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Automatic feedback control system for magnetic resonance charging

The invention concerns an automatic feedback control system for magnetic resonance (MR) charging.

Wireless charging of hearing aid devices has been proven viable by using near-field electromagnetic coupling between transmitter and receiver coils, located in the charger and hearing aid devices, respectively. To complete the entire charging process effectively, a robust and reliable automatic feedback control system is required. The control system preferably adapts the charging analogue system to external events, such as electromagnetic coupling and electrical loading variations. While there are several possible control system methodologies to employ, such approaches may not adequately fulfill overall requirements, which include feedback-data frequency, overshoots and undershoots, stability and accuracy. The main challenges of regulating magnetic resonance (MR) charging systems are the low frequency of data feedback (~1 second interval), highly dynamic coupling, and varying load profiles during the charging process of each hearing aid device.

Objectives of the present invention include, in particular, providing an improved hearing instrument, providing an improved charger and providing an improved method for charging a hearing instrument. A particular objective is to provide an improved circuit in a hearing instrument and/or charger for charging the hearing instrument with the charger. Further objectives can be derived from the following text.

One or several objectives are solved by the subject matter as claimed in the claims and as described in the following text. Further solutions and preferred embodiments are described in the following text as well.

General components

LM: Load modulation in-band communication protocol. Used to communicate charging relevant information from the magnetic resonance (MR) receiver coil to the MR transmitter coil by modulating the load at the receiver rectified voltage end. The loading modulation or variation, is sensed and demodulated at the transmitter side, and decoded to obtain the receiver's charging information. However, any other viable communication protocol can be used instead (e.g., Bluetooth, infrared, etc.).

Note that the feedback communication mechanism assumed in the present application is based on an existing Load Modulation (LM) protocol. Any other similar in-band or out-band communication protocol can be used instead.

DAC: Used to control the DC/DC converter, which determines the input voltage into the RF amplifier, connected to the transmitting coil. The voltage level control of the DC/DC converter, allows the RF amplifier to vary its output power, which in turn, controls the transmitting electromagnetic field levels.

Process: Sub-system mainly include the core components of the wireless power transfer system, such as RF amplifier, transmitting and receiving coils, charging controller and microcontroller on the receiver side.

Control systems, which are in principle suitable, are:

1) Look-up table based control system
2) PID control system

Look-up table based control system:

In such systems, an example of which is shown in Fig. 1, the error e(t) is obtained by comparing the V_{CC} reference value with the actual V_{CC} measured value $V_{cc}(t)$.

This error signal is used as input to a look-up table, where the compensating signal u(t) is selected to control the DAC, which in turn controls the input DC voltage level into the RF amplifier.

Typically, look-up table based control system are employed if the application is simple (e.g., binary actuation: ON/OFF) or requirements of the control system are relaxed or non-existent (e.g. over/undershoots, settling time, oscillation, perturbation, etc). In the case of MR charging system, the system presents a unique mix of challenges, namely low feedback data frequency, and a highly dynamic coupling and loading profile. This is exacerbated by the fact that the allowable tolerance of the V_{CC} is narrow: excessive V_{CC} margins could lead to communication loss, overheating, and reduced device performance, whereas insufficient V_{CC} margins could lead to persistent intermittent charging at certain coupling or loading situations.

Therefore, look-up based control systems are more suited for less complex and demanding systems, for example, closely and less varied inductively coupled charging system, or supported by higher feedback data frequency and less dynamic loading profiles.

PID based control system:

A classical PID controller based control system is based on three main components, namely Proportional (P), Integral (I) and Derivative (D), as illustrated in Fig. 2. By directly scaling the error signal, the Proportional controller is able to control the settling time by increasing or decreasing the proportional gain directly. However, large P values are known to introduce large overshoots or undershoots, which could destabilize the entire system. In addition, pure P controllers produce a steady-state error, meaning that the output oscillates steadily around the set value in a steady manner.

In the Integral controller, the error signal is summed up over time and scaled accordingly to give the accumulated offset that should have been corrected previously. This correction, based on the past values, allows the controller to

eliminate the residual steady-state error that occurs in P controllers. However, excessive accumulated errors could lead to overshoot or undershoot outcomes.

To compensate future errors, the Derivative controller determines the slope of the error over time and scales accordingly to give the required derivative offset. However, the usefulness of derivative controller is limited as the real-world input disturbances cannot be simplistically modelled and compensated.

While positive errors can be addressed by the PID controller (e.g., V_{CC} output is lower than a V_{CC} setpoint = undershoots = compensate system to have the next V_{CC} output instance to be lower than the V_{CC} setpoint) by increasing u(t) and DAC outputs, negative errors or overshoots may not be addressed. In such overshoot cases, the resultant u(t) would be decreasing and could become negative, which results in the inactivation of the transmitting circuitry or termination of load modulation communication. While saturation limits may be able to clamp the negative u(t) to zero or a low value, the worst case is that such corrective action could still cause intermittent charging issues for corner cases.

