A Wirelessly Tunable Low Drop-out Regulator for Subcutaneous Muscle Prosthesis

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***Abstract*— This paper presents a design technique to implement wirelessly tunable low-dropout regulators (LDOs) with application in electrical stimulation of ionic electroactive polymers (iEAPs) used in subcutaneous muscle prosthesis. The proposed technique, built upon the concept of frequency-based telemetry, converts the frequency of the sinusoidal signal at the primary side into an electrical current at the secondary side that will be proportional to the input frequency. This current is then used to change the reference level of the LDO and therefore, its output voltage, thereby, providing the capability to tune the output of LDO remotely. The proposed technique is designed using IBM $0.13\ \mu m$ BiCMOS technology. Simulation results suggest that the proposed wirelessly tunable LDO can be used as a reliable stimulator for iEAPs to allow different degrees of movement for the subcutaneous muscle prosthesis, enabling immediate movement restoration, upon implantation.**

I. Introduction

Implantable microelectronic devices, because of their great potential in offering solutions to problems in various clinical applications, have been receiving increased attention in recent years [1], [2]. One such clinical application is the development of the next generation implantable muscle prosthesis to aid immediate movement restoration upon loss of skeletal muscle [3]. Functional loss and impairment of skeletal muscle could occur as a result of aging and diseases such as amyotrophic lateral sclerosis, vascular disease or cancer, negatively impacting patients' quality of life [3]. Several approaches in the field of tissue engineering have been sought for the repair and regeneration of skeletal muscle offering solutions that display contractility only "after" new muscle has been regenerated [3].

A possible solution to the problem of immediate movement restoration is the development of new classes of subcutaneous muscle prosthesis, which combine biomaterials such as ionic electroactive polymers (iEAPs) [4] and integrated circuits [5], to facilitate controllable electrical and mechanical stimulations following implantation [3]. The degree of movement in the iEAP-based subcutaneous muscle prosthesis will be dependent on the level of the electrical stimulation that is received by iEAPs. This voltage level can be provided via an implantable wirelessly tunable voltage regulator (such as low dropout regulator (LDO)) that is powered-up via a wireless power transfer (WPT) link [3] (see Fig. 1). In addition to creating movement, such a module will also speed up the tissue regeneration process by enhancing cellular proliferation alignment via stimulation upon implantation.

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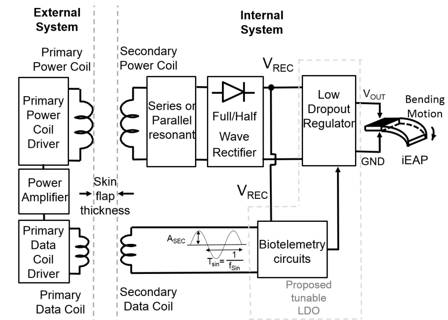


Fig. 1. Block diagram of an iEAP-based subcutaneous muscle prosthesis with wirelessly tunable LDO. A conceptual representation for the movement of iEAPs, when placed inside an electric field, is also shown.

Since the degree of movement will be controlled by the level of the voltage provided by LDO, the LDO should be capable of providing multiple output levels. Two possible classes of solutions to develop a multi-level regulator are 1) use of one LDO with the capability of tunable output, and 2) use of multiple LDO structures [6] along with a programmable multiple rail for enabling/disabling LDOs. Because of the limitation of area and space on the implant side, the first class of solutions will be considered here.

To remotely tune the output of the LDO, techniques for communicating with the LDO should be developed. Commonly used methods for data telemetry in biomedical implants are based on digital communication schemes such as amplitude shift keying (ASK), frequency-shift keying (FSK), and load-shift-keying (LSK) [2], [7]- [9]. Such schemes typically require modulation and demodulation circuitry, clock generators and digital blocks, and thus adding to the overall implant size. For the application under this study, the output voltage level of the LDO is the main parameter that needs to be controlled. Additionally, reverse telemetry is not required. Therefore, the use of digital telemetry schemes will be neither power nor space efficient.

In this paper, we present an analog-based technique that enables remote tuning of the output voltage of LDO based on the frequency applied at the transmitter. In [3] an external-capacitor-less LDO circuit meeting the requirements of iEAPs was presented. However, remote tuning the LDO and providing multi-level outputs were not considered. The technique proposed here is built on the concept of frequency-based telemetry [10], and to the best of our knowledge, this is the first time the concept is being introduced in biomedical implants.

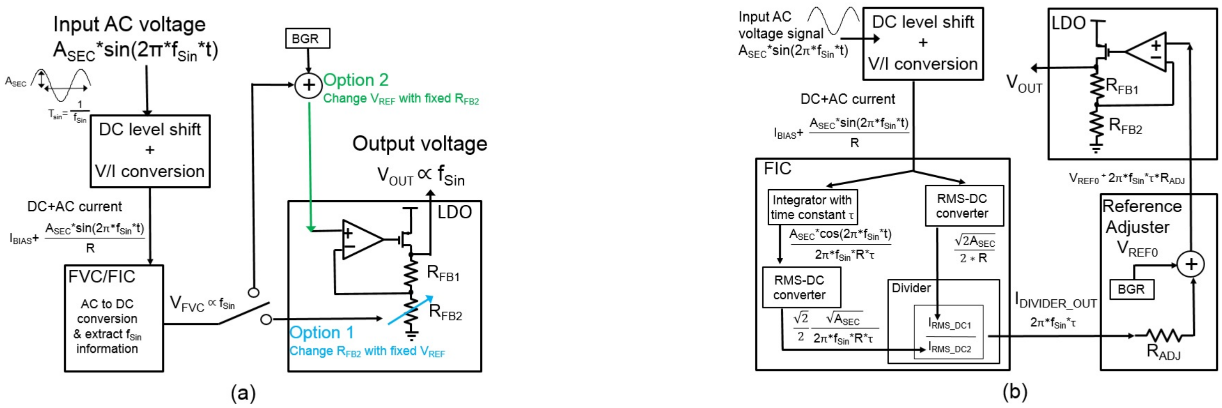


Fig. 2. a) Conceptual representation of the frequency-based control technique for wirelessly tunable LDO, and b) detailed block diagram of the proposed technique.

