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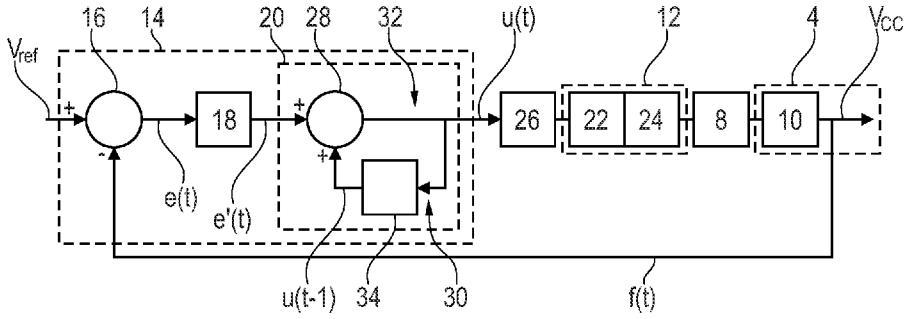


Fig. 2

(57) Abstract: System with a hearing device and a charger, charger, method of tuning a charger and computer program product A System (2) is described, comprising a hearing device (4) and a charger (6) for charging the hearing device (4), wherein the charger (6) comprises a transmitter module (8) for wireless transmission of power to the hearing device (4), a drive circuit (12), which is configured to control the power transmitted with the transmitter module (8) in dependence from a control signal (u(t)), a control system (14), comprising a combiner (16) for computing an error signal (e(t)) from feedback data (f(t) from the hearing device (4) and a reference value (Vref), a proportional element (18) for applying a proportional gain (Kp) to the error signal (e(t)) to obtain a modified error signal (e'(t)), an accumulator loop (20) for computing the control signal (u(t)) from the modified error signal (e'(t)) and an offset value, which is a previous value (u(t-1)) of the control signal (u(t)). In addition, a corresponding charger (6) is described as well as a method for tuning such a charger (6) and a computer program product.

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System with a hearing device and a charger, charger, method of tuning a charger and computer program product

The invention concerns a system, comprising a hearing device and a charger for charging the hearing device, a corresponding charger, a method of tuning a charger for such a system and a computer program product, in particular for implementing the method.

A hearing device is generally used to output sound signals to a user of the hearing device. A particular example of a hearing device is a hearing aid, which aids a user who has a hearing deficit by compensating said deficit. A hearing aid is in general designed to record sound signals from the environment, to process them and finally to output them in a modified (i.e. typically amplified) manner in such a way that the hearing deficit is at least partially compensated for. Other examples of hearing devices are headphones.

In general, a hearing device is a mobile device with its own, separate power supply, e.g., in form of a battery, which is part of the hearing device. The battery may be recharged once it is depleted. Recharging may be achieved by connecting the hearing device to a suitable power outlet. However, wireless charging is typically preferred in current and future mobile device applications. Apart from being more convenient than cable-based charging, wireless charging has the benefit of complete galvanic separation between the charger and the mobile device, thereby enabling a corrosion-proof operation of the mobile device. Here, “corrosion-proof” is understood to mean that the mobile device can be used and charged in a harsh environment due to it being completely sealed. Wireless charging also has aesthetic benefits, since no contact pins are exposed to the outside. Wireless charging also allows the mobile device to be charged with a somewhat higher degree of freedom of alignment relative to a charger as compared to contact-based charging as said contacts must be correctly aligned for successful charging. This provides a larger design freedom with respect to the mechanical design of the mobile device and the corresponding charger. All these benefits are particularly useful for hearing devices, which are regularly exposed to harsh conditions while worn in or around the user’s ear and

which may come in a variety of form factors (i.e., sizes and shapes) designed to fit various users.

Wireless charging of a hearing device is generally viable by using near-field electromagnetic coupling between transmitter and receiver coils, located in the charger and the hearing device, respectively. To complete the entire charging process effectively, a robust and reliable automatic feedback control system is required. Such a control system preferably adapts the charging system to external events, such as electromagnetic coupling and electrical loading variations. When selecting a system methodology for implementation in a charger, it is desirable that overall requirements are fulfilled, which include feedback-data frequency, overshoots and undershoots, stability and accuracy. In particular with respect to a magnetic resonance system for charging, the main challenges are a low frequency of data feedback on the order of 1 second intervals, a highly dynamic coupling and varying load profiles during the charging process of a hearing device.

Given the above observations, it is an object of the present invention to improve charging of a hearing device with a charger. In particular, the charger's design and tuning shall be as simple as possible. To achieve this, an improved system with a hearing device and a charger shall be presented as well as a charger and a method of tuning a charger. In addition, a corresponding computer program product shall be presented.

One or several of the objects mentioned herein are achieved according to the invention by a system with the features according to claim 1, by a charger with the features according to claim 8, by a method with the features according to claim 9 and by a computer program product with the features according to claim 11. Advantageous configurations, developments and variants are subject of the dependent claims as well as the following description. The statements in connection with the system also apply mutatis mutandis to the charger, the method and the computer program product and vice versa. Advantageous configurations for the system and the charger result from these being configured to carry out one or more of the method's steps, preferably by means of a control unit or control system, which is part of the system or charger. Advantageous configurations for the computer

program product result from that this comprises instructions which, when the program is executed by a computer, cause the computer to carry out one or several of the steps as described in the following.

The system comprises a hearing device and a charger for charging the hearing device. The hearing device preferably is a hearing device comprising one or several of the features described in the introduction above. The charger comprises a transmitter module for wireless transmission of power to the hearing device during charging. Correspondingly, the hearing device comprises a receiver module, for wirelessly receiving power from the charger during charging and provide a corresponding a supply voltage at the hearing device. In particular, the transmitter module and the receiver module each comprise a respective transmitter and receiver coil for wireless power transmission.

The hearing device is a mobile device with its own, separate power supply, preferably a secondary battery, which is charged during charging. The charging occurs wirelessly, i.e. the hearing device and the charger are configured for wireless charging. In general, however, the details of the hearing device are not important here, of particular concern are primarily the constraints and demands imposed by this particular application context.

The charger further comprises a drive circuit, which is configured to control the power transmitted with the transmitter module in dependence from a control signal. Said control signal is provided as an input signal to the drive circuit. Here and in the following, the term “signal” is preferably understood to mean a voltage signal, i.e. a voltage. The control signal defines the power transmission from the charger to the hearing device and the supply voltage at the hearing device.

To generate the control signal, the charger comprises a control system (long: “automatic feedback control system”, short: “controller”), which in turn comprises a combiner (i.e. first combiner) for computing an error signal from feedback data from the hearing device and a reference value (in particular: reference voltage). The control system further comprises a proportional element for applying a proportional gain to the error signal to obtain a modified error signal and an accumulator loop for

computing the control signal from the modified error signal and an offset value, which is a previous value of the control signal, in particular a running previous value. In other words: the control system implements a modified P-control scheme by first applying a proportional gain and second by applying an offset (the offset value) which is derived from the control signal itself. Hence, the accumulator loop is also a feedback loop, feeding back the control signal to affect itself. However, the control signal is not fed back instantaneously, but instead is delayed, such that the control signal is influenced by its past. In other words: a delayed version of the control signal is fed back and added to the modified error signal. Basically, the accumulator loop repeats the described operation until the reference value is reached, which is a desired setpoint for the supply voltage at the hearing device.

The control signal is, thus, defined as follows:

$$u(t) = K_p \times e(t) + u(t\text{-}1) = e'(t) + u(t\text{-}1),$$

wherein the control signal $u(t)$ is a function of time t, K_p is the proportional gain, $e(t)$ is the error signal, $e'(t)$ is the modified error signal $u(t\text{-}1)$ is the previous value of the control signal at time $t\text{-}1$.