Magnetic Resonance (MR) power transfer is a wireless power transfer solution in which both the transmitter and the receiver are tuned to the same resonance frequency, at least within a certain threshold range. In particular, MR is a type of contactless (inductive or capacitive) power transfer. The MR power transfer has the benefits of high efficiency when the transmitter and the receiver are loosely coupled. As such, the MR power transfer is preferably applied as a wireless charging approach for a hearing instrument to cater to a wide range of hearing instrument products with different form factors.

The effectiveness of the classical PID controller is dependent on the feedback time interval. In the case of MR charging, feedback data is expected once every second. This would mean that the Integral controller would take a substantial amount of time to gather sufficient past error data, to bring the system to the desired steady state. Considering the MR charging system case, during the initial time period the dominant controller is the P controller, which presents the design

dilemma as described earlier. In short, the MR charging system – controlled by PID controller – is challenging to be tuned and could limit the charging system to certain coupling or loading ranges, in order to achieve stability.

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

Fig. 1 Block diagram of closed loop control with lookup table implementation,

Fig. 2 Block diagram of closed loop control with PID controller implementation,

Fig. 3 DC/DC buck converter circuit with fixed internal feedback circuit,

Fig. 4 Class E power amplifier with resistive output tuning, and π-filter input,

Fig. 5 Block diagram of closed loop control with modified P controller implementation,

Fig. 6a V_{CC} versus u(t) for coupling, k = 0.025,

Fig. 6b V_{CC} versus u(t) for coupling, k = 0.045,

Fig. 6c V_{CC} versus u(t) for coupling, k = 0.065,

Fig. 6d V_{CC} versus u(t) for coupling, k = 0.085,

Fig. 7 Control system response for Kp = 0.04,

Fig. 8 Control system response for Kp = 0.10,

Fig. 9 Control system response for Kp = 0.07.

The present invention comprises a controller (Modified P controller) taking a similar approach as the pure Proportional controller (e.g., as described above). The invention makes use of the inclusion of an initial controller output (u(t0)) which allows the designer to set the starting compensation point, according to the prior working knowledge of the known boundaries of the magnetic resonance (MR) charging system. Based on the dynamics of the process (e.g., coupling and loading variations), the appropriate P gain is determined. Overall, this invention allows the closed loop MR system to be easily tuned (inclusion of two variables: 1 P gain, 1 initial compensation) and quickly stabilize at the desired setpoint, with the known limitation of a 1-second feedback data interval and minimal risk of an intermittent (charging) process.

A working description of the preferred power regulation mechanism for AC excitation of the transmitter coil is found in a parallel application from the same applicant filed on the same day as the present application and titled “Automatic power controlled Magnetic Resonance Charger System for multiple devices”. Briefly, the amount of the transmitter coil power is controlled by regulating the output and input voltage ratio of the DC/DC buck converter, e.g., as shown in Fig. 3. While the input voltage is assumed to be fixed at 5 V (i.e., USB applications), the output voltage is controlled by adjusting the feedback input voltage to the buck converter. In the subsequent detailed description of the control system, this feedback voltage is designated as discrete time-varying signal u(t). The DAC of the control system converts the discrete signals into respective voltages according to the reference voltage and at a pre-selected DAC resolution.

While the DC/DC buck converter largely controls the transmitter coil power, a DC/AC power conversion is preferably used to excite the transmitter coil to enable the electromagnetic power transfer. In the MR charging system, class E amplifier with resistive output tuning is preferably selected, e.g., as shown in Fig. 4. The class E amplifier takes the AC oscillation signal (as driver signal) to convert the regulated input DC power into output AC power, which is fed. in particular directly. to the transmitter coil and resonance circuit. Another key advantage of the class E

amplifier is the use of a resonance operation which enables a small DC input voltage to be amplified as a large AC output voltage.

Back to the control system portion, the block diagram of a preferred embodiment of the modified P controller implementation is shown in Fig. 5. The error signal e(t) is computed based on the V_{CC} feedback via BLE (Bluetooth Low Energy), with reference to the setpoint (in particular the V_{CC} setpoint). The error signal is processed with a proportional gain, Kp, and is fed into 2-data accumulator loop (where the past (u(t-1)) or initial (u(t=0)) controller output are summed). The output of this loop is fed as u(t) into the DAC, which produces the required analogue voltage to control the process accordingly. In the next time instance of the V_{CC} feedback, this loop repeats itself until reaching the desired setpoint.

The crux of effectively controlling an MR charging system is that the overshoots and undershoots must be managed within a known range, in order for the load modulation communication to function properly. This challenge is effectively met by the two variables of the control system described here: Kp and u(t=0). Under open loop conditions (i.e., DAC with process only), the system or process behavior can be modelled or measured. Based on the desired V_{CC} output and known operating boundaries (in terms of coupling and loading levels), the designer will be able to select the most likely and possible resultant controller output, to be initially assigned as u(t=0). The proportional gain Kp works well with the 2-data accumulator to provide a simple and effective compensating action. This three-step approach results in a control system that is easily designed and produces effective results for the MR charging system.

