P210546SG-CT/CK/JRO

Automatic power controlled Magnetic Resonance charger system for multiple devices

The invention concerns a charger designed for charging two or more chargeable wearable devices. The invention also concerns chargeable wearable device for such a charger and a charging system comprising such a charger and two or more such chargeable wearable devices.

Currently, more and more wearable devices are designed in such a way that they can be charged without cables. So wireless charging is the trend for chargeable wearable devices. This applies, for example, to devices such as smartphones, tablets, smartwatches or hearing instruments, especially hearing aids.

Wireless charging has different benefits. For example, wireless charging can have completely galvanic isolation between a charger and a chargeable device to achieve a corrosion-proof chargeable device. In other words, corrosion-proof means the chargeable device can be charged in a harsh environment due to the device is completely sealed. Wireless charging can also achieve a better aesthetic for a chargeable device without a contact pin exposed to the outside. Wireless charging also allows a chargeable device to be charged with a higher alignment-free which gives better design freedom to the mechanical design.

The current deployment for most wireless charging wearable devices is the so-called inductive charging. Inductive charging is a mistuned resonance frequency concept between a charger and a chargeable device. Charging according to the Qi-standard is one of the inductive charging systems. The inductive charging approach has the disadvantages of low charging efficiency when the receiver of the chargeable device and transmitter of the charger are far apart. To achieve a

good efficiency for the inductive charging, the receiver coil must be placed close to the transmitter coil and in the same orientation to achieve a good coupling factor. However, a higher degree of freedom placement is preferred for a wearable device because it would allow better design freedom for mechanical design to the charger and the chargeable wearable device. A higher degree of freedom placement means a lower coupling factor between the transmitter and receiver coils which can cause a lower charging efficiency for the adoption of inductive charging. A low charging efficiency can cause a high heat generation during charging due to the stronger magnetic field required to support charging.

The so-called Magnetic Resonance power transfer is the proposed wireless charging concept for chargeable wearable devices. It will hereinafter be referred to as MR power transfer for short. The MR power transfer can achieve a high power transfer efficiency and a far power transfer distance between a transmitter of a charger and a receiver of a chargeable wearable device at the same time. The MR power transfer has the benefits of 1) different form factors between transmitter and receiver antenna, 2) large gap distance up to 20 mm, 3) high tilt angle up to 60 degrees, 4) high efficiency with at least double of inductive power transfer and 5) low heat dissipation at the receiver. The advantages described for the charging technology by means of MR power transfer could facilitate the mechanical design of wearable devices. The range of resonance frequency for MR power transfer is 1 MHz to 100 MHz. At this moment, there is no product existing in the market which uses charging technology by means of MR power transfer.

For a charging system the so-called charger is an essential component. The charger is used to generate a magnetic field and transmit energy to charge a chargeable device. A charging system using MR power transfer is usually a weakly coupled system among a transmitter coil of the charger and a receiver coil of a chargeable device. As such, the charger must have a robust and resilient system that can deliver sufficient energy to charge a secondary battery in the chargeable device and complete a full charging. Besides, the charger system has to have the functionality of auto overcome the device charging function when the device is placed in a harsh positioning.

SUMMARY

The invention relates to a charger for charging two or more chargeable wearable devices. It further relates to a chargeable wearable device chargeable with a previously mentioned charger. Such a chargeable wearable device is hereinafter also referred to as a wearable device for short, or simply as a device. Furthermore, the invention relates to a charging system comprising a previously mentioned charger and two or more chargeable wearable devices which are chargeable with the charger. A corresponding chargeable wearable device is, for example, a hearing instrument and in particular a hearing aid. The mentioned devices charging system, charging device and chargeable mobile devices are designed for charging by means of the so-called Magnetic Resonance power transfer described at the beginning. It will hereinafter be referred to as MR power transfer for short.

To enable a MR power transfer, the charger has a Magnetic Resonance charger system. This Magnetic Resonance charger system is hereinafter also referred to as MR charger system for short, or simply as charger system. The Magnetic Resonance charger system is an essential component to complete the whole charging process. This invention discloses an architecture of a Magnetic Resonance charger system that can charge at least two devices at the same time. The MR charger system preferably has a common circuit and two or more duplicate circuits.

The common circuit preferably has a power source module, a system VI sensor, a system power converter, a microcontroller and an oscillator.

The duplicated circuit preferably has a channel power converter, a channel VI sensor, a channel power amplifier, a channel driver and a channel load demodulator.

Each of the block functions is described in detail concerning its feature and functionality to the charger system.

This invention also includes the operation flow of the charger system and a receiver system of a chargeable wearable device. The operation flow can automatically adjust the necessary transmitted power at the charger system to charge the receiver system. In addition, this invention also shows the charger board distribution and all the possible alternative solutions to the invented charger system.

