An Experimental Study on Passive Charge Balancing

Kriangkrai Sooksood¹, Thomas Stieglitz², Maurits Ortmanns¹
¹Institute of Microelectronics, University of Ulm, 89081 Ulm, Germany
²Laboratory of Biomedical Microtechnology, IMTEK, University of Freiburg, 79110 Freiburg, Germany

Abstract

This paper presents a simplified analysis of the electrode potential upon mismatched, biphasic stimulation using passive discharge techniques, e.g. by shortening of the electrodes. It turns out that especially for microelectrodes the required shorting intervals become as large as to limit a feasible stimulation interval. If no blocking capacitors can be used due to limited space and the degree of miniaturization, the passive discharge even imposes severe risks to the surrounding tissue and the electrode.

1 Introduction

Biomedical implants for functional electrical stimulation (FES), such as the cochlea implant, cardiac pacemaker, and retinal implant have received an increasing interest [1][2]. The principle is to excite a neural reaction upon the transfer of charge into the tissue. Thereby, constant current based stimulators use pulsatile current stimulation via an electrode, which is attached to the human body.

Principally, whenever current is conducted over an electrode into a conducting solution, chemical processes take place at the interface. By applying a large potential over a longer period of time, charge is massively exchanged over the electrode and strong faradaic currents flow which cause electrolysis, pH change, electrode dissolution as well as tissue destruction [3][4]. In order to avoid these irreversible electrochemical reactions, the stimulating current pulse is typically balanced and biphasic, which ensures that no net charge appears at the electrode after each stimulation cycle and the electrochemical processes are balanced to prevent net dc-currents.

But especially when integrated circuitry is used for the stimulator, due to imperfections of the fabrication process more than 1%-5% of mismatch of the current pulses has to be taken into account. Therefore, measures to achieve charge balancing are typically implemented. The most common solution is to insert a large, non-integrated dc blocking capacitor in series with the stimulation electrode, which guarantees that no dc-currents can flow to the electrode over time [3][5]. Nonetheless, regular discharge of the blocking capacitor is necessary in order to avoid saturation due to dc-current integration and consequently reduced output voltage compliance of the stimulator.

In modern FES applications, where many channels have to be provided concurrently [2], dc blocking capacitors can not be realized in the required number due to space limitations. Therefore, the only passive, charge balancing measure is to short the electrodes after the mismatched, biphasic stimulation in order to cancel accumulated charge.

In this work we analyze the dependency of current mismatch, electrode impedance and the resulting steady-state electrode dc-voltage. Within this paper, we model the electrode-electrolyte interface, calculate the net dc-voltage due to imbalance and validate the measurement results by experiments with platinum black electrodes in 0.9% saline solution.

2 Electrode-Tissue Interface Model

A simplified electrode model [5] can be described with three electrical components (Fig. 1), where \( C_H \) represents the double layer interface capacitor, \( R_S \) the solution spreading resistance, which is determined by the resistivity of the fluid, while \( R_F \) represents the faradaic resistance, which is governed by diffusion of reactive species to the electrode for charge-transfer reactions. Generally, in the case of safe operation only \( R_S \) and \( C_H \) are of interest. Current through the faradaic resistance \( R_F \) is, however, the source of corrosion and toxicity when there is no long-term charge balance [6].

It is important to note that the values of \( R_S \) and \( C_H \) will vary depending on the material and geometry of the electrodes being used. In this work, two sizes of platinum black electrodes were used with 1000 µm and 150 µm diameter, respectively. Lumped model parameters (\( R_S \) and \( C_H \)) have been measured using impedance spectroscopy with 25mV excitation in a 0.9% saline solution. Average values for these electrodes were found at \( R_S=1.2\,k\Omega \), \( C_H=47\,nF \), and \( R_S=4.7\,k\Omega \), \( C_H=18\,nF \), respectively.

