor 122. During the other states, the diode 226 prevents conduction of electric current, since the second inductor terminal 128 has a higher voltage than the ground level.

[0075] The driving circuit 200 of the second embodiment utilizes automatic switching operation of the diodes 216 and 226, thereby further simplifying control of the driving circuit.

[0076] FIG. 3 is a schematic circuit diagram of a driving circuit 300 for driving a capacitive load according to a third embodiment of the present disclosure. The driving circuit 300 is the same as the driving circuit 100 according to the first embodiment, except that a selector switch 350 is provided. The same components are given the same reference numerals and are not described again in detail. Although the power supply capacitor 185 and the other circuit 195 in FIG. 1 are not illustrated in FIG. 3, they may be connected to the driving circuit 300 in the same manner as in FIG. 1. Furthermore, the selector switch 350 can be equally applicable to the driving circuit 200 of the second embodiment.

[0077] The selector switch has two input terminals and one output terminal. One of the input terminals is connected to the power supply 180 and the other one of the input terminals is connected to the energy storage 140. The output terminal is connected to the first inductor 112 in the step-up circuit 110. The selector switch 350 can be controlled such that either the power supply 180 or the energy storage 140 supplies electric energy to the step-up circuit 110. In other words, the selector switch 350 enables selection between the power supply 180 and the energy storage 140 as an energy source for the step-up circuit 110.

[0078] In operation, if the energy stored in the energy storage 140 is not enough for increasing the load voltage as required during step-up operation, the selector switch 350 may be configured to select the power supply 180 as the energy source for the step-up circuit 110. Then, the power supply 180 supplies additional energy to the first inductor 112. Conversely, if the energy stored in the energy storage 140 is enough, the selector switch 350 may be configured to select the energy storage 140 as the energy source for the step-up circuit 110. Then, the energy storage 140 supplies electric energy to the first inductor 112.

[0079] In this manner, the selector switch 350 enables the driving circuit 300 to reuse the energy stored in the energy storage 140 for the driving circuit 300 itself. It should be noted that the driving circuit 300 may additionally reuse the energy stored in the energy storage 140 for the other circuit 195 (not shown in FIG. 3), as described with reference to the first embodiment.

[0080] FIG. 4 is a schematic circuit diagram of a driving circuit 400 for driving a capacitive load according to a fourth embodiment of the present disclosure. The driving circuit 400 is the same as the driving circuit 300 according to the third embodiment, except that a sensing block 452 for controlling the selector switch 350 is additionally provided. The same components are given the same reference numerals and are not described again in detail.

[0081] The sensing block 452 may be configured to continuously or periodically sense an amount of the electric energy stored in the energy storage 140 to obtain a sensed value 454. For example, the sensing block 452 can sense the voltage across the energy storage 140 to monitor the electric energy stored in the energy storage 140. Then, the sensing block 452 can control the selector switch 350 depending on the sensed value 454. Although the sensing block 452 is illustrated in FIG. 4 as being separated from the controller 130, the sensing block 452 may be integrated into the controller 130 to be a part of the controller 130.

[0082] In addition, the sensing block 452 may be configured to compare the sensed value 454 with a reference value 456. If the sensed value 454 is higher than or equal to the reference value 456, the sensing block 452 may control the selector switch 350 such that the energy storage 140 supplies the electric energy to the step-up circuit 110. If the sensed value 454 is lower than the reference value 456, the sensing block 452 may control the selector switch 350 such that the power supply 180 supplies the electric energy to the step-up circuit 110. The reference value 456 may be a preset value, or a configurable value, or a variable value. As an example, the reference value 456 may be set to a value lower than the supply voltage from the power supply 180. As another example, the reference value 456 may be dynamically changed depending on the load voltage.

[0083] In this manner, the sensing block 452 enables the selector switch 350 to be controlled depending on the sensed value 454, which represents an actual amount of the energy stored in the energy storage 140. This means that the driving circuit 400 can reuse the energy stored in the energy storage 140 for the driving circuit 400 itself, based on the actual amount of the stored energy.

[0084] FIG. 5 is a schematic circuit diagram of a driving circuit 500 for driving a capacitive load according to a fifth embodiment of the present disclosure. The driving circuit 500 is the same as the driving circuit 300 according to the third embodiment, except that an accumulation block 562 for controlling the selector switch 350 is additionally provided. The same components are given the same reference numerals and are not described again in detail.

[0085] The accumulation block 562 is configured to accumulate respective amounts of step-up operation and step-down operation based on information 564 obtained from the controller 130 to estimate an amount of the electric energy stored in the energy storage 140. For example, the accumulation block 562 may accumulatively monitor the control signals SU1, SU2, SD1, and SD2, which are provided from the controller 130 to the step-up circuit 110 and the step-down circuit 120. Alternatively, or additionally, the accumulation block 562 may accumulatively monitor the input signal 135 provided to the controller 130. Then, the accumulation block 562 can control the selector switch 350 depending on the estimated electric energy. Although the accumulation block 562 is illustrated in FIG. 5 as being separated from the controller 130, the accumulation block 562 may be integrated into the controller 130 to be a part of the controller 130.

[0086] In addition, the accumulation block 562 may be further configured to compare the estimated electric energy with a reference value, as with the sensing block 452 of the fourth embodiment. For details of such a reference value, refer to the foregoing descriptions in connection with the reference value 456 in the fourth embodiment.

[0087] In this manner, the accumulation block 562 enables the selector switch 350 to be controlled without sensing the actual electric energy stored in the energy storage 140. This means that the driving circuit 500 can reuse the energy stored in the energy storage 140 for the driving circuit 500 itself, based on the information obtained from the controller 130.