A working description of a preferred drive circuit (in particular: power regulation mechanism) for AC excitation of the transmitter module is found in the yet unpublished parallel Singaporean patent application no. 10202109496P, incorporated herein by reference, filed on August 30, 2021, from the same applicant. Briefly, the transmitter coil power is controlled in the charger by regulating an output and input voltage ratio of a DC/DC converter (e.g. buck converter). While the input voltage, which may be the same as the reference voltage mentioned above, is assumed to be fixed at, e.g., 5 V (i.e., USB applications), the output voltage is controlled by adjusting a feedback signal put into the DC/DC converter. The control signal described above is used as the feedback signal. The control signal preferably is a digital signal, which is converted by a DAC (digital-to-analog converter) of the charger into respective voltages according to a reference voltage and at a pre-selected DAC resolution before being input to the DC/DC converter. While the DC/DC converter largely controls the transmitter coil power, a DC/AC power converter (which is part of an RF amplifier) is preferably used for power conversion to excite the transmitter coil to enable the electromagnetic power transfer to the

hearing device. Preferably, a class E amplifier with resistive output tuning is used as the DC/AC power converter, in particular in the case of magnetic resonance charging. The class E amplifier uses an AC oscillation signal as a driver signal to convert the digital DC control signal, i.e. the output voltage, from the DC/DC converter into an output AC signal, which is fed to the transmitter coil of the transmitter module. A key advantage of the class E amplifier is the use of a resonance operation which enables a small DC input signal to be amplified as a large AC output signal. However, the details of the drive circuit are not important here. The focus of the present application is the control system.

The feedback data from the hearing device indicates to the charger, if and to what extent an adjustment is necessary in order to adjust the supply voltage towards the reference voltage. The charger's transmitter module is supplied with power to be transmitted to the hearing device, wherein the amount of said power is controlled by the control signal. The hearing device typically receives only a fraction of said power, depending on the coupling between the charger and the hearing aid, said coupling being characterized by a coupling factor, which is usually denoted in the range from 0 to 1. The coupling may vary, such that an adjustment of the transmitted power is necessary, with the aim to obtain a particular supply voltage at the hearing device. The charger has no direct knowledge of the coupling and, hence, feedback data is provided from the hearing device to the charger to facilitate appropriate control of the control signal and, thereby, achieve a desired supply voltage at the hearing device. In an advantageous embodiment the feedback data comprises said supply voltage at the hearing device. In particular, the supply voltage is measured by the hearing device. The supply voltage is used by the combiner for computing the error signal by simply adding the supply voltage to the reference value.

In an advantageous embodiment, the system is configured to transmit the feedback data from the hearing device to the charger via load modulation. Load modulation is an in-band communication protocol used to communicate charging relevant information (data) from the receiver module to the transmitter module by modulating the load at the receiver module's end (more precise: the receiver modules rectified voltage end). In other words: the transmitter module and the receiver module are also used to transmit data from the hearing device to the charger. To achieve this,

the hearing device encodes the data by modulating the load to the receiver module and thereby the received power. The load modulation (or variation), is sensed at the transmitter module and demodulated (i.e. decoded) to extract the data and obtain the hearing device's charging information, in particular the feedback data. In the alternative, any other viable communication protocol (in-band or out-of-band) can be used instead of said load modulation (e.g., Bluetooth, infrared, etc.).

In a suitable embodiment, the accumulator loop comprises a second combiner and a feedback path. The second combiner comprises a first input for the modified error signal and a second input for the offset value. The second combiner outputs (via an output) the control signal onto a forward path towards the transmitter module. The feedback path starts from this forward path and ends at the second combiner, such that the control signal is fed from the output of the second combiner back to its second input. The feedback path, then, comprises a delay element, which delays the control signal, such that at a given point in time, a delayed version of the control signal is received at the second combiner. Hence the term "accumulator loop", since it accumulates the control signal for later use. Preferably, the delay element is a buffer.

In a preferred embodiment, the control system is configured to use a starting value (also: initial control system output) as the offset value during a start-up when no previous value of the control signal is available. This acknowledges the fact, that during start-up of the system, i.e. at the beginning of the charging, no history of the control signal is available, i.e. no previous value exists. For that reason, a predetermined starting value is used instead. Also, the starting value allows during tuning of the charger to set a starting compensation point, according to the prior working knowledge of known boundaries of the system, in particular in the case of a magnetic resonance charging system.

The starting value and the proportional gain are design factors of the charger, which are preferably chosen and set during tuning of the charger (in particular during manufacture).

In an advantageous embodiment, the previous value of the control signal is obtained by delaying the control signal by a fixed amount of time, also designated as “delay”. Hence, the delay imposed to the control signal via the feedback path does not vary, but is fixed. In principle, said delay may also be considered as a design factor.

In a suitable embodiment the control signal is a digital signal (i.e. a discrete time-varying signal) sampled at a clock rate and at any given clock cycle the previous value of the control signal corresponds to the control signal’s value at the preceding clock cycle. The clock rate is preferably implemented by a clock signal provided by a clock circuit of the charger. Preferably, given a current clock cycle, e.g. cycle number t, the preceding clock cycle is that clock cycle which immediately precedes the current clock cycle, i.e. cycle number t-1. This may be achieved by a simple one-value buffer as the delay element, said one-value buffer only storing a single value, namely the value of the control signal at a current clock cycle (t), and releasing it (to the second combiner) upon the following clock cycle (t+1), while at the same time storing the next value of the control signal.

In a preferred embodiment the system is configured for magnetic resonance (MR) charging, i.e., the hearing device and the charger are configured for MR charging. MR charging is a special case of wireless charging and particularly benefits from the invention described here. MR charging is a solution in which both the transmitter module and the receiver module are tuned to the same resonance frequency, at least within a certain threshold range, e.g., 5 % of the resonance frequency. MR charging is also contactless and features the corresponding benefits. MR charging may be inductive or capacitive, wherein inductive resonance charging is preferred here. A power transfer based on MR charging has the benefits of a still high efficiency when the transmitter module and the receiver module are only loosely coupled, i.e. a wide range of coupling factors can be served. Therefore, the choice of MR charging has the following benefits: 1) a different form factor between transmitter module and receiver module is possible, 2) a large wireless charging distance (or gap) compared to the radius of the coils of the transmitter module and the receiver module is possible, 3) a large tilt angle of the transmitter module relative to the receiver module is possible, and 4) a low heat dissipation at the receiver module during charging is achieved. As such, MR charging is particularly suitable for a

hearing device application, to cater to a wide range of hearing device products, potentially with different form factors.

The invention is based on the notion, that regular look-up table based control systems or PID control systems have various disadvantages with respect to the particular use case of charging a hearing device as assumed here. For example, in a system based on look-up tables, the error signal may be obtained by comparing the reference value with the feedback data (supply voltage). This error signal is used as an input to a look-up table, where the control signal is selected to control the DAC, which in turn controls the input voltage level into the RF amplifier. A look-up table based control system may be suitable if the application is simple (e.g., binary actuation: ON/OFF) or requirements such as over-/undershoots, settling time, oscillation, perturbation etc. of the control system are relaxed or non-existent. In particular in the case of a MR charging system as preferred here, 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 received voltage is narrow: excessive received voltage margins could lead to communication loss, overheating, and reduced hearing device performance, whereas insufficient received voltage 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 than the one described here, e.g., closely and less varied inductively coupled charging system, or supported by higher feedback data frequency and less dynamic loading profiles.

A system based on a classical PID controller, then, comprises three main components, namely proportional (P), integral (I) and derivative (D) elements. By directly scaling the error signal, the proportional element is able to control the settling time by increasing or decreasing the proportional gain directly. However, large P values typically 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 element, the error signal is summed up over time and scaled accordingly to provide the accumulated offset that should have been corrected

previously. This correction, based on the past values, allows the PID controller to eliminate the residual steady-state error that occurs in pure P controllers. However, excessive accumulated errors could lead to overshoot or undershoot outcomes. To compensate future errors, the derivative element determines the slope of the error over time and scales accordingly to give the required derivative offset. However, the usefulness of a derivative element is limited as the real-world input disturbances cannot be simplistically modelled and compensated.

While positive errors can be addressed by a PID controller (e.g., the supply voltage is lower than the setpoint) by increasing the control signal, negative errors or overshoots may not be addressed. In such overshoot cases, the resultant control signal would be decreasing and could become negative, which results in the inactivation of the transmission module or termination of load modulation for data transfer. While saturation limits may be able to clamp the negative control signal to zero or a low value, the worst case is that such corrective action could still cause intermittent charging issues for corner cases. Moreover, the effectiveness of a classical PID controller is dependent on the feedback data rate. In the case of MR charging, feedback data is expected at a rate between once every 5 seconds to 5 times per second, e.g., once every second. This means that the integral element would take a substantial amount of time to gather sufficient past error data, to bring the system to a desired steady state. Considering the MR charging system case, the dominant element during the start-up time is the P element, which presents a design dilemma. In short, the MR charging system – controlled by PID controller – is challenging to be tuned and limits the charging system to certain coupling or loading ranges, in order to achieve stability.