![Fig. 1 Electrode-electrolyte interface model](image)

3 Electrode Potential Calculation

In the following, the derivation of an analytical expression for the steady-state mismatch voltage on an electrode employing passive charge balancing is found. Stimulation pulses in chronic applications are generally symmetric, biphasic and charge balanced (Fig. 2) [5]. The duty cycle of this pulse is...
If there is charge imbalance between the first (“push”) and the second (“pull”) current phase, then the average dc-current of this stimulation pulse is

\[ I_{DC} = \frac{Q_{PUSH} - Q_{PULL}}{t_{FRAME}} = \frac{I_{STIM}}{2} \cdot \%_{MM} \cdot DC \]  

where \( I_{STIM} \) is the stimulation current amplitude, \( \%_{MM} \) is the percentage charge mismatch between the push and pull duration, and \( DC \) is the duty cycle from Eq. 1. A stimulation current of \( \pm 1 \text{mA} \), a mismatch of 5% and a duty cycle of 20%, for example, corresponds to an averaged dc-current of 10 \( \mu \text{A} \) through an electrode.

From the dc-current in Eq. 2, the mismatch charge per each stimulation cycle, \( Q_{MM} \), can be calculated as:

\[ Q_{MM} = t_{FRAME} \cdot I_{DC} \]  

During the discharge period, \( t_{DIS} \), the switch is closed, thus, the blocking capacitor is discharged through \( R_S \) and \( R_{DIS} \). The charge during this period is:

\[ Q_{DIS} = \frac{V_0}{R_S + R_{DIS}} \cdot t_{DIS} \]

where \( V_0 \) is the quasi-static electrode potential during the discharge phase. To simplify the calculation, it is assumed that \( t_{DIS} \) is much smaller than \( \tau \). Then, the voltage at the capacitor and thus at the electrode remains constant during the discharge period. Hence, Eq. 4 and Eq. 5 are set equal:

\[ \frac{V_0}{R_S + R_{DIS}} \cdot t_{DIS} = t_{FRAME} \cdot I_{DC} \]

The electrode voltage can then be calculated to:

\[ V_0 = \frac{t_{FRAME} \cdot I_{DC} \cdot (R_S + R_{DIS})}{t_{DIS}} \]

This equation can also be used in the case of stimulator without blocking capacitor (since \( C_B \gg C_{HW} \)).

4 Experiments and Discussion

The given analysis is verified by circuit level simulations using the circuit in Fig. 3, and additionally with experiments using platinum black electrodes in a 0.9% saline solution. The following parameters were used for the experiments: \( I_{STIM} = \pm 500 \mu \text{A} \), a current mismatch of \( \%_{MM} = 2\% \), \( C_B = 22 \mu \text{F} \), while \( R_{DIS} \) was small and could be neglected.

For the pulse timing, in this experiment a high repetition rate of 5kHz was chosen, with \( t_{PUSH} = t_{PULL} = 50 \mu \text{s} \) and \( t_{FRAME} = 200 \mu \text{s} \). Please note that by extending all timings proportionally, the absolute results of the steady state voltage did not change, since the mismatch current depends only on the duty cycle of the frame (Eq. 2), while the resulting electrode voltage depends on the ratio of the frame and discharge time (Eq. 7).

Firstly, the 1000 \( \mu \text{m} \) diameter electrode was used. Fig. 4 presents the quasi-static electrode potential after each stimulation and discharge phase. The potential was measured for various discharge times \( t_{DIS} \) and is compared to the result in Eq. 7 and a simulation with the simple circuit in Fig. 3.

A comparison of the calculation, simulation and the experiment on a smaller electrode with 150 \( \mu \text{m} \) diameter is given in Fig. 5. Again, the stimulation parameters were chosen as above.
For illustration of the steady state behaviour, also the transient electrode potential is shown in Fig. 6, where the mismatch caused voltage after each stimulation cycle is seen.

![Excess electrode potential](image)

**Fig. 6** Excess electrode potential

### 5 Conclusion

This paper presents an electrode potential calculation method for functional electrical stimulation with passive charge balancing using blocking capacitors or electrode shorting. It is shown that a safe value for the discharging time strongly depends on electrode impedance. Thus, when small electrodes are used, a stimulation current mismatch can cause a quasi-static electrode potential exceeding the water window. Thus, either very large safety margins are required or active charge balancing techniques must be used.

### 6 Literature