[0088] Now referring to FIG. 6, a flowchart of a method 600 for driving a capacitive load according to an embodiment of the present disclosure is illustrated. As an example, the capacitive load is a piezoelectric MEMS sound transducer used for a speaker device. As another example, the capacitive load may be another type of capacitive load, such as a MEMS ultrasonic transducer, an ultrasonic motor, or the like.

[0089] The method 600 includes a step 602 of receiving an input signal. The input signal may be, for example, an audio signal.

[0090] The method 600 also includes a step 604 of controlling a load voltage across the capacitive load such that the load voltage is an amplified version of the input signal. For example, the load voltage may be a linearly-amplified version of the audio signal.

[0091] The step 604 may include a substep 606 of charging the capacitive load by supplying electric energy from a power supply to the capacitive load through a step-up circuit and a substep 608 of discharging the capacitive load by transferring electric energy from the capacitive load to an energy storage through a step-down circuit. The energy storage is separated from the power supply.

[0092] The electric energy discharged from the capacitive load and stored in the energy storage can be reused for, for example, another circuit, thereby realizing energy recycling from the capacitive load.

[0093] Optionally, the method 600 may further include a step of switching a selector switch such that either the power supply or the energy storage supplies electric energy to the capacitive load. This may allow for reusing the electric energy stored in the energy storage 140 for driving the capacitive load.

[0094] Optionally, the method 600 may further include a step of sensing the electric energy stored in the energy storage, and the step of switching the selector switch may include controlling the selector switch depending on the sensed electric energy. This may enable the energy stored in the energy storage to be reused for driving the capacitive load based on the actual amount of the stored energy.

[0095] Alternatively, the method 600 may further include a step of accumulatively monitoring the input signal and/or control signals provided to the step-up circuit and the step-down circuit to estimate electric energy stored in the energy storage, and the step of switching the selector switch may include controlling the selector switch depending on the estimated electric energy. This may enable the energy stored in the energy storage to be reused for driving the capacitive load based on the input signal and/or the control signals.

[0096] FIG. 7 is a schematic diagram of a speaker device 700 according to an embodiment of the present disclosure. The speaker device 700 includes a piezoelectric MEMS sound transducer 790, which acts as a capacitive load. The speaker device 700 further includes a driving circuit 705 configured to receive an input signal 735, which may be an audio signal, and to drive the piezoelectric MEMS sound transducer 790 according to the audio signal 735. Advantageously, the driving circuit 705 can linearly amplify the audio signal 735 and provide the amplified signal to the piezoelectric MEMS sound transducer 790. The driving circuit 705 further receives electric power from a power supply 780. The power supply 780 may be, for example, a low voltage power supply, such as a single cell Li-ion battery or the like.

[0097] The driving circuit 705 may be any one of the driving circuit 100, 200, 300, 400 and 500 as described above. Accordingly, the driving circuit 705 can generate a high voltage (e.g., over 30 Vpp) from a DC voltage (e.g., about 3.7 V) supplied from the low voltage power supply 780. In addition, the driving circuit 705 can transfer electric energy discharged from the piezoelectric MEMS sound transducer 790 and store it in an energy storage (see the energy storage 140 in FIGS. 1-5) for energy recovery. This energy recovery operation can occur without any complicated circuit and/or control. Furthermore, this energy recovery operation does not affect the supply voltage from the low voltage power supply 780, leading to a higher sound quality. In addition, this energy recovery operation can constantly occur in a wider range of the load voltage, leading to more efficient energy recovery. The electric energy stored in the energy storage can be reused to drive another circuit and/or the piezoelectric MEMS sound transducer 790 itself, as described above.

[0098] The speaker device 700 may be, but is not limited to, an earphone, a headphone, an earset, a headset, or a built-in speaker of an electronic device. An example of such a built-in speaker of an electronic device is shown in FIG. 8.

[0099] FIG. 8 is a schematic diagram of an electronic device 800 according to an embodiment of the present disclosure. In one example, the electronic device 800 may be a mobile device, such as a smartphone, tablet, or the like. The electronic device 800 includes a processor 810, a memory 820, a battery 830, a display panel 840, and a speaker 850. The display panel 840 may be assembled with a housing of the electronic device 800 in such a manner that the front surface of the display panel 840 is visible from a user of the electronic device 800, as shown by solid lines in FIG. 8. The speaker 850 can emit sound into an external ambient (namely, air) and is also shown by solid lines in that sense. The processor 810, the memory 820, and the battery 830 may be completely contained within the housing, as indicated by dashed lines in FIG. 8. The processor 810, the memory 820, the battery 830, the display panel 840, and the speaker 850 may be electrically connected to each other.

[0100] Although not shown, the electronic device 800 may optionally include a radio frequency (RF) circuit, a camera, a microphone, an input device, a sensor, an antenna, a near field communication module, and/or the like.

[0101] The processor 810 may be configured to invoke a software program and data stored in the memory 820 and execute the software program to perform various functions and/or data processing of the electronic device 800. The processor 810 may include any suitable special-purpose or general-purpose processing device or unit. Additionally, the processor 810 may include any suitable number of processors. For example, the processor 810 may include one or more of a microprocessor, a microcontroller, an application processor, a central processing unit (CPU), a graphics processing unit (GPU), a digital signal processor (DSP), an application-specific integrated circuit (ASIC), a Field Programmable Gate Array (FPGA), and the like.

[0102] The memory 820 may be configured to store a software program and data, and may include any suitable medium that may be accessed by the processor 810. Additionally, the memory 820 may include memory in any suitable number. The memory 820 can include volatile memory and/or non-volatile memory, and may include, for example, a random access memory (RAM), a read-only memory (ROM), and/or a flash memory. It should be noted that the term "memory" as used herein may refer to a mass storage that can store large amounts of data, such as multimedia data. Therefore, the memory 820 may also include, for example, a hard disk drive (HDD), a solid state drive (SDD), an optical disk drive, or the like.

