A 2.4μW 400nC/s Constant Charge Injector for Wirelessly-Powered Electro-Acupuncture

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Abstract—An ultra-low-power constant charge injector (CCI) circuit is presented for wirelessly-powered electro-acupuncture (EA). The CCI adopts adaptive pulse-width and frequency-drift (APF) calibration loop that not only accommodates to body impedance variation (BIV) of 100-200kΩ but also is tolerable to frequency-drift. The proposed 5Hz current starving clock generator combined with sub-Vth reference circuit provides supply voltage dependency of 0.2Hz/V and temperature dependency of 0.018Hz/°C while consuming only 1μW. These variations are finely calibrated by the APF loop to ensure injectable charge intensity as stable as 399.33-400.45nC/s. The low-power low-voltage Gm circuit in CCI incorporates diode-limited and chopper-modulated inputs to prevent the damage from static electricity of the body while providing linear voltage-to-current conversion. The proposed CCI, simulated in 0.18μm CMOS technology with supply voltage of 1.0V, consumes 2.4μW of power.

I. INTRODUCTION

An invasive medical treatment using electro-acupuncture (EA) [1] is a promising research area, and it has received more and more attention on the effectiveness for myalgia [2], depression [3], and anesthesia [4]. A pair of needles is exploited in EA to inject charge into the body by flowing electrical current from a bulky and wire-connected power supply.

To improve remedial value and subject’s convenience, a multi-channel wirelessly-powered EA system [5], [6] was proposed to remove cumbersome wires and to give the EA a compact form. To cope with limited power budget (<8μW), low supply voltage (1.0V), and injecting constant charge issue with respect to body impedance variation (BIV) of 100-200kΩ, it adopts an adaptive pulse-width (APW) control loop in which a chopper modulated Gm circuit with flipped voltage follower (FVF) is integrated. However, the previous approach [5], [6] of Fig. 1 still remains several technical issues to be answered. First, although the APW stimulator can detect the BIV dynamically, the voltage change across the BIV is not protected to be vulnerable to static electricity. Therefore, it may damage the succeeding Gm circuit so that the APW fails to proper operation. Second, the separated implementation between the reference circuit and the ring oscillator in APW will introduce large frequency-drift and power consumption. Third, the safety issue correlated to balanced charge intensity [7], which requires exact stimulation pulse frequency, was not considered.

In this paper, a hybrid frequency-drift compensation mechanism is presented for adaptively controlling stimulation pulse-width so that injected charge should be stable over time. The drift of the stimulation frequency as the functions of supply voltage and temperature is coarsely controlled to be a minimum by a low-power constant current starving ring oscillator combined with sub-Vth reference generator. It was finely regulated by adaptive pulse-width and frequency-drift (APF) calibration loop. To be resilient to static electricity [8], [9] and to ensure reliable operation of the APF loop, a diode-limited and Gm circuit incorporating chopper modulation is integrated.

This paper is organized as follows. Section II describes the system design challenges and operation of the proposed APF loop. Section III shows low-power sub-Vth reference and clock

Figure 1. The previous wirelessly-powered EA [5], [6]
frequency generator in detail. After the simulation results shown in Section IV, Section V will conclude the paper.

II. THE PROPOSED CONSTANT CHARGE INJECTOR BASED ON ADAPTIVE PULSE-WIDTH AND FREQUENCY-DRIFT CALIBRATION LOOP

Fig. 2 shows the structure of the proposed constant charge injector (CCI) based on APF calibration loop. It consists of: 1) diode-limited protection circuit prior to $G_m$-stage so that it is isolated from static electricity, 2) a low-power low-voltage chopper-modulated $G_m$ circuit [6], which linearly translates the voltage of the BIV into current signal regardless of process mismatch, 3) hybrid frequency-drift compensation blocks including low-power coarse frequency-drift controllable reference and clock generator together with fine frequency-drift constant current drain circuit, and 4) auxiliary control logic and EA driver for injecting charge. The operation of the proposed APF compensation loop is divided into 5 steps.

Step-1: Once BIV (100-200kΩ) is introduced, the integrated BIV sensing resistor of $R_O$ (10kΩ) converts it into 45-95mV voltage signal ($V_{RO}$).