DETAILED DESCRIPTION

The invention is described in detail below and with reference to the following figures, showing preferred embodiments of the invention:

Fig. 1 a block diagram and a connection flow of a charger circuit of a charger system of a charger,
Fig. 2 a block diagram of a power source module of the charger circuit,
Fig. 3 a block diagram of a system VI sensor of the charger circuit,
Fig. 4a a block diagram of a system power converter of the charger circuit with a buck converter,
Fig. 4b a buck converter circuit with a fixed internal feedback circuit,
Fig. 5 a block diagram of a microcontroller of the charger circuit for the charger basic function,
Fig. 6 a block diagram of an oscillator of the charger circuit,
Fig. 7a a block diagram of a channel power converter of the charger circuit with a buck converter,
Fig. 7b a buck converter circuit with a varying internal feedback circuit,
Fig. 8 a block diagram of a channel VI sensor of the charger circuit,
Fig. 9 a block diagram of a channel driver of the charger circuit,
Fig. 10a a block diagram of a channel power amplifier of the charger circuit with a resistive class E power amplifier,
Fig. 10b a schematic circuit of a resistive class E power amplifier,
Fig. 11 a block diagram of a load demodulator of the charger circuit,
Fig. 12 a charging operational flow of the charger system and a receiver system of a chargeable wearable device,
Fig. 13a an example of a charger and two chargeable wearable devices,

Fig. 13b an example of a board of the charger,

Fig. 14 a block diagram of a common low dropout regulator circuit of an alternative solution,

Fig. 15 a block diagram of a microcontroller of an alternative solution with a PWM output signal to the channel power converter feedback input,

Fig. 16 a block diagram of a microcontroller of an alternative solution with the PWM output signal to the channel driver to drive the channel power amplifier,

Fig. 17a a schematic diagram of a boost converter,

Fig. 17b a schematic diagram of a sepic converter,

Fig. 18 a schematic circuit of an inductive class E amplifier,

Fig. 19 a waveform result of a load demodulator circuit block function,

Fig. 20a an output frequency spectrum measurement of an inductive class E power amplifier,

Fig. 20b an output frequency spectrum measurement of a resistive class E power amplifier,

Fig. 21a an antenna impedance curve of an inductive topology,

Fig. 21b an antenna impedance curve of a resistive topology,

Fig. 22 an efficiency test result of an inductive topology and a resistive topology class E power amplifier,

Fig. 23 a full charging profile of a hearing instrument battery charging current and hearing instrument battery voltage over the time,

Fig. 24 an input power of the power amplifier and a hearing instrument charging power over hearing instrument battery voltage and

Fig. 25 two hearing instrument charging plot using the same invented charger system and operational flow.

This invention discloses a Magnetic Resonance charger system for multiple devices. This charger system is preferably designed as an automatic power controlled charger system. The MR charger system must be able to charge multiple devices at the same time and be controllable to deliver sufficient power from the charger system to charge the secondary batteries of the devices. The key functionality of this invention is the MR charger system that has a transmitted

power varying feature, especially to cater devices with different charging states. Hence, this invention shows a comprehensive architecture of a MR charger systems and a charging operational flow of a charger-receiver system.

The Magnetic Resonance charging system preferably has a charger with a transmitter system and multiple devices. Each device has a receiver system. This invention focuses only on the essential charging function of the MR charger system that is required for the charging operational flow for the wireless charging application. The transmitter system of the charger is a charger board that can be a single substrate or multiple substrates.

Fig. 1 shows a block diagram and a connection flow of a MR charger system of a charger and multiple devices. Each device has a receiver system Rx. The MR charger system preferably has a charger circuit with a common circuit, multiple duplicated circuits 1 to N and multiple transmitter modules (Tx modules) 1 to N. In Fig. 1 the red line indicates the power line and the dotted arrow line indicates the flow of the signal line.

The common circuit preferably has 1) a power source module, 2) a system VI sensor, 3) a system power converter, 4) a microcontroller or short MCU and 5) an oscillator.

The duplicated circuitry preferably has 1) a channel power converter, 2) a channel VI sensor, 3) a channel driver, 4) a channel power amplifier and 5) a channel load demodulator.

Each transmitter module or Tx module is preferably a tuned resonance frequency transmitter antenna that is especially in the shape of a loop antenna. The loop transmitter antenna can be in the shape of helical, spiral, helical-spiral (multilayer spiral). The resonance circuit of the transmitter module can be a series resonance circuit, a parallel resonance circuit, or a parallel series resonance circuit.

Such a parallel series resonance circuit is described, for example, in the parallel application entitled " Magnetic Resonance power transfer with parallel series-parallel resonance circuit for the hearing instrument application ". The contents of this application are hereby expressly referred to.

Each receiver system Rx 1 to N preferably has 1) a receiver module, 2) a power management module and 3) a secondary battery. The receiver module is preferably a turned resonance frequency receiver coil. The receiver module can receive the magnetic energy generated from the transmitter module with a similar resonance frequency and convert it to electrical energy. The receiver module preferably has the feature of converting the received AC energy to the DC energy before supply power to the power management module. The power management module preferably has the feature of regulating the voltage and provide a constant current to charge the battery. The power management preferably generates a load modulation signal at the power management module that contain all the charging data at the receiver system and modulates the signal at the receiver module.

The focus of this invention is the MR charger system. So, the transmitter module design and the design of the receiver systems are not showing detail in this invention. The transmitter module and the design of the receiver systems are only used as the supplementary component to support the description of charger system. For the MR charger system, the following shows the detail of each block function in the common circuit and duplicated circuit.