[0103] The battery 830 may be configured to supply power to each of components of the electronic device 800, such as the processor 810, the memory 820, the display panel 840, and the speaker 850. The processor 810 may run a power management program or module stored in the memory 820 to control power consumption of one or more components, as well as, charging and discharging of the battery 830. In addition to, or instead of, the battery 830, the electronic device 800 may have a power connector, adapter, or the like, which is connected to an external power supply, such as utility power.

[0104] The display panel 840 may be configured to display a variety of information and content, including information entered by a user and information provided for the user. The display panel 840 may include a user input device, such as a touch screen, on at least a part of the surface exposed from the housing.

[0105] The speaker 850 may include, for example, the speaker device 700 (specifically, the driving circuit 705 and the piezoelectric MEMS sound transducer 790) shown in FIG. 7. However, the electronic device 800 may include a plurality of speakers of different types. In an example, the speaker 850 may combine the speaker device 700 having the piezoelectric MEMS sound transducer 790 with another type of speaker device having, for example, an electro-dynamic sound transducer.

[0106] The speaker 850 including the speaker device 700 (the driving circuit 705 and the piezoelectric MEMS sound transducer 790) can provide the advantages as described above. In particular, the speaker 850 allows for reusing electric energy discharged from the piezoelectric MEMS sound transducer 790, leading to saving electric energy stored in the battery 830 having a limited capacity.

[0107] Although some preferred embodiments of the present disclosure have been described, persons skilled in the art may make changes and modifications to these embodiments without departing from the scope of the present disclosure. Therefore, the following claims are intended to be construed as to cover all changes and modifications falling within the scope of the present disclosure.

CLAIMS

What is claimed is:

1. A driving circuit for driving a capacitive load, the driving circuit comprising:

a step-up circuit configured to increase a load voltage across the capacitive load;

a step-down circuit configured to decrease the load voltage;

a controller configured to receive an input signal and control the step-up circuit and the step-down circuit such that the load voltage is an amplified version of the input signal; and

an energy storage configured to store electric energy discharged from the capacitive load,

wherein the step-up circuit is electrically connected between a power supply and the capacitive load, and the step-down circuit is electrically connected between the capacitive load and the energy storage, and

wherein the energy storage is separated from the power supply.

2. The driving circuit of claim 1, wherein the energy storage is configured to supply electric energy to at least one other device or system separated from the driving circuit.

3. The driving circuit of claim 1, further comprising:

a selector switch having two input terminals and one output terminal, one of the two input terminals being connected to the power supply, the other one of the two input terminals being connected to the energy storage, and the output terminal being connected to the step-up circuit,

wherein the selector switch is controlled such that either the power supply or the energy storage supplies electric energy to the step-up circuit.

4. The driving circuit of claim 3, further comprising:

a sensing block configured to sense electric energy stored in the energy storage and control the selector switch depending on the sensed electric energy.

5. The driving circuit of claim 4, wherein the sensing block is further configured to:

compare the sensed electric energy with a reference value; and

in response to the sensed electric energy being greater than or equal to the reference value, control the selector switch such that the energy storage supplies electric energy to the step-up circuit.

6. The driving circuit of claim 3, further comprising:

an accumulation block configured to:

monitor the input signal and/or control signals provided from the controller to the step-up circuit and the step-down circuit to estimate electric energy stored in the energy storage; and

control the selector switch depending on the estimated electric energy.

7. The driving circuit of claim 6, wherein the accumulation block is further configured to:

compare the estimated electric energy with a reference value; and

in response to the estimated electric energy being greater than or equal to the reference value, control the selector switch such that the energy storage supplies electric energy to the step-up circuit.

8. The driving circuit of any one of claims 1 to 7, wherein the amplified version of the input signal is a linearly-amplified version of the input signal.

9. The driving circuit of any one of claims 1 to 8, wherein the controller is further configured to receive or detect a value indicative of the load voltage as a feedback input.

10. The driving circuit of any one of claims 1 to 9, wherein the step-up circuit comprises a first inductor having one end connected to the power supply, a first switch connected between the other end of the first inductor and a ground, and a second switch connected between the other end of the first inductor and the capacitive load,

wherein the step-down circuit comprises a second inductor having one end connected to the energy storage, a third switch connected between the other end of the second inductor and the capacitive load, and a fourth switch connected between the other end of the second inductor and the ground, and

wherein the controller controls the first, second, third, and fourth switches based on the input signal.

11. The driving circuit of any one of claims 1 to 9, wherein the step-up circuit comprises a first inductor having one end connected to the power supply, a first switch connected between the other end of the first inductor and a ground, and a first diode having an anode connected to the other end of the first inductor and a cathode connected to the capacitive load,

wherein the step-down circuit comprises a second inductor having one end connected to the energy storage, a second switch connected between the other end of the second inductor and the capacitive load, and a second diode having an anode connected to the ground and a cathode connected to the other end of the second inductor, and

wherein the controller controls the first and second switches based on the input signal.

12. A method for driving a capacitive load, the method comprising steps of:

receiving an input signal;

controlling a load voltage across the capacitive load such that the load voltage is an amplified version of the input signal;

wherein the step of controlling the load voltage includes:

charging the capacitive load by supplying electric energy from a power supply to the capacitive load through a step-up circuit; and

discharging the capacitive load by transferring electric energy from the capacitive load to an energy storage through a step-down circuit, the energy storage being separated from the power supply.

13. The method of claim 12, further comprising a step of:

switching a selector switch such that either the power supply or the energy storage supplies electric energy to the capacitive load through the step-up circuit.

14. The method of claim 13, further comprising a step of:

sensing electric energy stored in the energy storage,

wherein the step of switching the selector switch comprises controlling the selector switch depending on the sensed electric energy.

15. The method of claim 13, further comprising a step of:

monitoring the input signal and/or control signals provided to the step-up circuit and the step-down circuit to estimate electric energy stored in the energy storage,

wherein the step of switching the selector switch comprises controlling the selector switch depending on the estimated electric energy.

