ADAPTIVE POWER CONVERTER FOR WIRELESS POWER TRANSFER IN BIOMEDICAL APPLICATIONS (INVITED)

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ABSTRACT

Wireless power transfer is a suitable method for powering electronic devices implanted in the human body or attached to the skin, as it prevents the need for inconvenient cables or surgeries to replace batteries. The power received by the device varies due to antenna misalignment, distance from the power source and objects present in the environment that reflect the electromagnetic waves. Moreover, different applications have different power requirements, e.g., a neural stimulator usually requires more power than a temperature sensor.

RF power receivers designed to operate at a specific minimum input power do not perform well at different available power levels [1]. Therefore, the power conversion chain must be adaptive to the changing power in order to present better overall efficiency. Since the rectifier is the most inefficient block in the chain [1], it is interesting to not add extra switches to it to keep its efficiency as high as possible. Thus, we can apply two techniques to compensate for the power variations: change the matching network between the antenna and the rectifier [2] (adaptive matching network) and the rectifier's output load [3] (adaptive DC-DC converter).

To modulate the rectifier's DC load, a buck-boost converter is proposed. Because this type of converter isolates its input from its output when operating in open-loop DCM (Discontinuous Conduction Mode), it is suitable in applications in which a storage capacitor is employed (since the voltage over it varies considerably) [4]. The designed converter can be dynamically adjusted for 1-μW to 1-mW available input power, meaning that it can supply many types of biomedical devices, and 0.38 to 1.3-V input voltage levels. Its peak efficiency is 76.3% at an input power of 1 μW and 86.3% at 1 mW. This was achieved by using pulse frequency modulation, reconfigurable power switches and adaptively biased zero-current-detection comparator. In order to dynamically select the best switching frequency of the converter, an MPPT (Maximum Power Point Tracking) circuit was designed. It employs a timing scheme that enables the entire circuit to be switched off for a long time, decreasing its average power consumption, and a novel input power estimation circuit that measures the input power indirectly, without sensing the input current and avoiding extra losses. With these characteristics, the presented power converter is suitable for several low-power biomedical devices or devices that require higher instantaneous power but can be duty-cycled.

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AN ULTRA HIGH-FREQUENCY MULTI-CHANNEL NEUROSTIMULATOR CIRCUIT WITH UNPRECEDENTED POWER EFFICIENCY

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Abstract: This work presents the design and the results from both schematic and post-layout simulations of a multichannel neural stimulator. The neurostimulator uses a different way of stimulating the neural tissue compared with state of the art constant-current stimulators. In fact, each stimulation phase is made of a sequence of current pulses injected at a frequency of 1 MHz, in which a duty cycle signal is used to control the stimulation intensity [1]. Significant size reduction is achieved by using only one inductor as external component. In contrast, conventional constant-current stimulators that use a DC-DC converter as a core, require at least two external components, both an inductor and a capacitor. The improvements with respect to [1] target to increase the power efficiency. The external high-voltage supply, usually used in current-steered stimulators, is avoided. Moreover, the employed zero-current-detection technique together with a power-efficient way of driving the high-voltage switches allows to achieve a record power efficiency while stimulating 8 channels connected to 16 reconfigurable electrodes in a time-interleaved fashion. The circuit is implemented in a 0.18 µm HV process, and the total chip area is 3.6 mm^2. Post-layout circuit simulations confirm the correct operation: when all the channels are used simultaneously and the load is modeled as a resistance R_{load} = 600 Ω with a series capacitance C_{load} = 500 nF, the power efficiency is increased to 70%. Because of the unique operating mechanism, [1] is the most suitable work for a power-efficiency comparison. When all the channels are used simultaneously, the power efficiency of this work is improved by up to 200% when compared to [1].

TOWARDS A FLEXIBLE IMPLANT WITH DISTRIBUTED ELECTRONICS, WIRELESS COMMUNICATION AND ENERGY TRANSFER

Ronaldo Martins da Ponte, Vasiliki Giagka, Wouter Serdijn

Abstract: Implants for neural recording or stimulation require arrays of microelectrodes to sense the signals or steer the stimulus current to the targeted nerve fibers or to specific brain circuits. In some applications, a higher number of microelectrodes is crucial to achieve the required high spatial-temporal resolution [1]. However, the larger the number of electrodes on the interface, the larger the number of long routing tracks to connect the external electronics, increasing the implant size and, often, compromising its reliability. To overcome this problem, we propose an implant containing electronics distributed over the microelectrode array for data routing, so the number of routing tracks can be drastically reduced. However, unlike previous works [2], the active electrodes herein proposed are capable of exchanging data over the array, such as mode selection of electrodes, communicating via a distributed network. The implant is also capable of communicating wirelessly with the outside world, receiving control information on magnitude and timing for the stimuli currents and providing feedback on the neuronal electrical activity, before, during and after a stimulation event. To cope with the power demand and chronic implantation, the fabrication of an antenna on a flexible substrate, combined with a power-management unit (PMU) and an energy storage element, is proposed, providing energy transfer [3] to the distributed electronic devices over the microelectrode array. In addition, the proposed implant will be fabricated using flexible materials since they have mechanical properties closer to those of living tissue, thus reducing the risk of inflammation and tissue damage.