Power source module

The power source module especially has the role of getting the power externally and supply the power to the whole charger system. The power source module preferably has 1) an input power module, 2) an internal power storage module and 3) a MCU (microcontroller) read-write module.

Fig. 2 shows a block diagram of an exemplary power source module and its connection. The input power module has a connector port that allows an external power port to be plug-in and supply power to the charger. The input power module

also has the protection functionality to overcome a sudden high surge voltage and high surge current. The supplied power from the input power module can go to the intermediate power storage module to charge the power storage or bypass it to directly supply power to the downstream charger system. The MCU read-write module allows communication between the external device and the MCU in a low noise condition.

The input power module has 1) a connector port, 2) a ESD circuit, 3) a fuse, 4) a common mode filter and 5) an overvoltage protection module. The connector port must be the first block function of the input power module that is used as connecting to the external source. There is no restriction of sequence arrangement for the rest of the block function in the input power module.

The connector port is usually a female socket of Universal Serial Bus (USB) input power or it can also be a female socket of Apple cable. The USB is an industry-standard cable and connector protocol for many electronic devices. Generally, the connector port has an output of 5V direct current (DC) voltage to the succeeding block function. The 5V DC voltage comes from a 5V DC adapter output converted from the 110V/230V AC power socket, or a 5V DC USB output from an external battery bank or any USB port power source device.

The ESD circuit has the feature of preventing an electrical shock or a dielectric breakdown caused by electrostatic induction when any different charged objects are brought close to the charger. The fuse is a protection component to interrupt and cut off the power when there is a power surge or the charger's internal short circuit. The common-mode filter is used as filtering the current noise generated from other external devices. The overvoltage protection module cuts off the power when the input voltage is more than the rated voltage.

There is an option for the power source module to have internal power storage. Adding the internal power storage to the charger is to realize a portable charger which users can carry the charger and charging the device at the same time. The

two-block functions needed to realize internal power storage to the charger are 1) a battery management circuit and 2) a power storage.

A battery management circuit is required to regulate a constant charging current to the output to charge the power storage. The battery management circuit also monitors the voltage of power storage at the charging state. In discharging state, the internal power storage draws the power from the battery and step up or step down the voltage before supply power to the downstream charger circuit. The step-up or step-down function can be integrated into the battery management circuit or a discrete component such as buck converter (step-down), boost converter (step-up), or sepic (buck-boost) converter. The selection of discharging topology is based on the selected power storage. The commonly seen power storage is a lithium-based battery such as lithium-ion battery and lithium polymer battery with a nominal voltage 3.7V, or a nickel-based battery such as nickel-cadmium battery and nickel-metal hydride battery with a nominal voltage 1.2V. The MCU read-write module is a block function to have the communication between the microcontroller and the external device. Similar to the input power module, the ESD circuit is also applied to the MCU read-write module to prevent distortion program/data when the external device has an electrical shock or a dielectric breakdown.

System VI sensor

The system VI sensor preferably is the combination of a voltage measurement sensor and a current measurement sensor. Fig. 3 shows a block diagram of an exemplary system VI sensor arrangement for a voltage and a current measurement. The system VI sensor is applied just after the power source module to calculate the input power of the whole charger system. The input power line of the system VI sensor is the power source module and the output power line of the system VI sensors is the system power converter and the channel power converter. The voltage measurement is taken from the voltage across the power line and the system ground. The voltage measurement sensor is usually realized by a voltage divider circuit. The current measurement is taken from the current flow through the power line. The current measurement sensor can be done by

using the voltage across a small resistance through the power line and amplify its signal. As such, the current measurement sensor is a current to voltage conversion circuit. Both the voltage sensor and current sensor signals are then output to the microcontroller (MCU).

System Power converter

The system power converter has the feature of regulating the output voltage. The input voltage of the downstream circuit such as a microcontroller, operational amplifier, oscillator, etc. usually requires a lower fixed input voltage for it to power up and function. As such, a fixed output voltage buck converter is used as the system power converter. The buck converter is a DC-DC power converter and it has the step-down voltage feature with a regulated output voltage. Fig. 4a shows a block diagram of an exemplary system power converter and Fig. 4b shows a circuit diagram of an exemplary fixed output voltage buck converter as the system power converter. The input power of the system power converter is from the system VI sensor. The output power of the system power converter is connected to all the channel load demodulator, all the channel drivers, microcontroller, and oscillator.

The buck converter has an active switch in series to the input power line and a capacitor in parallel to the output line. There is a passive diode and an inductor at the intermediate circuitry of the buck converter. The operation of the buck converter starts with charging the inductor when the switch is turned on. The charging current flow through the switch and inductor, then the inductor current ramping up linearly when the switch is turned on. When the switch is turned off, the current flows through the diode and inductor. The inductor is then discharged and declining down linearly. The capacitor in parallel to the output is used as smoothing the output ripple voltage that generated from the switch and external noise. A voltage divider at the output of the buck converter shown in Fig. 4b is pulled to the feedback control to form a closed loop system and stabilize the buck converter system. The closed loop system can regulate the output of the buck converter to a fixed desired voltage.