16. A speaker device comprising:

a piezoelectric MEMS sound transducer; and

a circuit configured to:

receive an input signal and electric power; and

drive the piezoelectric MEMS sound transducer as a capacitive load,

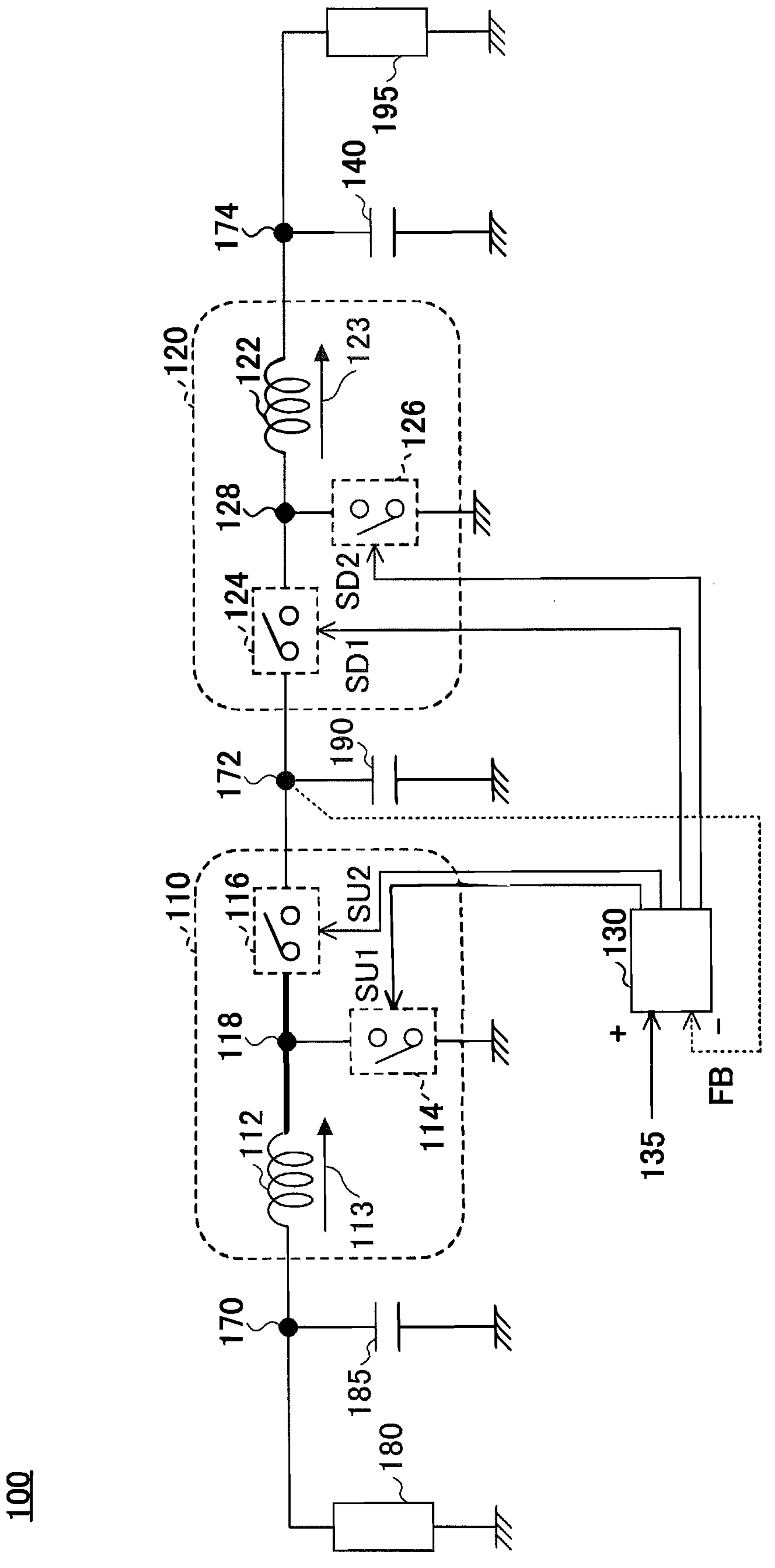
wherein the circuit comprises the driving circuit of any one of claims 1 to 11.

17. An electronic device comprising:

the speaker device of claim 16;

