Frequency-optimized rectangular pulses for deep brain stimulation

Rauno Gordon, Mart Min, Raul Land
Thomas Johann Seebeck Department of Electronics
Tallinn University of Technology
Tallinn, Estonia
rauno@elin.ttu.ee

***Abstract*—We propose in this paper that short minimum length rectangular chirp pulses can very effectively be used for neural stimulation or more specifically – for deep brain stimulation. It has been proposed that the ideal frequency window for neural tissue stimulation by microelectrodes lays in the mostly resistive area between the lower frequency electrode interface dispersion and the higher frequency cell membrane dispersion. We demonstrate that the frequency spectrum of the short chirp pulses can be tuned to be exactly in the desired spectrum window. The rectangular short chirp pulses can also be very efficiently generated with undemanding electronics which makes them a very compelling solution for implanted devices using microelectrodes for deep brain stimulation.**

Keywords—neural stimulation, chirp, rectangular pulse, spectrum, energy-efficient stimulation, impedance, implanted devices, cardiac pacemaking

I. Introduction

There are many situations in medical practice where patient health is benefited from neural tissue stimulation. So called brain pacemakers are routinely implanted for treatment of epilepsy, Parkinson's disease and major depression [1]. Cochlear implants are routinely used for mitigating the loss of hearing and retinal implants are used now in medical practice too in case of blindness caused by retinitis pigmentosa or macular degeneration [2]. Recent discoveries on how the vagus nerve stimulation can be used for treatment of arthritis, ischemia and other inflammatory diseases point to rapidly expanding applications of neural stimulation [3]. Future advances in neural tissue stimulation are additionally expected to treat paralysis caused by injury to the spinal cord or to other parts of the nervous system and could also lead to various cognitive enhancement systems.

II. Methods

Stimulation of neural tissue for treatment purposes needs to be extremely energy efficient for several reasons. The energy input needs to be optimal from physiological reasons because electrodes are small with high impedance and tissue heating can occur because of highly concentrated energy [4, 5]. Also the electric charge must be counted with positive and negative electric charge in the alternating signal balancing out exactly without any excess electric charge left in the tissue that could damage the tissue areas next to the electrodes [6].

From the technology aspect we want to optimize the energy usage because the devices for neural tissue stimulation are in most practical cases totally implanted and therefore separated from outside power sources. The effects of the treatment must last for years or decades but at the same time the available space for the electronics and battery is very restricted. Therefore we are looking for very simple and efficient electronics for the stimulation pulse generation.

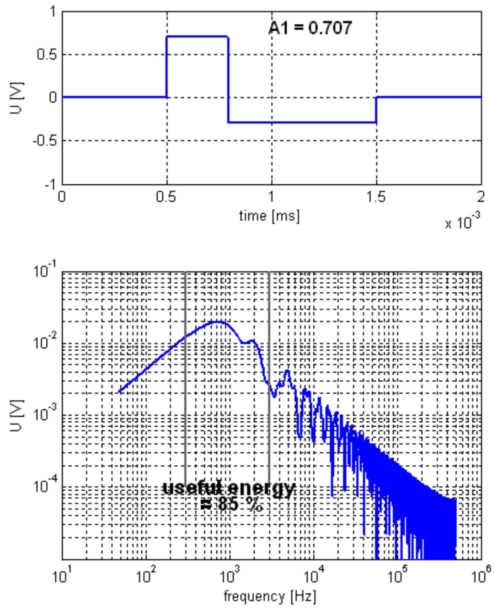

Figure 1. Balanced rectangular pulse with spectrum.

It has been proposed that it is most practical to stimulate deep brain tissue with energy concentrated into the resistive region in the impedance spectrum that lays above the low frequency electrode polarization effects and below the cell membranes effects manifested at higher frequencies [4, 5]. Depending on the electrode size and application area the frequency band for electrode polarization can extend up to 1 kHz or 10 kHz [6]. It is know that dielectric dispersion of tissue impedance due to cell membranes can normally start from 100 kHz to 1MHz but can be lower too depending on the tissue [6].

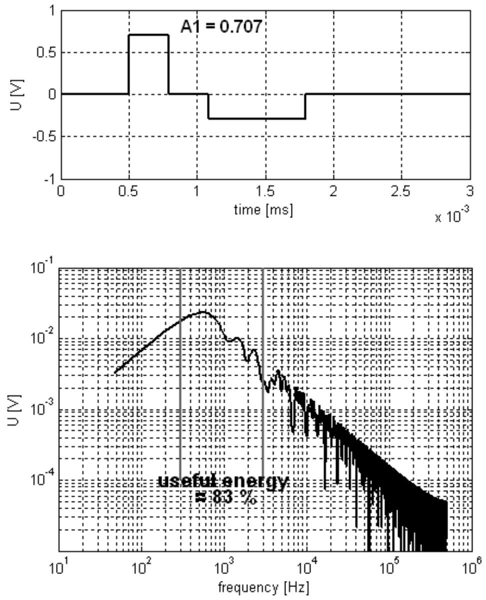

Figure 2. Balanced rectangular pulse with a gap with spectrum.

We tested the type of minimum length rectangular pulses that are currently used in implanted devices [7]. All signals were 1ms long rectangular signals with charge-balance that has equal positive and negative voltage*time area (Figure 1). The tests included signals from equal length positive-negative pulses to also common 1:15 time and amplitude ratio pulses and also pulses with a gap (Figure 2). Frequency spectrum of the pulses was calculated with FFT and the ratio of pulse energy in 1 decade (3 kHz-300 kHz) was determined.

III. Results

The comparison results showed that the best signals for energy-efficiency were with equal time and amplitude. But the high energy efficiency of over 80% in the 300 Hz-3 kHz band of was also present in pulses with down to $1/\sqrt{2}$ ratio of excitation/balancing pulses (Figure 1). Below that threshold and with ratio 1:15 – that is commonly proposed for excitation – the energy efficiency was considerably less.

We therefore propose more research in stimulation of the deep brain with rectangular waveforms that have ratio of $1/\sqrt{2}$ between excitation and balancing pulse amplitude and duration. Those pulses are very energy-efficient to produce with implantable electronics and that can be optimized to have excitation energy in the right frequency spectrum window. The signals can in the minimum configuration consist of only one positive rectangular pulse and one negative pulse immediately after that for charge balancing (Figure 1). Energy efficiency of 83% can be gained when the short bandwidth of 1 decade is desired. The pulse can also feature a gap between the excitation and balancing parts that is commonly used [7]. The gap has certain benefits and it does not worsen the energy-efficiency in spectrum too much.

We have demonstrated before that the spectrum of these minimum length rectangular pulses is concentrated into a frequency window of limited width [8]. The frequency spectrum of these pulses can be concentrated into a narrow band with optimizing the pulse durations and positive/negative amplitudes. This optimization can be performed for the electrode and tissue combination at hand for maximally efficient stimulation.

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