Microcontroller

A single unit microcontroller (MCU) that contains multiple input pins and multiple output pins is preferably used in the charger system to control multiple channels and charge multiple devices at the same time. The microcontroller (MCU) is a processing component to manipulate the transmitted power. It is used as processing the retrieve information of the receiver system and provide the next action to control the charger circuit. Fig. 5 shows a block diagram of an exemplary MCU with the basic functionality needed in the MR charger system. The input power of MCU is from the system power converter with a fixed voltage. The input signals are voltage system measurement signal, system current measurement signal, channel voltage measurement signals, channel current measurement signals, channel load demodulator signals, and MCU read-write program/data. The output signal is a signal that is given to the channel power converter feedback input.

The voltage measurement signal and current measurement signal are from the system VI sensor and the channel VI sensors. These voltage and current measurement signals are in analog and converted into a digital signal via the analog to digital converter (ADC) in the MCU. The load demodulation signal generated from the channel load demodulator is also an input to the MCU. The load modulation signal is detected using the MCU GPIO pin via the rising edge or falling edge of the signals. All the input signals are conveyed to the processing unit and convert to a data format. Then, the data are processed and provide to the next instruction. The MCU controls the transmitted power of the channel power converter via the digital-analog converter (DAC). The firmware is an algorithm flow that determines the processing sequences of the retrieve signal and the output signal. The memory is used to store all the processed data. The firmware algorithm can be written from the external device via the input port. The stored data in the memory can also be read and write from the external device via the input port.

For a fixed duty ratio on-off channel power amplifier, the output power of the channel power amplifier is controlled via the output voltage of the channel power

converter. The microcontroller regulates the output voltage of the channel power converter via a DAC direct input to the feedback input of the channel power converter.

Oscillator

The oscillator has the feature of oscillating a DC signal to an AC signal in a constant frequency. The oscillated AC signal frequency is usually in the range of ten of kHz up to hundreds of MHz. The exemplary selected oscillator is a crystal oscillator that has the output of an electronic oscillated signal with a fixed frequency generated via the mechanical vibration of piezoelectric material. Fig. 6 shows a block diagram of the oscillator. The input power of the oscillator is from the system power converter. The output of the oscillator is an oscillated signal with a fixed frequency that is direct to the channel drivers.

The selection of oscillators is preferred not to drift too much from the desired frequency. As such, the measurement index of the frequency drift stability is based on the Part Per Million (ppm) which means the output frequency variation from the desired frequency. A 50 ppm is the usual specification of the oscillator frequency drift stability. For the oscillator frequency with 13.56 MHz as an example, the 50 ppm frequency drift stability has an output frequency bandwidth of about +/- 7 kHz. The frequency 13.56 MHz +/- 7 kHz complies with the bandwidth of industrial, scientific, and medical (ISM) standards.

Channel Power Converter

Similar to the system channel power converter, the channel power converter requires a feature of regulating the output voltage. However, the output voltage of the channel power converter must have varying features to generate different output power levels for the power amplifier. The varying output power at the channel power converter is to cater to the different charging orientations of the receiver. For the power amplifier is chosen as the DC to AC power conversion, the buck converter is the recommended topology as the channel power converter due to the power amplifier has the feature of boost up the voltage at the output of the power amplifier. The buck converter is a DC-DC power converter and regulate

output voltage. It has the feature of step-down the input voltage which results in a lower voltage at the output. The difference between the channel power converter and the system power converter is the channel power converter has a varying output buck converter and the system power converter has a fixed output buck converter. Fig. 7a shows a block diagram of a exemplary channel power converter and Fig. 7b shows a circuit diagram of a exemplary varying output voltage buck converter as the channel power converter. The input power is of the channel power converter from the system VI sensor and the output power is to the channel VI sensor. The available input signal pins are the feedback input and the interrupt signal.

The output voltage of the buck converter is manipulated by setting a voltage to the feedback control. The voltage at the feedback control is controlled by the DAC signal from the MCU to the feedback input. The feedback input then passes through a high cut-off frequency (~1kHz) low pass filter to eliminate the high-frequency noise that generated along the trace. The filtered feedback input signal is then going to the feedback control pin via a resistor. The feedback input circuitry and the voltage divider circuitry forming voltage source circuit loops. The relationship between the feedback input and the feedback control can be derived using the Kirchhoff current law or the superposition theorem. As a result, a higher voltage given to the feedback input generates a lower output voltage at the buck converter.

The interrupt signal from the channel VI sensors is used to provide a protection signal to cut off the buck converter when there is any short circuit happening or overcurrent drawn at the downstream circuit. The interrupt signal is given to the feedback control pin via a resistor. As a protection application, the resistor of interrupt signal circuitry is at least 2 times larger than the resistor of the feedback input circuitry. The resistor with the interrupt signal circuitry, the feedback input circuitry, and the voltage divider forming few voltage source circuit loops. As a result, the output voltage of the buck converter change to 0 V instantly when the voltage of the interrupt signal suddenly rises higher than the threshold voltage.

Channel VI sensor

The channel VI sensor has a similar function as the system VI sensors. The voltage measurement of the channel VI sensor is the output DC voltage of the channel power converter and also the input DC voltage of the channel power amplifier. The current measurement of the channel VI sensor is a DC flow of the channel power amplifier input. The only difference between the channel VI sensor and the system VI sensor is the additional current protection feature which is to monitor the current drawn to the channel power amplifier. Fig. 8 shows a block diagram of an exemplary channel VI sensors. The input power is from the channel power converter and the output power is to the channel power amplifier. The voltage measurement signal and the current measurement signal are input to the microcontroller. The current protection signal is given to the interrupt signal input of the channel power converter.