WIRELESS POWER TRANSFER AND OPTOGENETIC STIMULATION OF FREELY MOVING RODENTS

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Abstract: Animal studies are commonly used to test the feasibility and effectiveness of promising novel neuroscience research ideas. One such new technique is optogenetic stimulation, a state-of-the-art brain stimulation technique. In optogenetics, genetic techniques are used to create light-sensitive proteins within the neuron membrane, thus allowing the affected region to become sensitive to light stimulation, for example through an inserted LED. Current optogenetic stimulation methods use tethered setups and, typically, the animal-under-study is put into a fixed position. This introduces stress, which, besides an obvious reduction in animal welfare, may also influence the experimental results. Hence, an untethered setup is highly desirable. Therefore, in this study, we propose a wireless optogenetic stimulation setup, which allows for full freedom of movement of multiple rodents-under-study in a 40x40x20 cm environment. We investigate a variety of wireless power transfer methods, which results in the choice for wireless power transfer through inductive coupling, as this allows for efficient power transfer over short range and has the least side-effects, making it the most suitable approach for this particular environment. The efficiency of inductive coupling is highly susceptible to vertical, lateral and angular misalignment of the coils. The wireless link is, therefore, designed to maximize the link efficiency and minimize the misalignments between the coils. In order to maximize the inductive power transfer link, we look into all the aspects that have an influence on the link efficiency, including coil shape and coil material. The goal is to obtain an inductive link that provides sufficient link efficiency throughout the entire 40x40x20 cm region of interest to be able to power the optogenetic stimulation receiver. The entire wireless receiver module resides on the animal and, as such, is severely restricted in both size and weight. The complete module with receiver coil, rectifying and regulating electronics, micro-controller and stimulation optrodes can be at most 1x1x1 cm. A significant additional contribution is the creation of a novel micro-LED mounting technique, which allows for the micro-LED array with multiple LEDs to be directly inserted into the brain. The use of a micro-LED array greatly improves the power efficiency, as the traditional LED-to-optical-fiber coupling is accompanied by large losses in light intensity. Moreover, a single micro-LED array is able to replace a number of optical fibers, resulting in a less-invasive procedure for more stimulation sites.

STRUCTURED ELECTRONIC DESIGN OF HIGH-PASS ΣΔ CONVERTERS AND THEIR APPLICATION TO CARDIAC SIGNAL ACQUISITION

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Abstract: Motivation: With the bandwidth of the ECG signal extending from sub-Hz to 200 Hz, a major challenge for an ECG readout system lies in implementing the high-pass (HP) cut-off frequency as this translates into the realization of large time constants on-chip [1]. Although techniques such as those based on the use of pseudo-resistors to obtain very large time constants exist [2], they are heavily limited in both linearity and accuracy, which clearly dictates the need for alternative structures. Proposed methodology: A structured electronic design approach based on state-space forms is proposed to develop HP ΣΔ converters targeting high accuracy of the HP cut-off frequency. Based on transfer function calculations, various specific HP ΣΔ topologies namely, biquad, observable and controllable canonical and orthonormal HP ΣΔ, can be made to satisfy the desired HP signal transfer with 2nd order noise-shaping. In order to establish the noise contributions of the integrators, intermediate transfer functions, viz., from the system input to the integrator outputs, and from the integrator inputs to the system output, respectively, are mathematically derived and evaluated. Results: The evaluation of the intermediate transfer functions show that the orthonormal topology is better than the observable canonical HP ΣΔ topology in terms of noise. Simulations conducted in MATLAB confirm the noise behaviour of the integrators and show that, apart from the first integrator, the HP integrator significantly contributes to the total noise. Secondly, the noise and the harmonics at higher frequencies from the HP integrator are low-pass filtered. A 2nd order orthonormal HP ΣΔ modulator with a sampling frequency of 128 kHz for a bandwidth of 1-200 Hz to be implemented in 0.18 μm technology achieves a resolution of 12-bits at the HP cut-off frequency of 1 Hz which is a major improvement over pseudo-resistors at the cost of higher area and power consumption. A robust, area-efficient and parasitic insensitive large time-constant switched-capacitor Nagaraj integrator leads to a HP cut-off frequency realization determined solely by the ratio of capacitors with an accuracy upto 1%. In conclusion, we investigated HP ΣΔ topologies that can be used to realize very large time constants with high linearity and accuracy which shows a major improvement over the conventionally used topologies that employ pseudo-resistors. Keywords: ECG, State-space forms, High-Pass ΣΔ converters, Orthonormal topology