a processor configured to provide the input signal to the speaker device; and

a battery configured to supply the electric power to the speaker device.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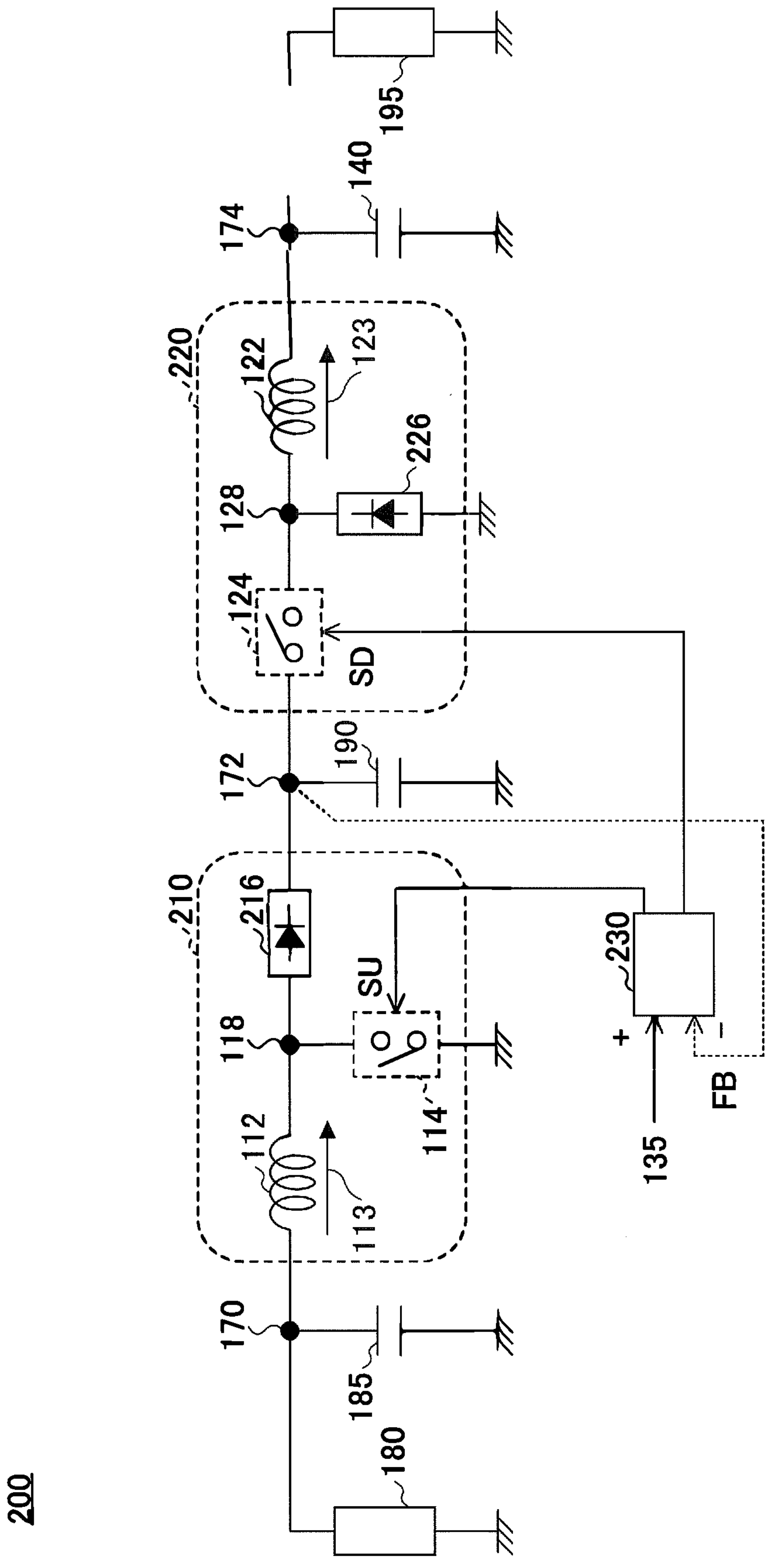
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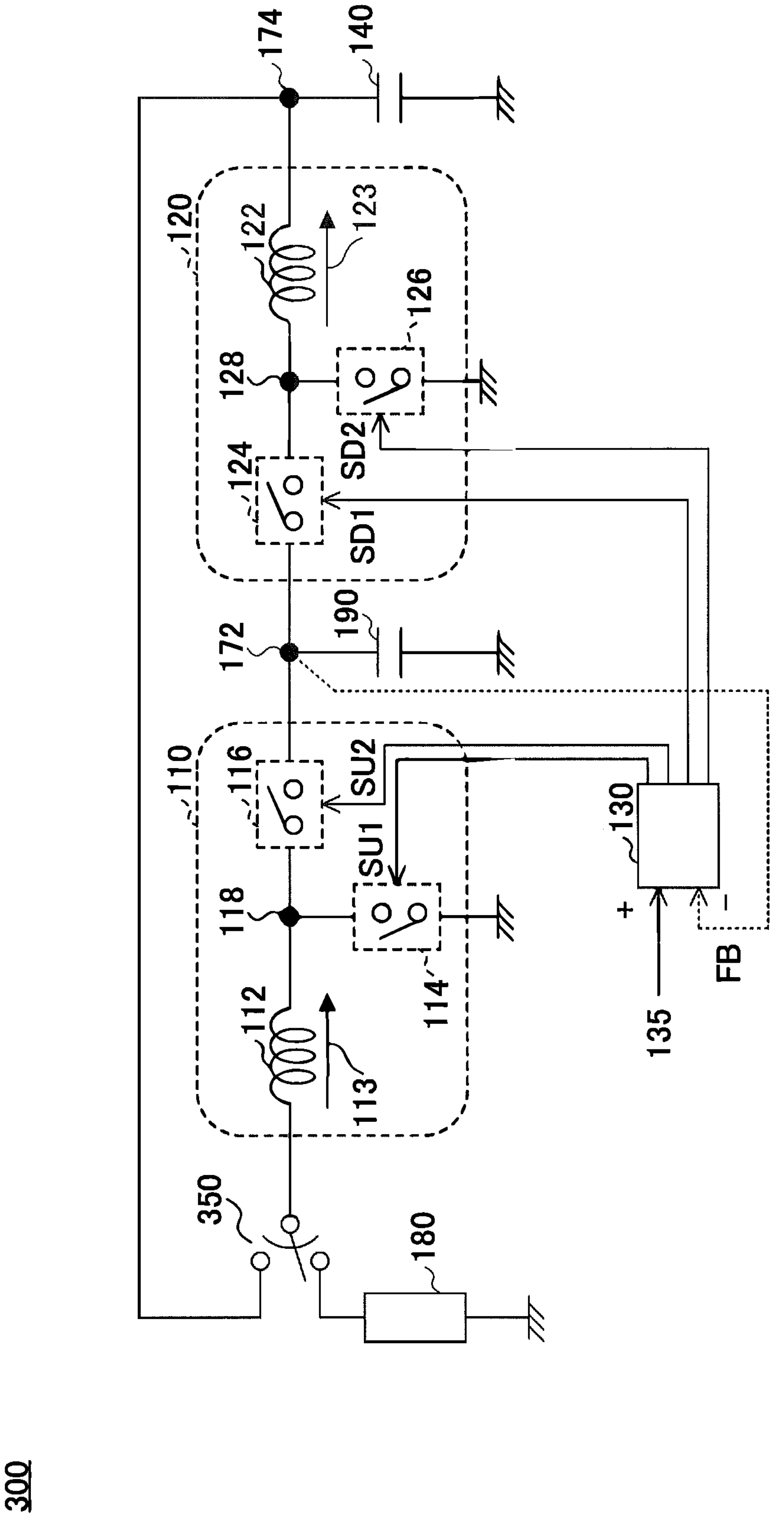
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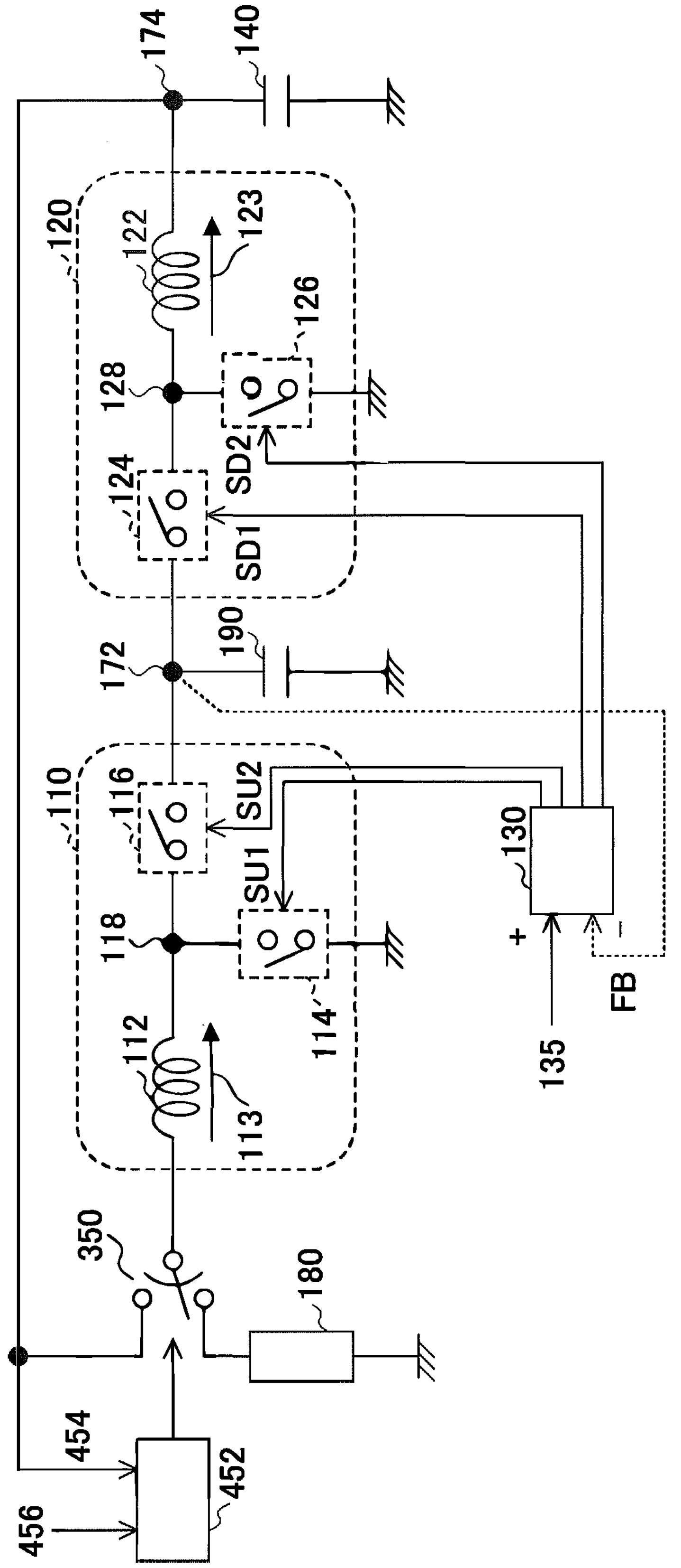