Channel Driver

The channel driver is a buffer circuit that can charge the input capacitance of the transistor and giving a sufficiently high voltage to turn on the transistor. Fig. 9 shows a block diagram of an exemplary channel driver. The input power of the channel driver is from the system power converter. The input signal is from the oscillator and the output signal is a drive signal to the transistor of the channel power amplifier. The driver signal is a level-up voltage to charge the input capacitance of transistor and to turn the channel power amplifier transistor on-off. The transistor of the channel power amplifier is turned on when the driver signal is in the high state and turned off when the voltage signal is in the low state.

Channel Power Amplifier

The channel power amplifier has the functionality of converting the input DC power to the output AC power. The channel power amplifier takes the oscillator signal from the oscillator and the channel driver signal from the channel driver as a reference and converts the input DC power to the respective power form. The oscillator signal and driver signal are then magnified to a larger power form at the output of the channel power amplifier. As such, the output power of the channel power amplifier has the same waveform as the oscillator signal but with a much

higher power level. The AC power output is then input to the transmitter module. Fig. 10a shows a block diagram of an exemplary channel power amplifier and Fig. 10b shows the schematic circuit of a resistive class E power amplifier. The class E power amplifier operates in a resonance principle allowing a small DC input to be amplified to a large AC output. The DC input power is from the channel VI sensor and the AC output power is to the transmitter module. The input signal is a driver signal to drive the transistor of channel power amplifier. The input of the resistive class E power amplifier has a filter circuit to reduce the noise in the power line. The output of the resistive class E amplifier has a low pass filter with a big inductor to reduce output harmonic

The resistive class E power amplifier is the selected topology of the channel power amplifier. The resistive class E power amplifier has the benefit of less effect from transmitter line length due to a large nominal impedance dominate the resistance of the transmitter line. The resistive class E amplifier also has the feature of a low pass filter that can lower the output power harmonic amplitude. The resistive class E amplifier has a high output resistance which facilitates the load tunning such as the input resistance of the transmitter module.

Channel Load demodulator

The channel load demodulator has the feature of 1) capture the communication signal from the receiver and 2) demodulate the communication signal into a readable format. Fig. 11 shows a block diagram of an exemplary channel load demodulator. The input power of the channel load demodulator is from the system power converter. The input signal is a voltage form or current form signal that comes from the transmitter module containing the charging data. The input voltage or current is conveyed to a detector to determine the existence of the receiver system and communication signal. Then, the signal goes to the DC blocker or high pass filter to remove out the unknown DC bias voltage. The DC bias removed signal is magnified via the amplifier and input to the comparator to generate the square waveform output signal. The output signal of the channel load demodulator then goes to the MCU to process the received communication signal.

The key aspect of this MR charger system invention is the architecture of the MR charger system and the capability to supply sufficient power to the receiver system. The combination of Class E power amplifier and buck converter has the benefit of making the system immune to input voltage ripple, such as a light load voltage ripple. The architecture of the MR charger system with common circuitry and multiple channels duplicated circuit allow a single charger system to charge multiple devices at the same time.

The invented charger system architecture is different from the charger introduced in the patent US 9,796,281 B2 which it has only a single charger circuit and it does not show the capability of charging multiple devices at the same time.

Furthermore, the input source of the patent US 9,796,281 B2 is an AC source and this charger system invention input source is a 5V DC source come from the external adapter socket or power bank. This invented charger system also introduced a internal power storage module to realize a portable charger. The transmitted power of this invention is manipulated by the output power of channel power converter via the feedback input signal from the MCU DAC, but the power supply of patent US 9,796,281 B2 is controlled from the input frequency via the frequency controller. Furthermore, the power flow and the operation flow of this invention is totally different from the patent US 9,796,281 B2. The following will show the power flow and the charging operational flow of the whole MR charger system.

The block diagram as shown in Fig. 1 illustrates the power flow of the MR charger system from the power source to the secondary battery of the receiver system. The power source draws the power externally or the internal power storage, then supply to the whole charger system. The system VI sensors measure the voltage and current from the power source module and calculate the input power of overall charger system. The power from the VI sensor is converted to an appropriate voltage level via the channel power converter. The system power converter commonly steps down the voltage and supplies a fixed regulated voltage to the microcontroller, the oscillator, all channels' driver, and all channels' load

demodulator. The channel power converter varying the output voltage and supply a varying regulated voltage to the downstream channel VI sensor and the channel power amplifier. The channel VI sensor are used as measuring the output power drawn at the individual channel and monitor the current flow through the input of the channel power amplifier. The regulated output from the channel VI sensor then input to the power amplifier to generate an oscillated power at the resonant frequency. The oscillated current flows in and out from the transmitter module to generate a magnetic power with the respective resonance frequency.

The receiver system with the same tuned resonance frequency as the transmitter module exposed to the generated magnetic field then captured the magnetic energy and convert it to electrical energy. The electrical energy is then regulated by the power management module in the receiver system and charge to the secondary battery.