The present invention overcomes these problems by the special control system, which is a modified version of a classical proportional controller, thereby taking a similar, yet different approach as the pure proportional controller. Based on the dynamics of the process (e.g., coupling and loading variations), the appropriate proportional gain is determined. Also, the invention allows a closed-loop system, in particular MR system, to be easily tuned via only two variables (proportional gain and starting value) and quickly stabilize at the reference value with a limitation

regarding the feedback data rate and minimal risk of an intermittent charging process.

The main challenge, in particular for an MR charging system, is that it provides relatively slow and discrete feedback data, while requiring fast settling times with strict boundaries of the supply voltage (in order for the 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 the key design factors of the 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 as presented here is the comprehensive understanding of the charging process. 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, though, a PID controller may also be used for a closed-loop system at least in a non-MR charging application, in which the coupling range is typically much narrower than for MR charging. This narrow variation of coupling eases the tuning of the PID controller, as the transfer function of such a closely coupled process is much more deterministic.

In the method of tuning a charger for a system as described above, said system is in a first step simulated under open-loop conditions to obtain a first function, which relates the supply voltage at the hearing device to the starting value, and a second function, which describes the supply voltage at the hearing device over time. In a second step, the first function is then used to choose the starting value such that the supply voltage at the hearing device corresponds to the reference value, which is a predetermined setpoint. The reference value preferably is an operating voltage of the hearing device, optionally with an added safety margin of, e.g., 2 % to 5 %. The reference value is, e.g., 5 V. In a third step, the second function is used to choose the proportional gain such that the supply voltage at the hearing device does not exceed predetermined minimum and maximum values and has a minimum settling

time. The minimum value preferably is in the range of 50 % to 90 % of the reference value. The maximum value preferably is in the range of 150 % to 250 % of the reference value. The settling time indicates how fast the control system achieves adjusting the supply voltage to a desired value, e.g., the reference value. In particular, the settling time indicates the amount of time that the system needs to get the supply voltage to assume the reference value within a 5 %-accuracy. The settling time preferably is as low as possible, a settling time below 10 s is considered adequate. Preferably, the method is repeated for different values of the coupling factor, which – as already mentioned – characterizes the coupling between the transmitter module of the charger and a receiver module of the hearing device.

In particular, the method addresses the problem that for a more effective control of a system with a charger the overshoots and undershoots have to be managed at least within a predetermined range, in order for the load modulation to function properly. This problem is effectively met by the two design factors of the system described herein: namely the proportional gain and starting value. Under open-loop conditions, the system's behavior can be modelled or measured and subsequently simulated. Based on the desired supply voltage and known operating boundaries (in terms of coupling and loading levels), a designer (in particular a computer) will be able to select the most likely and possible resultant control signal, to be initially assigned as starting value. The proportional gain, then, works well with the accumulator loop 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, in particular for a system that uses MR charging.

To illustrate a suitable tuning process, the starting value is preferably determined using a simulation model of the open-loop system (e.g., the system without the feedback data). The resulting first function, which is also denoted as process transfer function, is preferably linearly estimated. In addition, this result gives the designer insight on the most probable starting value, while remaining strictly within working boundaries for the supply voltage, in particular boundaries required for load modulation. Next, the proportional gain is determined, preferably in an iterative process. In general, the maximum and minimum supply voltage levels are defined, e.g., as 10 V and 4 V, respectively. While there may be no critical undershoots or

overshoots for a given proportional gain, the proportional gain may nevertheless be deemed to be too low, which results in a long settling time, e.g. 10 seconds or more. Hence, the proportional gain is preferably further adjusted (in particular increased) in the next iteration and generally, until a suitable settling time has been found, all the time avoiding undershoots and overshoots. In this abbreviated and exemplary illustration of the tuning method, only a single coupling factor was considered. In particular with the use of a computer, this tuning approach is preferably scaled up to include other coupling factors in order to achieve a stable and fast settling control system response.

In addition, as the system is based on electromagnetic power transfer from the transmitter module to the receiver module, 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 margin for the supply voltage, to prevent any unwanted perturbations destabilizing the control system. In this case, at various operating conditions, the open-loop system is preferably used to record the received voltage as a function of time. In the case of an MR charging system, a ±100 mV margin is sufficient and preferred to mask such unwanted noise.

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 a typical range.

The entire method, including simulating the system as well as choosing the design factors (optionally for several different coupling factors), is preferably carried out with a computer. Correspondingly, the inventive computer program product comprises instructions which, when the program is executed by a computer, cause the computer to carry out the method as described above.

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

Fig. 1 a system with a charger and a hearing device,

Fig. 2 a block diagram of a closed-loop control with a modified P controller implementation,

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

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

Fig. 5 a block diagram of a closed-loop control with lookup table implementation,

Fig. 6 a block diagram of a closed-loop control with PID controller implementation,

Fig. 7 a method of tuning a charger,

Fig. 8a supply voltage versus control signal for a coupling factor k = 0.025,

Fig. 8b supply voltage versus control signal for a coupling factor k = 0.045,

Fig. 8c supply voltage versus control signal for a coupling factor k = 0.065,

Fig. 8d supply voltage versus control signal for a coupling factor k = 0.085,

Fig. 9 a control system response for a proportional gain of 0.04,

Fig. 10 a control system response for a proportional gain of 0.10,

Fig. 11 a control system response for a proportional gain of 0.07.

Fig. 1 shows an exemplary embodiment of a system 2 comprising a hearing device 4 and a charger 6 for charging the hearing device 4. Without loss of generality, the hearing device 4 shown here is a binaural hearing aid. The charger 6 comprises a transmitter module 8 for wireless transmission of power to the hearing device 4 during charging. Correspondingly, the hearing device 4 comprises a receiver module 10, for wirelessly receiving power from the charger 6 during charging and provide a corresponding a supply voltage V_{cc} at the hearing device 4. The system 2 shown here is configured for magnetic resonance (MR) charging, i.e., the hearing device 4 and the charger 6 are configured for MR charging.

The charger further comprises a drive circuit 12, which is configured to control the power transmitted with the transmitter module 8 in dependence from a control signal u(t), which is provided as an input signal to the drive circuit 12. Here and in the following, the term “signal” is understood to mean a voltage signal, i.e. a voltage. The control signal u(t) defines the power transmission from the charger 6 to the hearing device 4 and the supply voltage V_{cc} at the hearing device 4.

To generate the control signal u(t), the charger 4 comprises a control system 14 (also denoted as “automatic feedback control system” or “controller”), an example of which is illustrated in Fig. 2. The control system 14 comprises a first combiner 16 for computing an error signal e(t) from feedback data f(t) from the hearing device 4 and a reference value V_{ref}. The control system 14 further comprises a proportional element 18 for applying a proportional gain K_p to the error signal e(t) to obtain a modified error signal e’(t) and an accumulator loop 20 for computing the control signal u(t) from the modified error signal e’(t) and an offset value, which is a previous value u(t-1) of the control signal u(t), in particular a running previous value u(t-1). In other words: the control system 14 implements a modified P-control scheme by first applying a proportional gain K_p and second by applying an offset (the offset value) which is derived from the control signal u(t) itself. Hence, the accumulator loop 20 is also a feedback loop, feeding back the control signal u(t) to affect itself. However, the control signal u(t) is not fed back instantaneously, but instead is delayed, such that the control signal 14 is influenced by its past. In other words: a delayed version (here u(t-1)) of the control signal u(t) is fed back and added to the modified error signal e’(t). Basically, the accumulator loop 20 repeats the described operation until

the reference value V_{ref} is reached, which is a desired setpoint for the supply voltage V_{cc}.

A suitable drive circuit 12 for AC excitation of the transmitter module 8 is described in the following and comprises a DC/DC converter 22, e.g., as shown in Fig. 3 and a DC/AC power converter 24 (part of an RF amplifier, which is not shown), e.g., as shown in Fig. 4. The power to the transmitter coil (in the transmitter module 8) is controlled in the charger 6 by regulating an output voltage V_{out} and input voltage V_{in} ratio of the DC/DC converter 22. While the input voltage V_{in}, which may be the same as the reference voltage V_{ref}, is assumed to be fixed at, e.g., 5 V, the output voltage V_{out} is controlled by adjusting a feedback signal put into the DC/DC converter 22. The control signal u(t) described above is used as the feedback signal. In the embedment shown here, the control signal u(t) is a digital signal, which is converted by a DAC 26 of the charger 6 into respective voltages according to a reference voltage and at a pre-selected DAC resolution before being input to the DC/DC converter 22. While the DC/DC converter 22 largely controls the transmitter coil power, the DC/AC power converter 24 is used for power conversion to excite the transmitter coil to enable the electromagnetic power transfer to the hearing device. For example, a class E amplifier with resistive output tuning as shown in Fig. 4 is used as the DC/AC power converter 24. The class E amplifier uses an AC oscillation signal as a driver signal V_{dr} to convert the digital DC control signal V_{DC}, i.e. the output voltage V_{out}, from the DC/DC converter 22 into an output AC signal V_{AC}, which is fed to the transmitter coil of the transmitter module 8.