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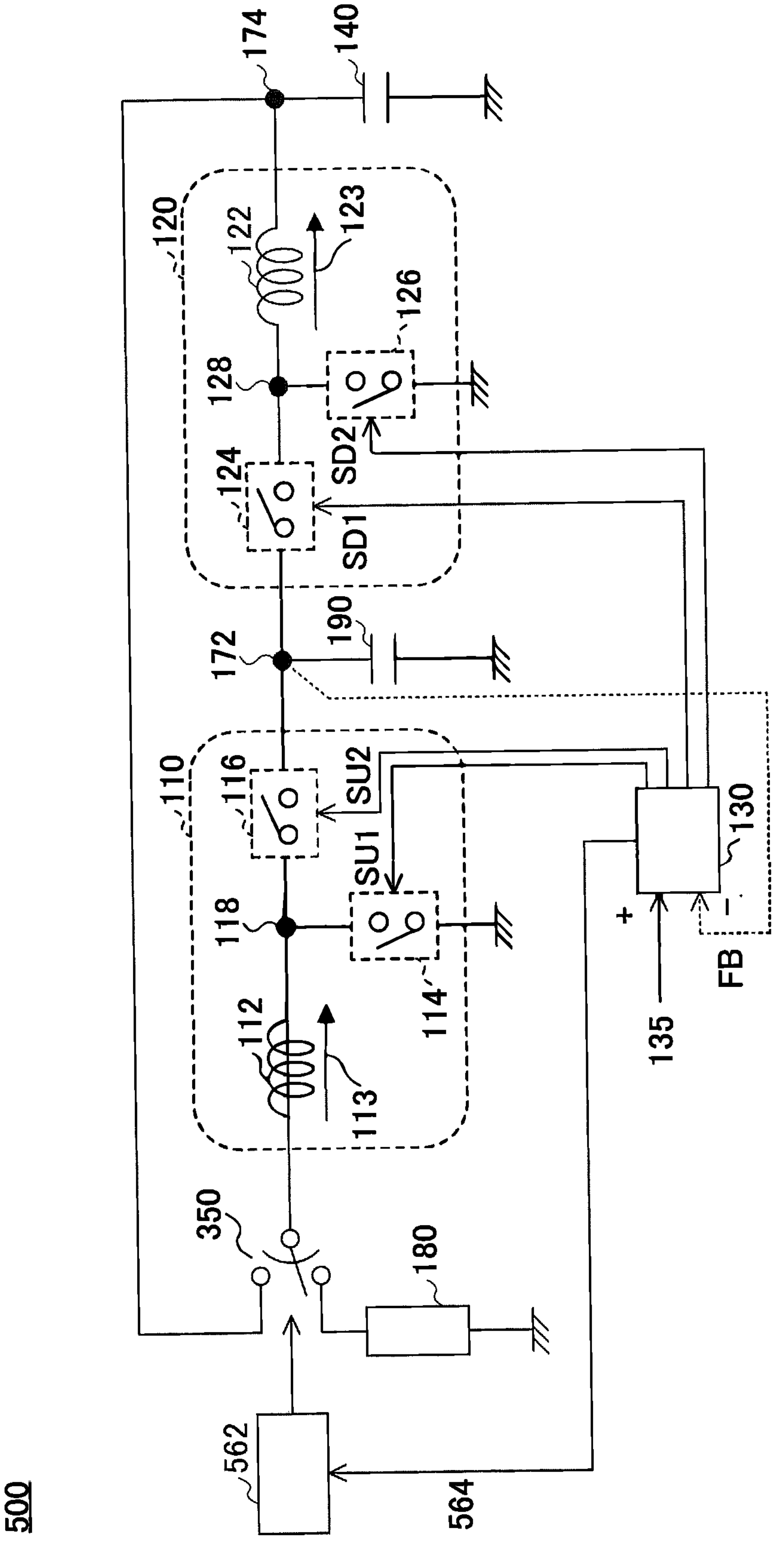
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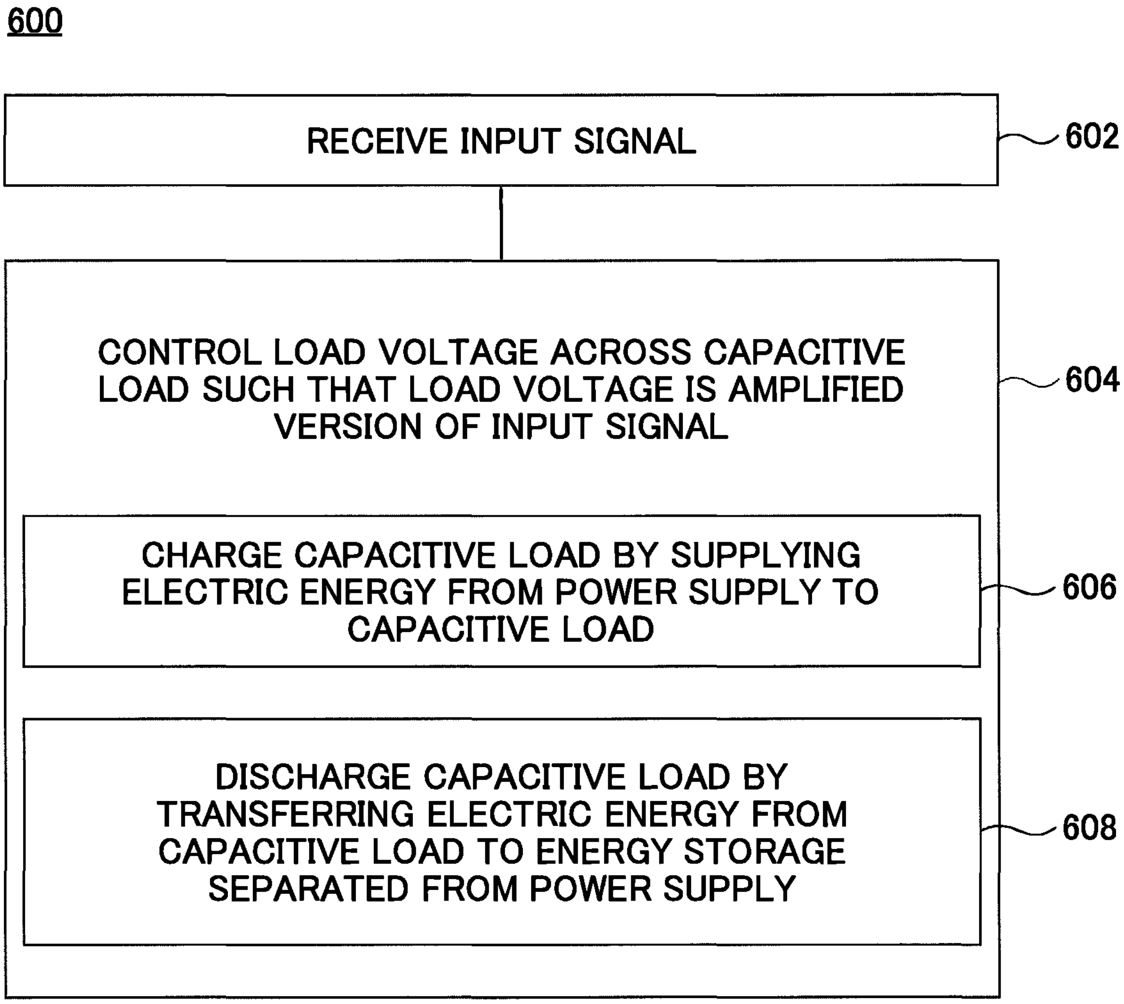
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DISCHARGE CAPACITIVE LOAD BY TRANSFERRING ELECTRIC ENERGY FROM CAPACITIVE LOAD TO ENERGY STORAGE SEPARATED FROM POWER SUPPLY
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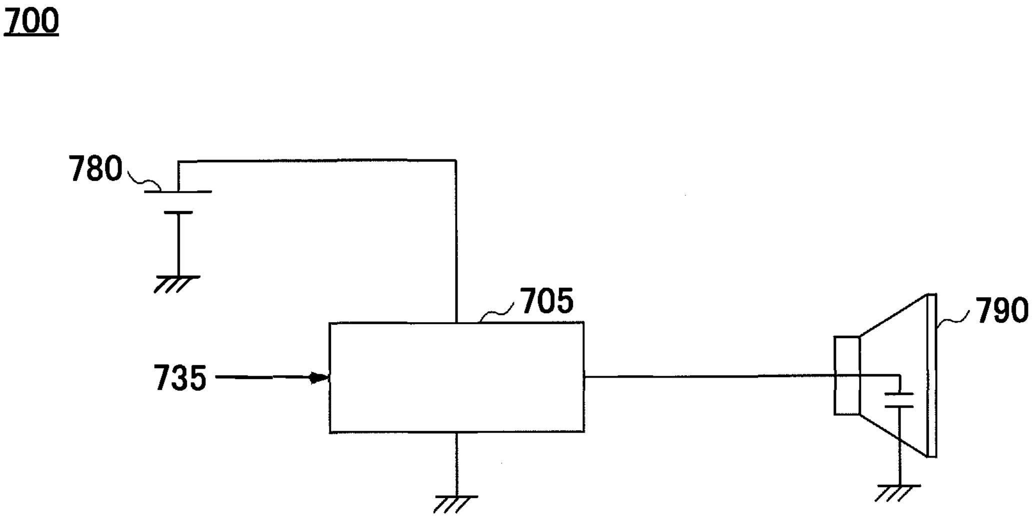