To illustrate the tuning process, u(t=0) is preferably determined using a simulation model of the open loop system (e.g., DAC + process). A suitable simulation model's results is shown in Figs. 6a – d. The process transfer functions are preferably linearly estimated and are shown in Fig. 6a – d. In addition, this result gives the designer insight on the most probable u(t=0), while remaining strictly within the V_{CC} working boundaries for LM communications. In this case, with the desired setpoint of for example 5.2 V, u(t=0) can be suitably set at 0.6.

Next, to determine the gain Kp, an iterative process is preferably employed. In general, the maximum and minimum initial V_{CC} levels are defined, e.g., as 10 V and 4 V, respectively. In an example, Kp is set to be 0.04 and the corresponding control system response is found in Fig. 7. While there are no critical undershoots or overshoots, the Kp of 0.04 is deemed too low, as the settling time is more than 10 seconds. Kp gain needs to be further increased in the next iteration.

In the next iteration, Kp is exemplarily set to be 0.10 and the control system response is found in Fig. 8. While the sluggish settling time was reduced significantly, the maximum initial V_{CC} shows a critical undershoot below 4 V, due to the excessive Kp gain. This would disrupt load modulation communication and cause the MR charging system to be intermittent. To mitigate critical undershoot or overshoot, the Kp gain will be lowered in next iteration.

In the last iteration, Kp was exemplarily set to be 0.07 and the control system response is found in Fig. 9. No critical undershoots or overshoots are detected, and the settling times for both maximum and minimum V_{CC} levels are within 7 seconds.

In this abbreviated and exemplary illustration of the preferred Kp tuning process, coupling of 0.045 was considered only. With the use of a computer script (i.e., program), this tuning approach is preferably scaled up to include other coupling levels in order to achieve stable and fast settling controller responses.

In addition, as the MR charging system is based on electromagnetic power transfer from the transmitter coil to the receiver, there are many possible paths and entry points for noise to be introduced into the control system. As such, it is preferred to introduce an allowable V_{CC} margin, to prevent any unwanted perturbations destabilizing the control system. In this case, at various operating conditions, the open loop system is preferably used to gather V_{CC} time-varying data. In the case of MR charging system, a ±100 mV margin is sufficient and preferred to mask such unwanted noise.

The main challenge statement for an MR charging system is that it provides relatively slow and discrete feedback data, while requiring fast settling times with strict boundaries of V_{CC} (in order for feedback mechanism to remain viable). PID control systems are well-established control concepts, but their tuning processes to optimize to the specific application remains challenging, complex and tedious. The inventive control system proposed here aims to resolve this complexity, using the basis of a strong understanding of MR charging systems (e.g., a full functioning simulation model) to comprehensively understand its behavior and to implement key control parameters of the proposed control system.

While it may be argued that the control system proposed here may not be as widely applicable as the PID control concept, the key enabler for such an efficient and effective control system is the comprehensive understanding of the process (or, MR charging system in this application). Without this, it may not be feasible to apply the proposed control system, and instead may require a PID controller along with its tedious and complex tuning processes.

I principle, a PID controller may be used for a closed loop system. In a corresponding charging application, the coupling range is deemed much narrower than MR charging system. This narrow variation of coupling eases the tuning of the PID controller, as the transfer function of such closely coupled process is much more deterministic.

In addition, an input impedance measurement may be used to determine, if the constant current charging phase has completed. The main objective of such a control scheme is to determine if the load (which is charging of a rechargeable battery) has completed the constant current charging phase, whereby the charging system will terminate charging. However, this does not cover all phases of a battery charging application, where the typical charging of lithium-ion based rechargeable battery cells involves termination of charging after completion of constant voltage charging phase and pre-charging phase if the battery voltage is lower than typical range.

The features and embodiments described in this application and in connection with the figures are not restricted to the specific combinations and values as described and shown 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. Charging system, in particular magnetic resonance (MR) charging system for use with a hearing instrument, in particular hearing aid.

2. Charging system according to claim 1,
comprising a control system (also denoted as “controller”) with a modified P controller implementation,
wherein the control system is configured to
compute an error signal e(t) based on a V_{CC} feedback with reference to a setpoint,
process the error signal with a proportional gain Kp,
feed the error signal into a 2-data accumulator loop, an output of this loop is fed as u(t) into a DAC, which produces an analogue voltage, for controlling, said loop repeating itself until reaching the setpoint.

3. Method of operating a charging system according to claim 1 or 2.

4. Method of designing and/or tuning a charging system.

5. Method according to claim 3,
wherein overshoots and undershoots of the charging system are managed within a known range by two variables of a control system, namely proportional gain Kp and u(t=0),
wherein under open loop conditions the charging system is modelled or measured,
wherein, based on a desired V_{CC} output and/or known operating boundaries (e.g., in terms of coupling and loading levels), a most likely and possible resultant controller output is selected to be initially assigned as u(t=0).

6. Hearing instrument system, comprising a hearing instrument and a charging system for charging the hearing instrument.