In Fig. 1, the drive circuit 12, the DAC 26 and the control system 14 are shown only once and connected to both transmission modules 8, however, they may be implemented twice to serve both transmission modules 8 independently.

The feedback data f(t) from the hearing device 4 indicates to the charger 6, if and to what extent an adjustment is necessary in order to adjust the supply voltage V_{cc} towards the reference value V_{ref}. The charger's transmitter module 8 is supplied with power to be transmitted to the hearing device 4, wherein the amount of said power is controlled by the control signal u(t). The hearing device 4 typically receives only a fraction of said power, depending on the coupling between the charger 6 and the

hearing aid 4, said coupling being characterized by a coupling factor k, which is usually denoted in the range from 0 to 1. The coupling may vary, such that an adjustment of the transmitted power is necessary, with the aim to obtain a particular supply voltage V_{cc} at the hearing device 4. The charger 6 has no direct knowledge of the coupling and, hence, feedback data f(t) is provided from the hearing device 4 to the charger 6 to facilitate appropriate control of the control signal u(t) and, thereby, achieve a desired supply voltage V_{cc}. In the example shown here, the feedback data f(t) comprises said supply voltage V_{cc}, which is measured by the hearing device 4 and used by the first combiner 16 for computing the error signal e(t). In the exemplary embodiment shown in Fig. 2 the system 2 is configured to transmit the feedback data f(t) from the hearing device 4 to the charger 6 via load modulation. In the alternative, any other viable communication protocol (in-band or out-of-band) can be used instead of said load modulation (e.g., Bluetooth, infrared, etc.).

In the exemplary embodiment shown in Fig. 2, the accumulator loop 20 comprises a second combiner 28 and a feedback path 30. The second combiner 28 comprises a first input for the modified error signal e'(t) and a second input for the offset value. The second combiner 28 outputs (via an output) the control signal u(t) onto a forward path 32 towards the transmitter module 8. The feedback path 30 starts from this forward path 32 and ends at the second combiner 28, such that the control signal u(t) is fed from the output of the second combiner 28 back to its second input. The feedback path 30, then, comprises a delay element 34, which delays the control signal u(t), such that at a given point in time, a delayed version u(t-1) of the control signal u(t) is received at the second combiner 28. The previous value u(t-1) of the control signal u(t) is obtained by delaying the control signal by a fixed amount of time, also designated as "delay". Here, the delay element 34 is a buffer. More precisely, the control signal u(t) is a digital signal sampled at a clock rate and at any given clock cycle the previous value u(t-1) of the control signal u(t) corresponds to the control signal's u(t) value at the preceding clock cycle, which here is that clock cycle which immediately precedes the current clock cycle. This is be achieved by a simple one-value buffer as the delay element 34, said one-value buffer only storing a single value, namely the value of the control signal u(t) at a current clock cycle (t), and releasing it (to the second combiner 28) upon the following clock cycle (t+1), while at the same time storing the next value of the control signal u(t).

In addition, the control system 14 shown here is configured to use a starting value u(0) (also: initial control system output) as the offset value during a start-up when no previous value u(t-1) of the control signal u(t) is available. The starting value u(0) as well as the proportional gain K_p are design factors of the charger 6, which are chosen and set during tuning of the charger 6.

For comparison, alternative approaches which are not part of the invention are shown in Fig. 5 and 6. For example, in a system 2 based on look-up tables as shown in Fig. 5, the error signal e(t) may be obtained by comparing the reference value V_{ref} with the supply voltage V_{cc}. This error signal e(t) is used as an input to a look-up table 36, where the control signal u(t) is selected to control the DAC 26, which in turn controls the input voltage level into the RF amplifier (not explicitly shown). A look-up table 36 based control system 14 may be suitable if the application is simple or requirements of the control system 14 are relaxed or non-existent. However, such a system presents a unique mix of challenges, namely low feedback data frequency, a highly dynamic coupling and loading profile and the fact that the allowable tolerance of the received voltage is narrow.

Fig. 6, then, shows a system 2 based on a classical PID controller 38, then, comprises three main components, namely proportional P, integral I and derivative D elements. While positive errors can be addressed by a PID controller 38 by increasing the control signal, negative errors or overshoots may not be addressed. Moreover, the effectiveness of a classical PID controller 38 is dependent on the feedback data rate, which at least in the case of MR charging, is expected about once every second. This means that the integral element I would take a substantial amount of time to gather sufficient past error data, to bring the system to a desired steady state. Considering the MR charging system case, the dominant element during the start-up time is the proportional element P, which presents a design dilemma. In short, it is challenging to tune the system and limit it to certain coupling or loading ranges, in order to achieve stability.

The special control system 14 described here is a modified version of a classical proportional controller. Based on the dynamics of the process (e.g., coupling and

loading variations), the appropriate proportional gain K_p is determined. Also, the invention allows the closed-loop system to be easily tuned via only two variables (proportional gain Kp and starting value u(0)) and quickly stabilize at the reference value V_{ref} with a limitation regarding the feedback data f(t) rate and minimal risk of an intermittent charging process.

Fig. 7 shows an exemplary embodiment of a method of tuning a charger for a system as described above. In the method, said system 2 is simulated in a first step S1 under open-loop conditions to obtain a first function F1, which relates the supply voltage V_{cc} at the hearing device 4 to the starting value u(0), and a second function F2, which describes the supply voltage V_{cc} over time t. The first function F1 is then used in a second step S2 to choose the starting value u(0) such that the supply voltage V_{cc} corresponds to a predetermined reference value V_{ref}, e.g., 5 V. The second function F2 is used in a third step S3 to choose the proportional gain K_p such that the supply voltage V_{cc} does not exceed a predetermined minimum value V_{min} and maximum value V_{max} and has a minimum settling time t_{set}. The minimum value V_{min} may be in the range of 50 % to 90 % of the reference value V_{ref}. The maximum value V_{max} may be in the range of 150 % to 250 % of the reference value V_{ref}. The settling time t_{set} indicates how fast the control system 14 achieves adjusting the supply voltage V_{cc} to a desired value, e.g., the reference value V_{ref}. Optionally the method is repeated for different values of the coupling factor k, which – as already mentioned – characterizes the coupling between the transmitter module 8 and the receiver module 10.

A possible embedment of the tuning process is further described in following and with reference to Fig. 8a – 8d and 9 – 11. The starting value u(0) is determined using a simulation model of the open-loop system 2 resulting in a first function F1 as shown in Figs. 8a – 8d, each showing the first function for a different coupling factor k. Said first function F1 is also denoted as process transfer function and is linearly estimated. This result gives the designer insight on the most probable starting value u(0), while remaining strictly within working boundaries for the supply voltage V_{cc}. Next, the proportional gain K_p is determined in an iterative process. In general, the maximum and minimum supply voltage levels V_{max}, V_{min} are defined, e.g., as 10 V and 4 V, respectively. In Fig. 9, a proportional gain K_p of 0.04 is chosen. While there

may be no critical undershoots or overshoots for this value of the proportional gain K_p, the proportional gain K_p is nevertheless be deemed to be too low, because it results in a long settling time t_{set} of 10 s. Hence, the proportional gain K_p is further increased to 0.10 in the next iteration as shown in Fig. 10. In this case, the previously sluggish settling time t_{set} is reduced significantly, however, the maximum initial supply voltage V_{CC} shows a critical undershoot below the minimum value V_{min} of 4 V, due to the excessive proportional gain K_p. This would disrupt load modulation and lead to intermittent charging behavior. To mitigate critical undershoots and overshoots, the proportional gain K_p is lowered again to 0.07 in the next iteration as shown in Fig. 11. No critical undershoots or overshoots are detected here, and the settling time t_{set} for both maximum and minimum supply voltage V_{CC} levels are within 7 s, which is deemed adequate.