The transmitted power is preferably controllable at the charger system and must not set to pump a maximum transmitted power to charge the receiver system. A maximum transmitted power to charge the receiver system can cause excessive heat generation to both the transmitter system and the receiver system. As such, the maximum charging power at the transmit power at the charger system will cause the temperature of both the receiver system and charger system rise to a higher degree. A high temperature could cause damage to the internal component for both sides and probably shorten the life span of the charger and receiver system.

For the charging operational flow, the charger system preferably always starts with the initial state which is the state when the device is first placed into the charger. The initial state is usually an initial magnetic field strength that is sufficient to detect the receiver system. The initial state of the charger system starts with setting the MCU DAC with an initial value and output to the channel power converter feedback input. The feedback input from the MCU DAC then regulates the output voltage of the channel power converter to an initial voltage. Then, an initial oscillated power is generated at the output of the channel power amplifier

and flows into the transmitter module. As a result, the transmitter module produces an initial strength of the magnetic field that is sufficient for the receiver system to capture.

The receiver system exposed to the generated magnetic field induces a power at the receiver module. The induced power then transforms to the DC voltage at the receiver module and regulates the voltage at the power management module. The regulated voltage then generates a constant current to charge the secondary battery of the receiver system. The load modulation signal that contains the receiver system charging information is generated at the power management module to the receiver module. The load modulation signal is reflected to the transmitter module via the magnetic field and demodulated at the charger system via the load demodulator. The MCU GPIO detects the demodulated signal and generates an interrupt signal to allow the MCU to go into the state of decode and process the demodulated signal. The processed signal then sets a new MCU DAC value to the channel power converter feedback input and varies the output of the channel power converter to a new DC voltage. A new DC voltage input to the channel power amplifier generates a new oscillated power at the output. The new oscillated power to the transmitter module generates a new magnetic field strength. Finally, the receiver system placed at the same position will capture the new magnetic field and induced a new power at the receiver module. The charger system normal operation flow looping again with the same step until the receiver system is removed from the MR charger system and reset the charger back to the initial state for receiver system detection.

Fig. 12 shows an exemplary charging operational flow of the charger system and the receiver system. The charging operational flow forming a loop to ensure sufficient power is output from the charger system to charge the receiver system wirelessly.

The charger system has to pump more power to the transmitter module to compensate for a bad coupling when the receiver system is placed far apart from the transmitter module or the receiver system has a high tilt angle with respect to

the transmitter module. In contrast, the charger pumps less power to the transmitter module when the receiver system and the transmitter module have a good coupling. The power control at the charger system is manipulated via the MCU DAC output. The charger system outputs a high power when the MCU DAC value is low and it pumps a low power when the MCU DAC value is high. With the introduced operation flow, the charger system can automatically vary power to generate the respective magnetic field strength that is needed to charge the receiver system. Overall, the introduced operational flow can ensure sufficient delivered power to charge the receiver system, and control not to deliver excessive power to the receiver system.

Exemplary, preferred embodiments

Charger system example and Charger Board Distribution

The invented charger system will for example be employed as a board of a charger. Fig. 13a shows a picture of an exemplary charger and two hearing instruments as chargeable devices. Fig. 13b shows an exemplary board of the charger with many discrete components integrated and mounted on a printed circuit board (PCB) to form a charger system. In this example the chargeable wearable devices are hearing instruments. The two hearing instruments preferably built a binaural hearing system. The distribution of the charger system on the board or charger board is the common circuit at the middle of the board and the left-right duplicated circuit at the left and right of the board. This introduced charger board arrangement can achieve a high charging efficacy.

For the common circuit distribution, the power source module is located at the top edge of the charger board and the MCU is placed at the middle of the charger board. The power source module is placed near the charger board edge to facilitate an external power cable port to easily plugin and supply power to the whole charger system. The MCU as the brain of the charger board is placed in the middle because it has many input and output signals that require easy access from and to many block functions. The system VI sensors and the system power converter are placed in between the power source module and the MCU. The

oscillator is also located in the middle of the charger board so that it can provide the oscillated signal to both the left and right channel driver.

For the duplicated circuit, all the channel circuits are placed at the top left and top right of the charger board for both the left channel circuit and right channel circuit except the load demodulator circuit. The channel circuits include the channel power converter, channel VI sensor, channel driver, and channel power amplifier. The left and right channel transmitter module ports are placed at the left edge and right edge of the charger board. The channel power converter is located close to the power source module and the system VI sensors because it is the source supply for each channel. The channel power amplifier is placed close to the transmitter module port because it provides the oscillated power to the transmitter module. The channel VI sensor is placed in between the channel power converter and the channel power amplifier to measure the power flow across these two block functions. The channel driver takes the input signal from the oscillator and output to the transistor of the channel power amplifier, so the channel driver is placed close to the power amplifier. The load demodulator circuit placed far from other circuits can reduce the interference signal from other circuits, so the load demodulator is placed at the bottom left and bottom right of the charger board.

In addition, the charger system has a center barrier. It is placed between two channel transmitter modules to suppress the cross-coupling. Such a center barrier is described, for example, in the parallel application entitled " Wireless charging device for hearing instruments and hearing instruments system ". The contents of this application are hereby expressly referred to. The suppression of cross-coupling allows the receiver system to transfer the load modulation signal to the respective channel transmitter module but not interfere with the adjacent channel.