Step-2: $I_{CS}$ flowing into $C_S$ will increase the $V_{CS}$ of Fig.2 when clock signal (CLK) is high. Once the $V_{CS}$ equals to $V_{REF}$ of Fig. 2, the charging switch of SW 1 will be turned off to determine the stimulation pulse-width of $t_{pw}$ in (1). As such, the injectable amount of charge ($Q_{inj}$) is calculated as (2).

$$t_{pw} = \frac{C_S \cdot V_{REF}}{G_m \cdot R_O \cdot V_{DD}} \quad (1)$$

$$Q_{inj} = \frac{C_S \cdot V_{REF}}{G_m \cdot R_O} \quad (2)$$

Step-3: When CLK is low, the switch of SW 2 turned on to discharge $C_S$ with a constant current of $I_B$. It results in voltage drop of $\Delta V_{CS}$ in (3) which is inversely proportional to the frequency of CLK ($f_{CLK}$).

$$\Delta V_{CS} = \frac{I_B}{2 \cdot C_S \cdot f_{CLK}} \quad (3)$$

Step-4: In the succeeding CLK period, the Step-3 and Step-4 are repeated to correct $t_{pw}$ as (4). As such, the injectable amount of charge ($Q_{inj}$) will be modified as (5).

$$t_{pw} = \frac{R_{BI} \cdot I_B}{G_m \cdot R_O \cdot V_{DD}} \cdot 2 \cdot f_{CLK} \quad (4)$$
Consequently, the inject-able charge intensity \( Q_{\text{inj}} \) of Fig.3 becomes constant regardless of drift of \( f_{\text{CLK}} \) and \( BIV \) as (6), but depends on constant value of current drain, \( G_m \), and \( R_O \). To minimize the contribution from non-ideality of \( G_m \) the chopper-modulated \( G_m \) circuit [6] of Fig.4 is adopted to ensure precise linearity (0.2\( \mu \)A/V) with respects to process mismatch of (±10%), which affects only 2% of \( t_{\text{pw}} \) while consuming only 1\( \mu \)W.

\[
Q_{\text{inj}} = \frac{I_B}{2 \cdot G_m \cdot R_O} \cdot \frac{1}{f_{\text{CLK}}} \quad (5)
\]

\[
Q_{\text{inj}} \times f_{\text{CLK}} = \frac{I_B}{2 \cdot G_m \cdot R_O} \quad (6)
\]

III. LOW-POWER SUB-VTH REFERENCE AND CLOCK FREQUENCY GENERATOR

To achieve a constant \( I_B \) in (6) with low-power consumption, a sub-Vth constant current generator of Fig. 5 (a) is utilized [10].

IV. SIMULATION RESULTS

Fig. 6 shows the simulation results of the proposed APF calibration loop. The APF with the \( f_{\text{CLK}} \) of 4Hz provides the constant \( Q_{\text{inj}} \) of 98nC/stimulation, which is shown in (2), with respects to \( t_{\text{pw}} \) of 10.2-20.0ms and \( BIV \) of 100-200k\( \Omega \). As the \( f_{\text{CLK}} \) is increased to 6Hz, the \( Q_{\text{inj}} \) is decreased to 66.8nC/stimulation, which well verifies (5), with respects to \( t_{\text{pw}} \) of 13.62ms and the \( BIV \) of 200k\( \Omega \). In both cases, the inject-able charge intensity maintains constant of 400nC/s which also verifies (6).

Fig. 7 shows the stability of the inject-able charge intensity as the function of (a) supply voltage variation and (b)
temperature variation. The sub-V\textsubscript{th} reference and clock frequency generator provides the sensitivity of 0.2Hz/V and 0.018Hz/\textdegree C, respectively. As a result, the stimulation frequency drifts only between 4.995Hz and 5.035Hz over supply voltage variation of 0.9-1.1V, and between 4.64Hz and 5.7Hz over temperature variation of 0-60 \textdegree C, respectively.

Within this frequency range, the APF stabilizes the inject-able charge intensity of 399.33-400.45nC/s with the variation of 0.4nC/s (0.01%) and 1.12nC/s (0.3%), respectively.

V. CONCLUSION

A 2.4\mu W CCI is presented for wirelessly-powered EA. The CCI incorporates APF calibration loop to finely calibrate stimulation pulse-width for maintaining constant charge intensity regardless of BIV (100-200k\Omega), supply voltage variation (0.9-1.1V), and temperature variation (0-60 \textdegree C). The simulation results, under 0.18\mu m CMOS technology with supply voltage of 1.0V, show that the proposed APF in CCI provides supply voltage dependency of 0.2Hz/V and temperature dependency of 0.018Hz/\textdegree C, which is sufficiently stable for inject-able charge intensity of 399.33-400.45nC/s. For the low-power consumption of CCI, the ring oscillator is embedded in reference circuit operated in sub-V\textsubscript{th}, and its frequency is coarsely controlled by a constant current starving oscillator. The proposed CCI prevents the damage from the static electricity of the body with a diode-limiter in APF, and it is expected to be more safe and lower power consumption than the previous APW stimulator [5],[6].

REFERENCES