List of references

2	system
4	hearing device
6	charger
8	transmitter module
10	receiver module
12	drive circuit
14	control system
16	first combiner
18	proportional element
20	accumulator loop
22	DC/DC converter
24	DC/AC power converter
26	DAC (digital-to-analog converter)
28	second combiner
30	feedback path
32	forward path
34	delay element
36	look-up table
38	PID controller
e(t)	error signal
e'(t)	modified error signal
F1	first function
F2	second function
D	derivative element
f(t)	feedback data
I	integral element
k	coupling factor
K_p	proportional gain
P	proportional element
t	time
t_{set}	settling time
u(0)	starting value

u(t)	control signal
u(t-1)	previous value (of the control signal), delayed version
V_{AC}	output AC signal
V_{cc}	supply voltage
V_{DC}	DC control signal
V_{dr}	driver signal
V_{in}	input voltage (to DC/DC converter)
V_{max}	maximum value
V_{min}	minimum value
V_{out}	output voltage (from DC/DC converter)
V_{ref}	reference value

Claims

1. System (2),

   comprising a hearing device (4) and a charger (6) for charging the hearing device (4),

   wherein the charger (6) comprises

   – a transmitter module (8) for wireless transmission of power to the hearing device (4),

   – a drive circuit (12), which is configured to control the power transmitted with the transmitter module (8) in dependence from a control signal (u(t)),

   – a control system (14), comprising

   - a combiner (16) for computing an error signal (e(t)) from feedback data (f(t) from the hearing device (4) and a reference value (V_{ref}),
   - a proportional element (18) for applying a proportional gain (K_p) to the error signal (e(t)) to obtain a modified error signal (e'(t)),
   - an accumulator loop (20) for computing the control signal (u(t)) from the modified error signal (e'(t)) and an offset value, which is a previous value (u(t-1)) of the control signal (u(t)).

2. System (2) according to claim 1,
   wherein the control system is configured to use a starting value (u(0)) for the offset value during a start-up when no previous value (u(t-1)) of the control signal (u(t)) is available.

3. System (2) according to claim 1 or 2,
   wherein the previous value (u(t-1)) of the control signal (u(t)) is obtained by delaying the control signal (u(t)) by a fixed amount of time (t).

4. System (2) according to one of claims 1 to 3,
wherein the control signal (u(t)) is a digital signal sampled at a clock rate and at any given clock cycle the previous value (u(t-1)) of the control signal (u(t)) corresponds to the control signal's (u(t)) value at the preceding clock cycle.

5. System (2) according to one of claims 1 to 4,
which is configured for magnetic resonance charging.

6. System (2) according to one of claims 1 to 5,
wherein the feedback data (f(t)) comprise a supply voltage (V_{CC}) at the hearing device (4) for computing the error signal (e(t)).

7. System (2) according to one of claims 1 to 6,
which is configured to transmit the feedback data (f(t)) from the hearing device (4) to the charger (6) via load modulation.

8. Charger (6) for a system (2) according to one of claims 1 to 7.

9. Method of tuning a charger (6) for a system (2) according to one of the claims 2 to 7,
   - wherein the system (2) is simulated under open-loop conditions to obtain a first function (F1), which relates a supply voltage (V_{cc}) at the hearing device (4) to the starting value (u(0)), and a second function (F2), which describes the supply voltage (V_{CC}) over time (t),
   - wherein the first function (F1) is used to choose the starting value (u(0)) such that the supply voltage (V_{CC}) corresponds to the reference value (V_{ref}),
   - wherein the second function (F2) is used to choose the proportional gain (K_p) such that the supply voltage (V_{CC}) does not exceed predetermined minimum and maximum values (V_{min}, V_{max}) and has a minimum settling time (t_{set}).

10. Method according to claim 9,
wherein the method is repeated for different values of a coupling factor (k), said coupling factor (k) characterizing the coupling between the transmitter module (8) of the charger (6) and a receiver module (10) of the hearing device (4).

11. Computer program product comprising instructions which, when the program is executed by a computer, cause the computer to carry out the method of claim 9 or 10.

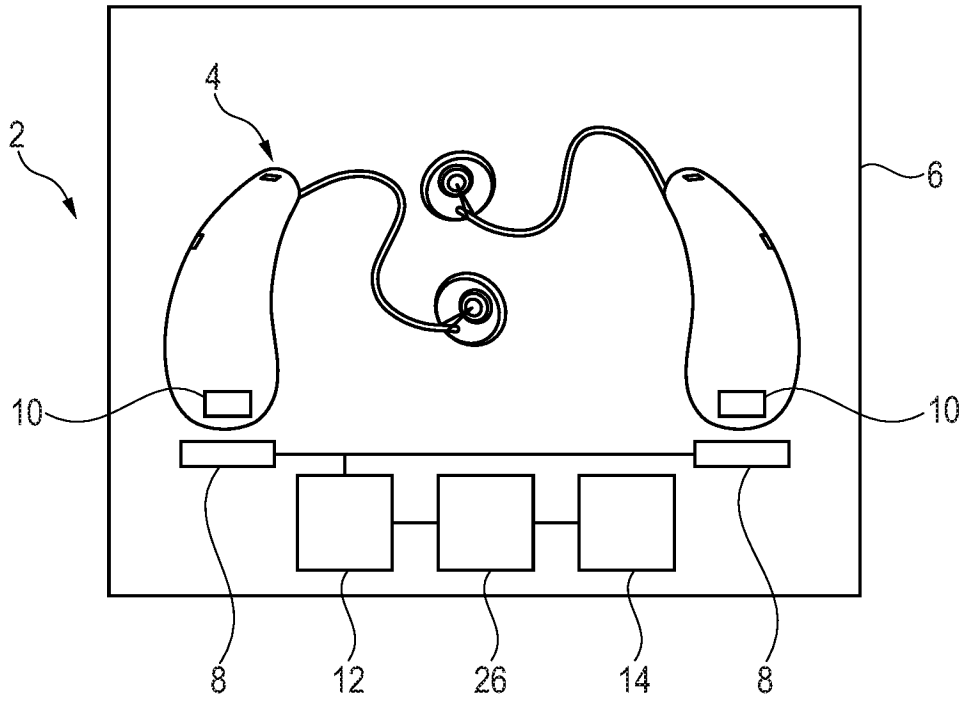

2
4
6
10
10
8
12
26
14
8

Fig. 1

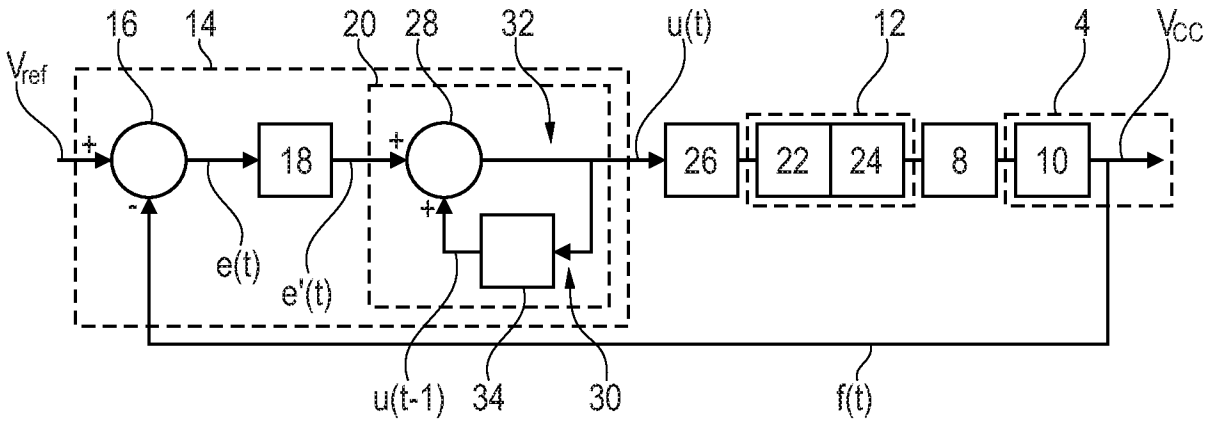

16
14
20
28
32
u(t)
12
4
Vcc
Vref
+
-
18
+
+
26
22
24
8
10
e(t)
e'(t)
u(t-1)
34
30
f(t)