Alternative solutions

System Power Converter

The low dropout (LDO) regulator can also be used as the system power converter. The LDO has the function of regulating the output to a fixed voltage. A block

diagram of an exemplary common LDO circuit is shown in Fig. 14. The LDO has the benefit of no additional passive component required to regulate the output voltage. As such, the LDO as the system power converter has a lower overall cost than the buck converter. However, the buck converter generally has the benefit of higher conversion efficiency compared to the LDO. The buck converter normally has a higher power rating than the LDO.

Microcontroller

For a fixed duty ratio channel power converter, the output power of the channel power amplifier is controlled via the output voltage of the channel power converter. The microcontroller can also regulate the output voltage of the channel power converter via a or pulse width modulation (PWM) with a low pass filter which has a much lower cut-off frequency to the feedback input of the channel power converter as shown in (1). As such, the utilization of resistor and capacitor value in the low pass filter circuit as shown in Fig. 7b for the MCU PWM output signal require a larger value than the MCU DAC output signal. Fig. 15 shows an exemplary MCU with a PWM output signal to the channel power converter feedback input. The PWM requires a filter to get the average signal but the DAC does not need it.

$$f_{c,pwm} \ll f_{c,DAC} \qquad (1)$$

Oscillator

The oscillated power at the output of the channel power amplifier can be generated via a fixed frequency-fixed duty ratio pulse width modulation (PWM) signal from the MCU to the channel driver to drive the switch of the power amplifier circuit. The input of the channel power amplifier is normally the channel power converter and control via the DAC. Fig. 16 shows a block diagram of an exemplary MCU with the PWM output signal to the channel driver to drive the channel power amplifier. The utilization of MCU PWM to the channel driver to drive the channel power amplifier has the advantage of eliminating the oscillator circuit. The high-frequency PWM signal is generated via a phase-locked loop (PLL) control feature of MCU. The MCU that has a PLL feature is generally a digital signal processor or digital signal MCU. The digital signal is normally higher cost than a normal MCU.

Channel Power Converter

The channel power converter topology can also be a boost converter or sepic converter which depends on the required output voltage. The boost converter has the feature of step up the input voltage and provides a higher voltage to the output. The sepic converter is a kind of converter that can perform step up and step down the voltage to the output. For an application that requires step up and step down voltage, the sepic converter is recommended as the selected converter compares to the normal buck-boost converter and Ćuk converter. The reason is that 1) the output of buck-boost converter and Ćuk converter is in reverse polarity and 2) sepic converter has a common ground between the output and input. Fig. 17a shows a schematic diagram of an exemplary boost converter and Fig. 17b shows a schematic diagram of an exemplary sepic converter. For the component count comparison, the boost converter has the same amount of components as the buck converter whereas the sepic converter has an additional capacitor and an additional inductor.

Channel Power Amplifier

For the channel power amplifier, the inductive class E amplifier can also be used as oscillating a DC input power to an AC output power. Compare with the resistive class E amplifier, the inductive class E amplifier has the benefit of smaller form factor and less component count. As such, the inductive class E amplifier is cheaper in overall cost compare with the resistive class E amplifier. Furthermore, the inductive class E amplifier has a feature of lower output resistance than the resistive class E amplifier. Fig. 18 shows a schematic circuit of an exemplary inductive class E amplifier. The inductive class E amplifier has similar input lower pass filter circuit as the resistive class E amplifier. Compare with the resistive class E amplifier, the inductive class E amplifier does not have a series capacitor to the output inductor and a output capacitor. The output inductor of the inductive class E amplifier is smaller value than the output inductor of resistive class E amplifier. Overall, the efficiency of inductive class E amplifier is better than the resistive class E amplifier due to less component and smaller inductor with a lower resistance at the output.

Load demodulator Test

A test is carried out to check the feasibility of the proposed load demodulator circuit. Fig. 19 shows a waveform result of a load demodulator circuit block function as shown in Fig. 11. The yellow waveform is the load modulation signal at a devive, especially a hearing instrument (HI), the green waveform is the detector output, the blue waveform is the amplifier output, and the red waveform is the comparator output. The detector output waveform follows the rising and falling waveform trend of the HI load modulation signal. The amplifier output waveform has eliminated the AC of the detector output waveform and magnify it to a larger signal. The comparator output has generated a smooth square waveform that has a steep rising edge and falling edge that allows MCU easily read the signal.

Inductive class E power amplifier vs Resistive class E power amplifier Test

A test is carried out to compare the inductive and resistive topology of class E power amplifiers to verify the statement shown in the previous power amplifier section. Fig. 20 shows the frequency spectrum measurement of the inductive (Fig. 20a) and resistive (Fig. 20b) class E power amplifier at its output. Overall, the resistive topology harmonic is lower than the inductive topology. The first harmonic amplitude of inductive topology is -40dB and the first harmonic amplitude of resistive topology is -58dB. This comparison result indicates the resistive topology of the class E power amplifier has an output filtering feature that can lower the harmonic amplitude.