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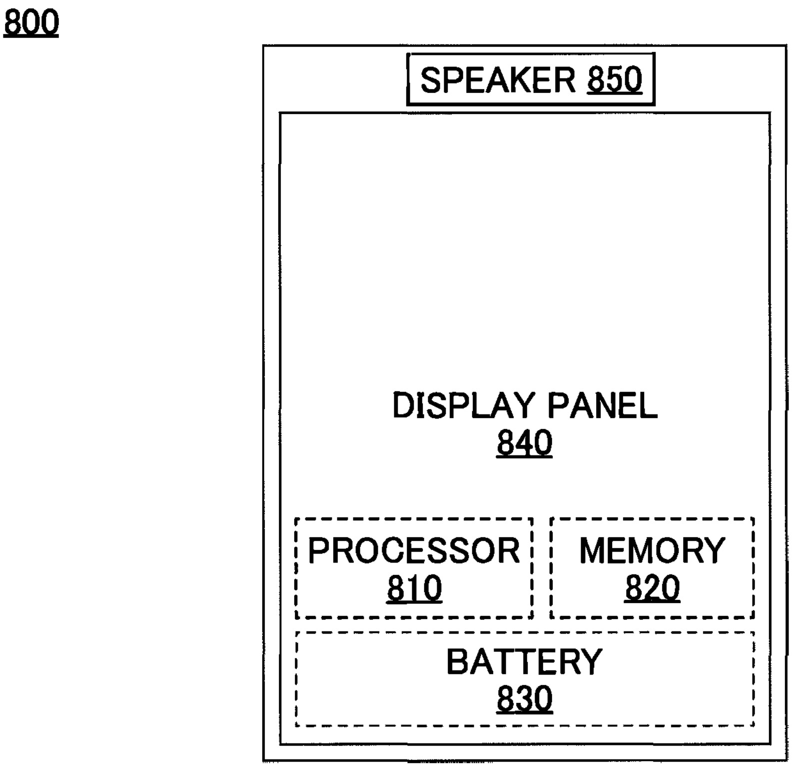
【Fig. 8】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DISPLAY PANEL
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PROCESSOR
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MEMORY
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BATTERY
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INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2022/106403