Fig. 2

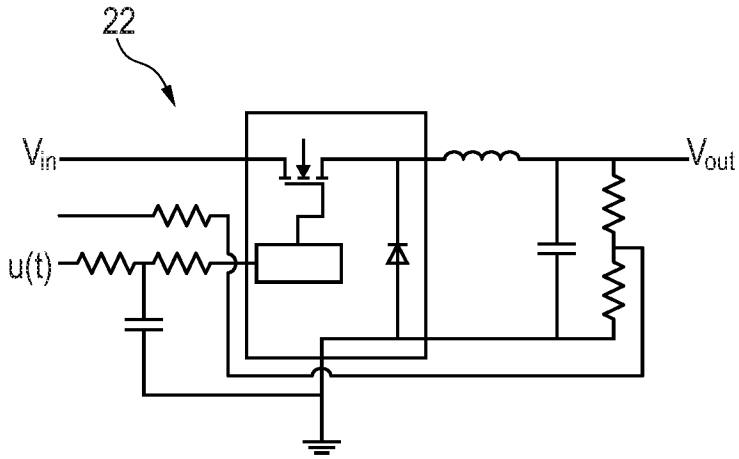


Fig. 3

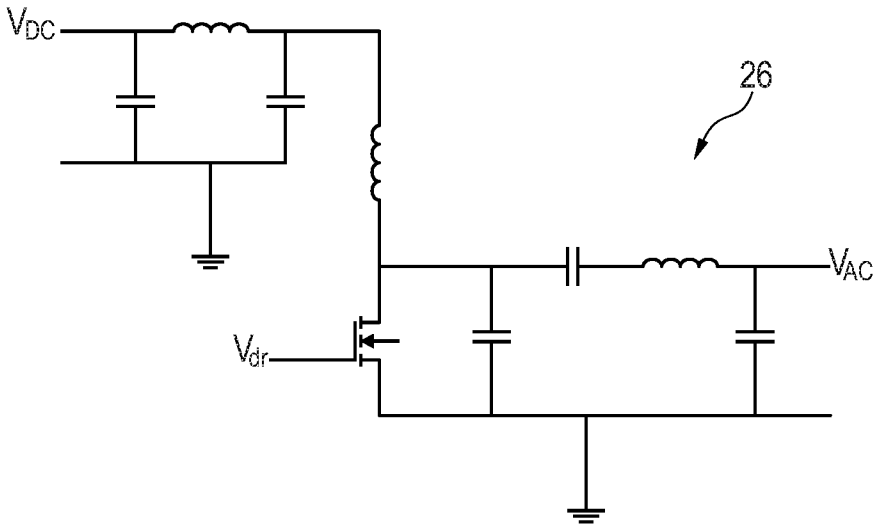


Fig. 4

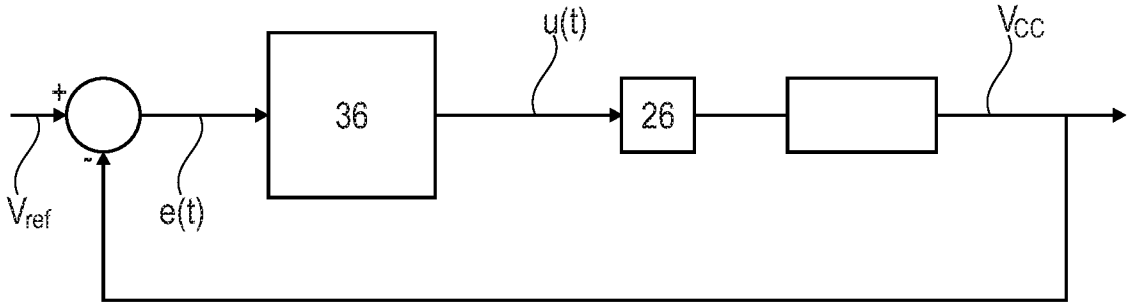


Fig. 5

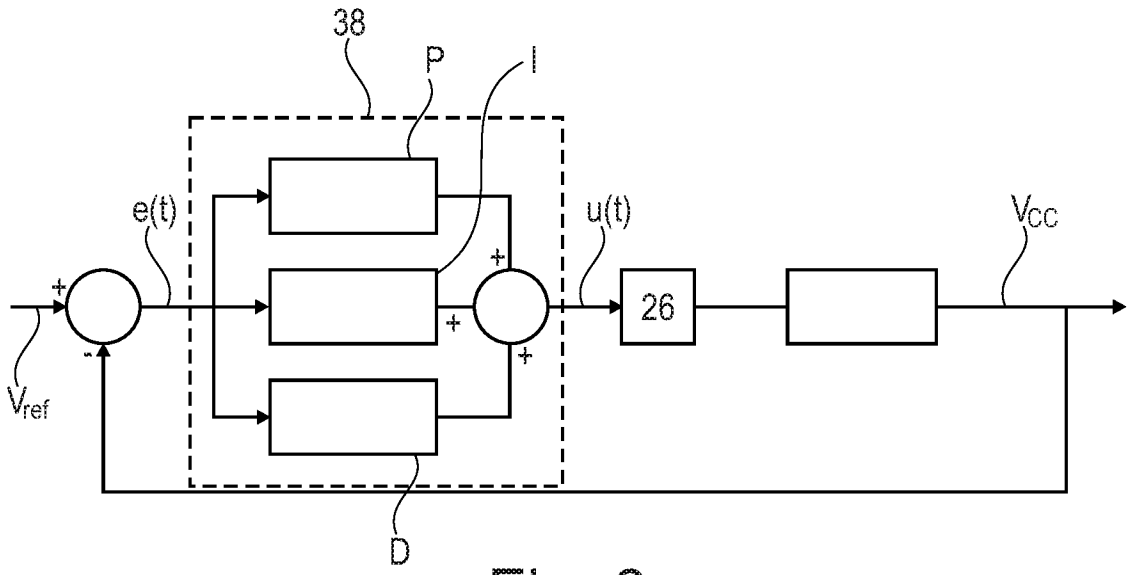


Fig. 6

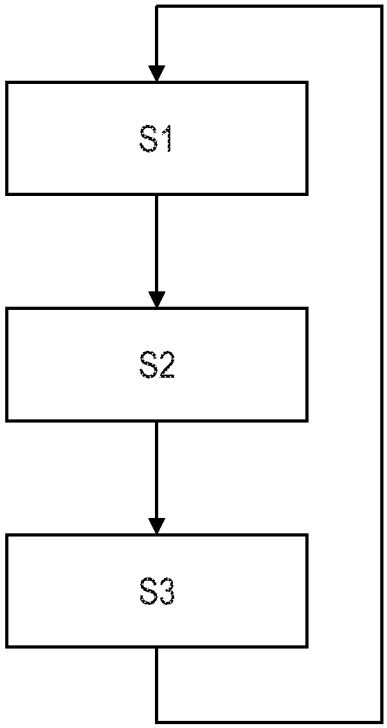

S1
S2
S3

Fig. 7

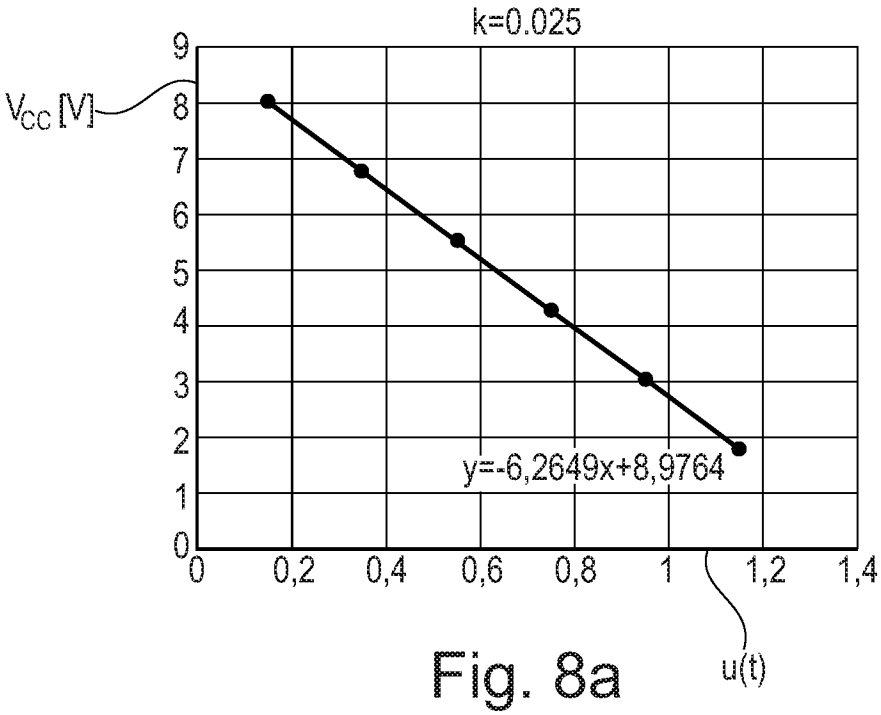

k=0.025
V_{CC} [V]
9
8
7
6
5
4
3
2
1
0
0
0,2
0,4
0,6
0,8
1
1,2
1,4
y=-6,2649x+8,9764
u(t)