Fig. 21 shows the antenna impedance curve of the inductive (Fig. 21a) and resistive (Fig. 21b) topology. The antenna impedance is similar to the output impedance of the inductive and resistive class E power amplifier to achieve maximum power transfer. The resistive topology has a peak antenna impedance at 13.56MHz. Compare to the resistive topology, the overall antenna impedance curve of inductive topology shifted to a right position which means shifted to a higher frequency. With such shifted phenomenon for the inductive topology, the inductive topology has a lower nominal impedance than the resistive topology at 13.56MHz.

An efficiency test is carried out to compare the differences between the inductive and resistive topology class E power amplifier. The efficiency test is conducted with using 12 pieces different shell shape hearing instrument with respect to the inductive topology charger and the resistive topology charger. The efficiency is taken account from the input power of power amplifier to the output power of HI. Fig. 22 shows the efficiency test result of inductive and resistive class E power amplifier. Based on the test result shown, the resistive topology has up to 1.5% lower efficiency than the inductive topology.

Based on all three tests and their results, both topologies have the benefit to be chosen as the channel power amplifier. The resistive topology has the advantages of lower harmonic and a higher nominal impedance that can dominate the transmission line from the output of channel power amplifier to the input of transmitter module and facilitate the tuning of transmitter module.

A preferred design of such a transmitter module is described, for example, in the application with the file number PCT/SG 2021/050228. The contents of this application are hereby expressly referred to.

Full Charging test

A full charging test is carried out to verify the invented MR charger system as shown in Fig. 1 and the introduced operation flow as shown in Fig. 12. A load modulation hearing instrument (HI) is the charging device of the full charging test. The power management module is pre-set to charge the HI battery with different charging currents at different battery voltages. The charging current is preset to charge the battery with a constant current of 10 mA as the fast-charging state when the battery voltage is below 3.85 V. The charging current is pre-set to charge the battery with a constant 5 mA as the common charging state when the battery voltage is above 3.85 V. At the constant voltage (CV) mode which the battery is almost fully charged and the battery voltage is about 4.18 V, the charging current will slowly ramp down and stop charging. With such pre-set conditions at the HI, the MR charger system has to vary the transmit power to ensure sufficient power

to charge at different charging states. The combination of the invented MR charger system and the introduced operation flow can simply achieve sufficient power delivery to charge the HI device.

Fig. 23 shows the full charging profile result of the HI battery charging current and HI battery voltage over time. Fig. 24 shows the input power of the power amplifier and the HI charging power over HI battery voltage. The power amplifier input power is the transmitted power from the power amplifier to the transmitter module. The HI power is the multiplication of the battery voltage and the charging current. The HI has different charging power at different battery voltages. For the battery voltage in between 3.2 V to 3.85 V, the HI battery charging current is 10 mA. The input power of the power amplifier is about 330 mW to 340 mW at 3.3 V to 3.7 V, and the HI charging power is about 33 mW to 38 mW. For the HI battery voltage above 3.8 V to 3.85 V, the battery voltage having a different charging slope as shown in Fig. 23. The changes in battery voltage charging slope are due to internal battery structure or battery chemical composition. As such, the input power of the power amplifier is reduced to cater to different battery voltage charging slopes. For the HI battery voltage in between 3.85 V to 4.18 V, the battery charging current is about 5 mA. The power amplifier output power is about 170 mW to 180 mW, and the charging power at the hearing instrument is about 20 mW. When the battery voltage reaches about 4.18 V, the charging current slowly ramps down and stops charging when it hits a preset 2 mA. The charging result shown implies the invented charger system and the invented operation flow can successfully varying transmitted power at different charging states.

Two channels full charging test

Another full charging test is carried out to test charging two HI at the same time using the same charger. Fig. 25 shows the plot of charging two HI at the same time using the same invented charger system and operational flow. The two HI channels are termed here as the left channel and right channel. Similar to single-channel charging, the invented charger system can control both channels transmitted power simultaneously to charge HI battery at different charging states.

The features and embodiments described above and in connection with the figures are not restricted to the specific combinations and values as described therein. Rather, further advantageous embodiments of the invention result from omitting some features and/or from different combinations of the mentioned features and/or by selecting different values.

Claims

1. Charger designed for charging two or more chargeable wearable devices at the same time and designed for charging by means of a Magnetic Resonance power transfer.

2. Charger according to claim 1, wherein the charger has a common circuit with a power source module and a microcontroller.

3. Charger according to claim 2, wherein the common circuit has an oscillator.

4. Charger according to claim 2 or 3, wherein the common circuit has a sensor unit for voltage measurement and current measurement.

5. Charger according to one of the claims 1 to 4, wherein the charger has a duplicated circuit with a channel power amplifier.

6. Charger according to one of the claims 1 to 5, wherein the duplicated circuit has a channel power converter.

7. Charger according to one of the claims 1 to 6, wherein the duplicated circuit has a channel load demodulator.

8. Charger according to one of the claims 1 to 7, wherein the duplicated circuit has a sensor unit for voltage measurement and current measurement.

9. Chargeable wearable device, especially hearing instrument, which is designed to be chargeable by a charger according to one of the claims 1 to 8.

10. Charging system comprising a charger according to one of the claims 1 to 8 and two or more chargeable wearable devices according to claim 9.