A. CLASSIFICATION OF SUBJECT MATTER

H02M 3/155(2006.01)i; H02M 1/08(2006.01)i; H04R 17/00(2006.01)i

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 H04R

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)

CNPAT, WPI, EPODOC, CNKI:capacitive, load, step-up, boost, step-down, buck, energy, recycling, MEMS, speaker

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2021175798 A1 (XMEMS LABS, INC.) 10 June 2021 (2021-06-10) description, paragraphs [0027]-[0096] and figure 1	1-2, 8-12, 16-17
X	US 2021175864 A1 (XMEMS LABS, INC.) 10 June 2021 (2021-06-10) description, paragraphs [0027]-[0096] and figure 1	1-2, 8-12, 16-17
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A	CN 114025284 A (XMEMS LABS, INC.) 08 February 2022 (2022-02-08) the whole document	1-17
A	CN 103918181 A (HAMAMATSU PHOTONICS K.K.) 09 July 2014 (2014-07-09) the whole document	1-17

☐ Further documents are listed in the continuation of Box C. ☑ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"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 **12 December 2022**	Date of mailing of the international search report **21 December 2022**
Name and mailing address of the ISA/CN **National Intellectual Property Administration, PRC** **6, Xitucheng Rd., Jimen Bridge, Haidian District, Beijing** **100088, China** Facsimile No. **(86-10)62019451**	Authorized officer **ZHANG,Zhen** Telephone No. **86-(10)-53961244**

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Information on patent family members

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				KR	101855555	B1	04 May 2018