Fig. 8a

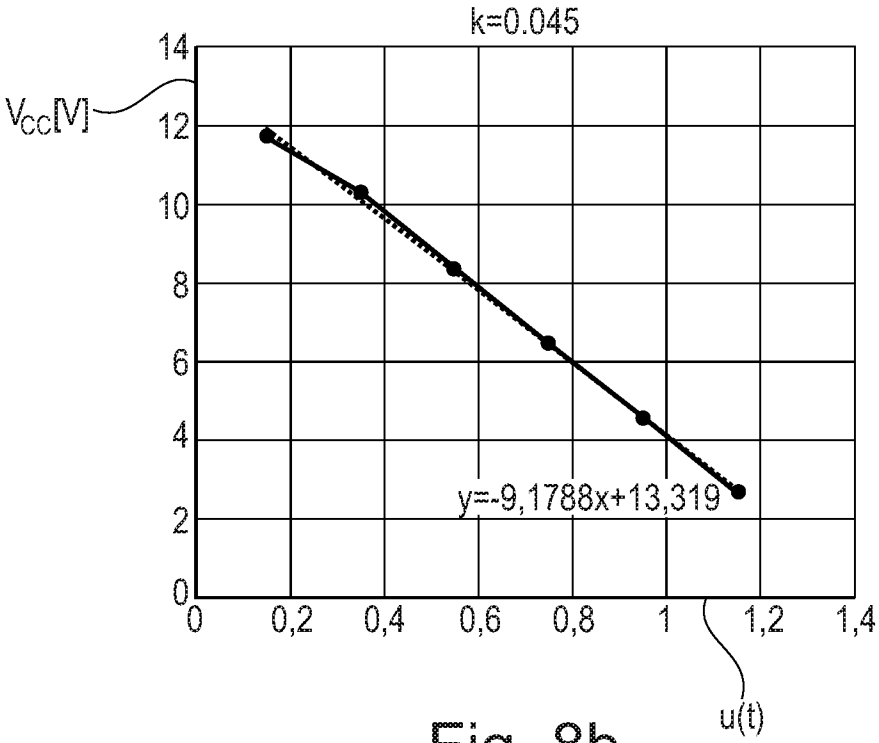

k=0.045
V_{CC}[V]
14
12
10
8
6
4
2
0
0
0,2
0,4
0,6
0,8
1
1,2
1,4
y=-9,1788x+13,319
u(t)

Fig. 8b

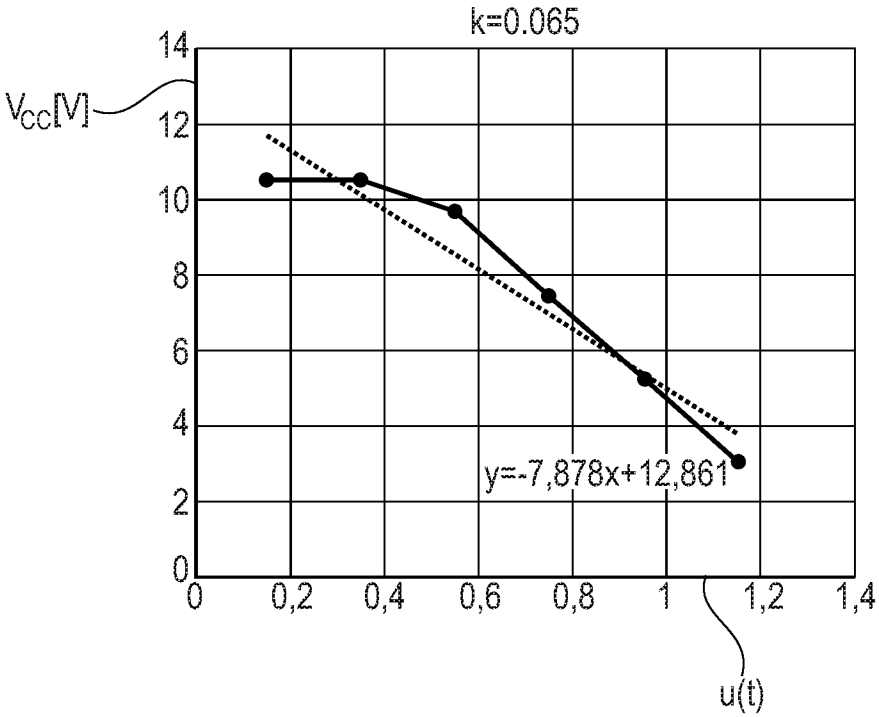

k=0.065
V_{CC}[V]
14
12
10
8
6
4
2
0
0
0,2
0,4
0,6
0,8
1
1,2
1,4
y=-7,878x+12,861
u(t)

Fig. 8c

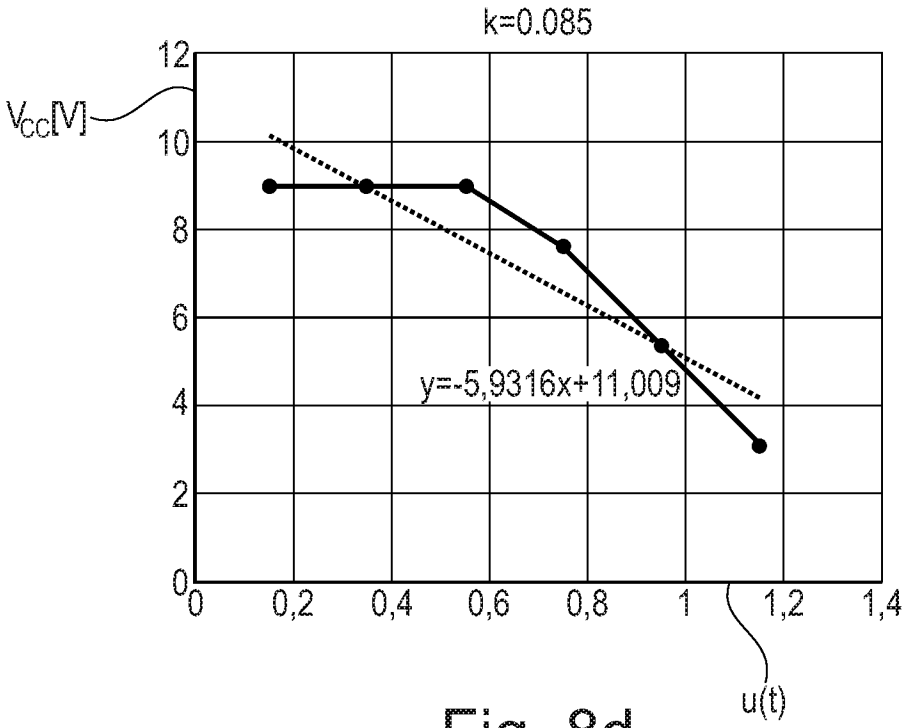

k=0.085
V_{cc}[V]
12
10
8
6
4
2
0
0
0,2
0,4
0,6
0,8
1
1,2
1,4
y=-5,9316x+11,009
u(t)