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HIGH-RESOLUTION NEURAL READOUT FOR FUTURE CLOSED-LOOP COCHLEAR IMPLANTS

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Abstract: A lot of people worldwide suffer from hearing losses. Quite a few of them can be helped with a simple hearing aid that amplifies the external sound, but for many other people a more complex device that is able to substitute for the work of the damaged parts of the inner ear (cochlea) is needed. Such a device is called a cochlear implant. A complete cochlear implant has a stimulator module as well as a readout module. A stimulator module has been designed in [1], while the main focus of this work is the implementation of the readout module. 16 readout channels are needed in parallel to record the neural response on multiple electrodes. Since the channels are equivalent, the idea is to design a readout system that allows real time sensing of single-channel neural signals and then connect 16 of these in parallel. While the cochlea is stimulated by the stimulator, its neural response is read by the readout module, which is a challenging task. In fact, the neural response is in the range of 10 uV whereas the stimulus itself and the corresponding artefact can range up to 15 V, leading to a required dynamic range of 123 dB. Moreover, due to the rapid transients of the composite signal, the bandwidth ranges to 300 kHz. Moreover, the noise in the band of interest of the whole readout system should be lower than 1 uV. Due to its application in a cochlear implant, the readout system should consume as little power as possible. In this work a discrete circuit realization on a Printed Circuit Board (PCB) that meets all the mentioned specifications is designed. The first block of the readout module is an instrumentation amplifier with a really low input referred noise (< 1uV) and a variable gain from 0.1 to 1000. By doing so, the aforementioned dynamic range can be handled. To prevent damage to the tissue and electrodes in the cochlear implant the input bias current is not allowed to exceed 20 pA. The output of the instrumentation amplifier needs to be processed by a microcontroller. Therefore in between an Analog-to-Digital Converter (ADC) is needed. The designed PCB realization, together with the stimulator implemented in [1] implements a high-resolution neural stimulation and readout system, which will be used, initially, for animal experiments and paves the way to fully-integrated closed-loop cochlear implants.

TOWARDS A FAMILY OF CUSTOMISABLE FLEXIBLE NEURAL IMPLANT

Vasiliki Giagka, Wouter Serdijn

Abstract: Since the appearance of the first active implantable device, a cardiac pacemaker, in 1958, technology improvements have paved the way for the development of several diagnostic or therapeutic devices that target a large variety of applications (e.g. hearing loss, bladder control, chronic pain). More recently, it has been proposed that precise electrical impulses targeting individual nerve fibres or specific brain regions could be used in a fashion analogous to pharmaceuticals, repairing lost function and restoring health [1]. These bioelectronic medicines, or electroceuticals, would have to be administered through miniature devices close to their targeted nerves. Today, most implantable devices are still inherently hybrid systems, comprising a variety of components (i.e., electrodes, integrated circuits for electrical stimulation and recording of signals, decoupling capacitors, micro-controllers, batteries and a number of discrete components) that are typically individually fabricated and assembled together. These hybrid systems tend to be rather large for neural applications. Furthermore, these systems are normally custom designed for the targeted application and their structure and functionality are tailored to the specific requirements. This approach involves a massive design effort early on in the development process and implies many iterations and long prototyping times, usually even before the first proof-of-concept phase. Neuromodulation systems share many common characteristics which can be grouped into families or “libraries” of components. We suggest that a co-ordinated effort for the development of such “libraries” would enable the desired miniaturisation and integration that is currently lacking. Towards such a technology library we propose the development of a platform technology on flexible and biocompatible materials. This platform will be used for the design and fabrication of unit devices, modules, with a minimum channel count for electrical and optogenetic stimulation, recording of neural signals, and the possibility of scaling the number of channels to fulfil different requirements. Custom designed integrated circuits will be developed and assembled on flexible substrates to meet the aforementioned goals and create a family of “universal implantable devices”. The characteristics of prototype implants will be customisable by selecting from a pre-defined set. Such devices could be used during the proof-of-concept phase, saving design time before the specifications are finalised for the final implant. The ambitious goal is to concentrate and combine all efforts to develop the technology suitable to fabricate a set of “universal implantable devices”.