Fig. 8d

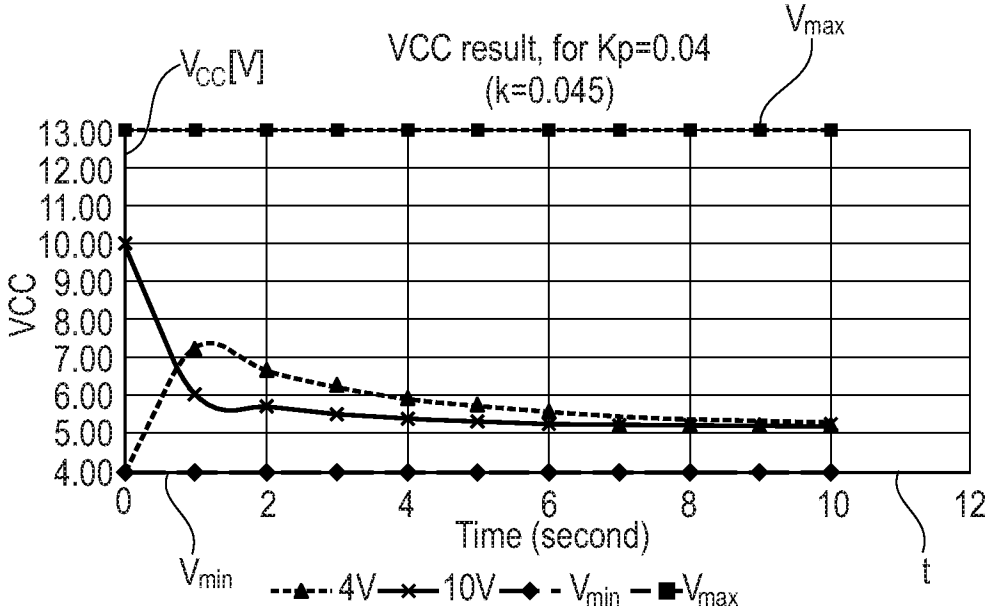

V_{max}
V_{cc}[V]
VCC result, for Kp=0.04
(k=0.045)
VCC
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
0
2
4
6
8
10
12
Time (second)
V_{min}
t
4V
10V
V_{min}
V_{max}

Fig. 9

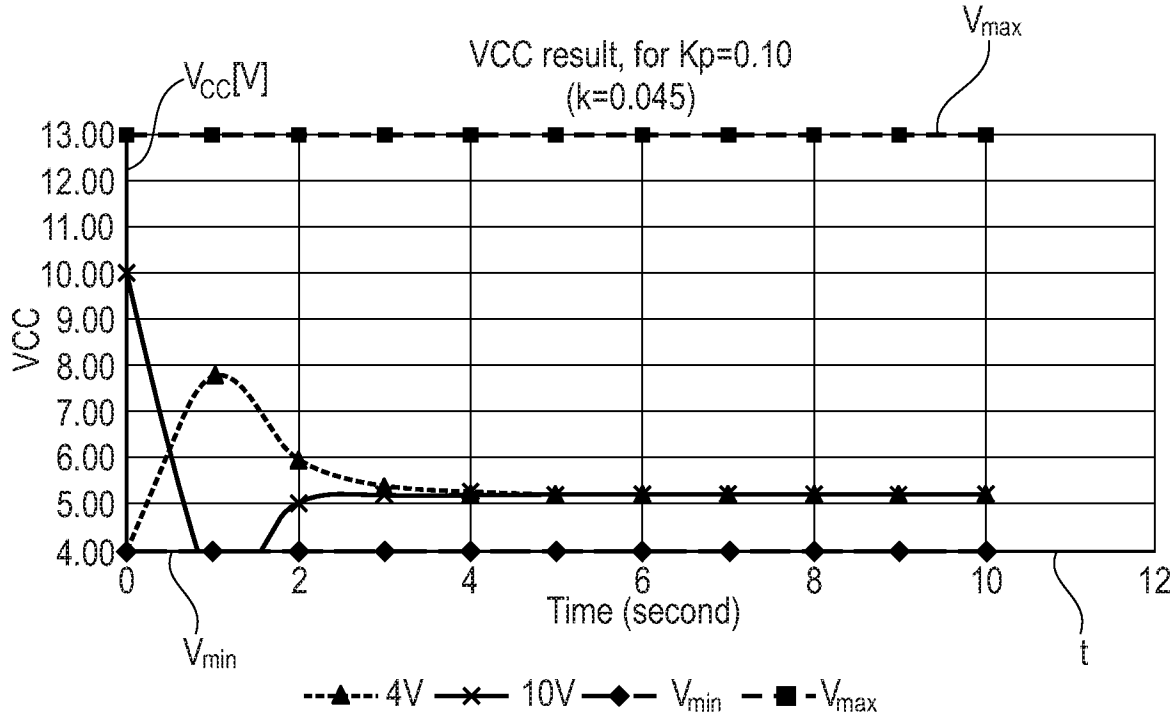

VCC result, for Kp=0.10
(k=0.045)
Vmax
Vcc[V]
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
VCC
0
2
4
6
8
10
12
Time (second)
Vmin
t
4V
10V
Vmin
Vmax

Fig. 10

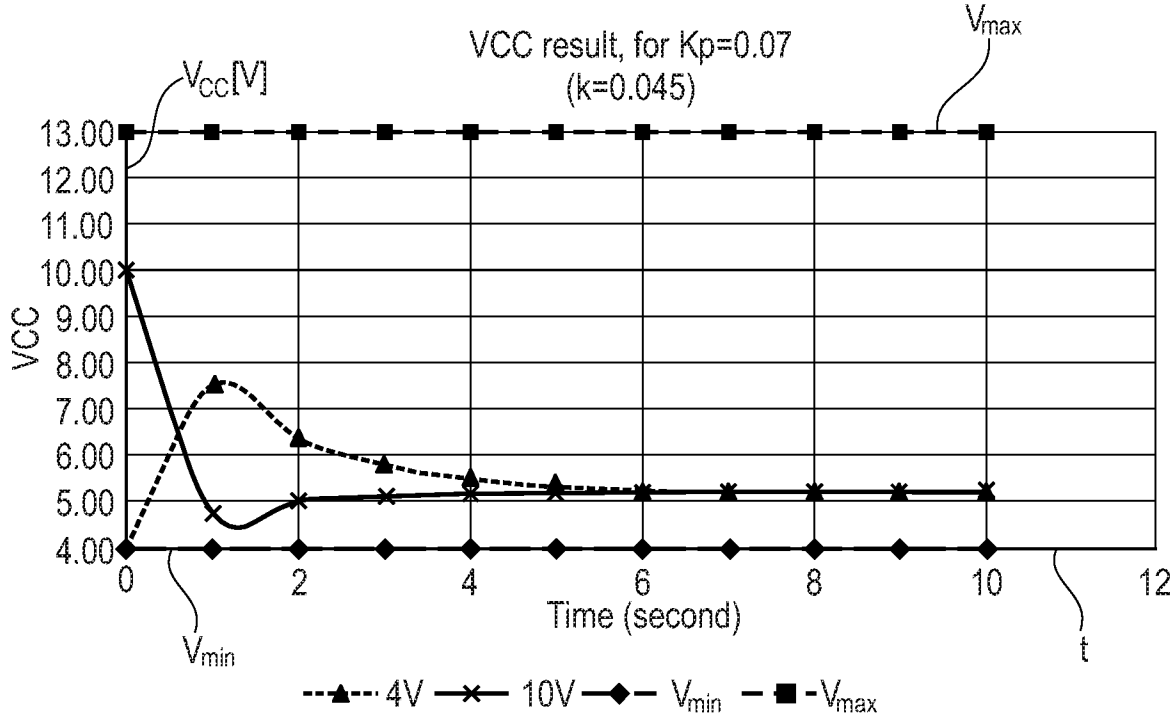

VCC result, for Kp=0.07
(k=0.045)
Vmax
Vcc[V]
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
VCC
0
2
4
6
8
10
12
Time (second)
Vmin
t
4V
10V
Vmin
Vmax

Fig. 11

INTERNATIONAL SEARCH REPORT

International application No
PCT/SG2022/050626

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04R25/00 H02J50/12 H02J50/80 H02J7/00 G06F30/20
ADD.

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)
H04R H02J G06F

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2020/251929 A1 (PARTOVI AFSHIN [US]) 6 August 2020 (2020-08-06)	1-7
Y	paragraphs 31,32,43-63 - pages 1,2 -----	8-11
Y	Anonymous: "PID controller - Wikipedia", , 10 August 2021 (2021-08-10), pages 1-27, XP093021062, Retrieved from the Internet: URL:https://web.archive.org/web/2021081020 5633/https://en.wikipedia.org/wiki/PID_con troller [retrieved on 2023-02-06] the whole document -----	8-11

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

☒ See patent family annex.

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"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

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"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	Date of mailing of the international search report
7 February 2023	15/02/2023

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Borowski, Michael

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/SG2022/050626

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2020251929 A1	06-08-2020	US 2020251929 A1	06-08-2020
		US 2022416578 A1	29-12-2022