The rest of the paper is organized as follows. In Section II, the proposed wirelessly tunable technique is presented. In Section III, a transistor level implementation of the proposed technique is described. Simulation results are presented in Section IV, and conclusions are given in Section V.

II. Proposed Wirelessly Tunable Technique for LDO

As discussed in Section I, the LDO with multiple voltage level capability will be required for the development of the next generation iEAP-based muscle prosthesis. To save on the power, area and space on the implant side, the single LDO design option is considered.

The proposed idea for wirelessly tuning the LDO is realized upon the concept of frequency-based telemetry. The frequency-based telemetry concept utilizes frequency-to-voltage converter (FVC) or frequency-to-current converter (FIC) to generate an electrical signal (voltage/current) at the secondary (receiver) side that will be related to the frequency of the periodic signal at the primary (transmitter) side. In the application of interest, since the frequency of generated electrical waveform at the primary and secondary sides of the inductive link will be identical [11], frequency-based telemetry can be used to provide remote tune capability to this class of biomedical implants, with the frequency at the transmitter side being the control signal. By using FIC or FVC, the electrical signal related to the frequency applied to the primary coil will be generated, which can then be used to control the output voltage of the LDO at the receiver side.

The design of proposed tunable LDO includes two major sections: 1) design of FIC/FVC block, and 2) choice of the control mechanism that will be used to tune the output voltage of the LDO. The conceptual block diagram is shown in Fig. 2-a with two possible realization options for the control block.

The choice of the architecture for the frequency conversion block depends on the nature of the input signal and whether it is sinusoidal [12], or square waveform [13]. Here, we consider the input signal received at the secondary coil to be sinusoidal. We also consider the FIC architecture [12] which, as we will discuss later, offers an advantage of being insensitive to the variations in the amplitude of the input signal.

For the choice of the control mechanism block, we note that the output voltage of the LDO is determined by two main parameters: the reference level (V_{REF}) and the ratio of two resistors R_{FB1} and R_{FB2}. Based on these two parameters, two possible options for the control mechanism are illustrated in Fig. 2-a. In the first option (Option 1) the reference level is fixed, and the output of LDO is controlled by varying the resistors [14]. In the second option (Option 2), the resistors are fixed, and the reference level from the bandgap reference circuit (BGR) is adjusted [15]. The realization of the first option would require the replacement of either R_{FB1} or R_{FB2} with a programmable resistor network, switches for the selection of appropriate resistors, and an analog-to-digital converter (ADC) to convert the output from FVC/FIC to a digital signal for controlling the switches. In the second option, the reference level can be adjusted based on the current generated from the FIC. To save power and area on the implant side, it is apparent that the second option is the appropriate choice for this application. Fig. 2-b illustrates the conceptual representation for the proposed wirelessly tunable LDO. The technique has several advantages including simplicity (no antenna/ receiver /modulator /demodulator /data recovering circuits /oscillator needed at the secondary side), integrability and CMOS compatibility, low power consumption, and low noise (no switching action is required).

III. Circuit Implementation

In this section, transistor level implementation of the proposed wirelessly tunable LDO is presented. As shown in Fig. 2-b, the AC component of the input voltage is first converted to an AC current with DC offset. This signal is then mirrored to flow into two blocks that form the FIC (Fig. 3-a). The first mirrored signal is integrated and then converted to the DC level equivalent to the RMS value of the AC input signal (Fig. 3-b), and the second mirrored signal flows into another RMS-DC converter to generate a second level DC signal (Fig. 3-c). Fig. 3-d shows the divider circuit generating an output current that will be proportional to the input frequency [12].

Both the integrator and the RMS-DC converter are implemented by bipolar transistors. However, they can also be implemented using conventional CMOS technologies. For

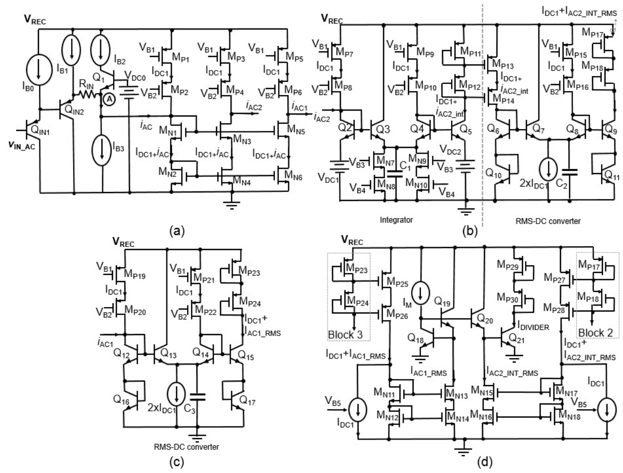


Fig. 3. Schematic of four major blocks of FIC, a) block 1-the input stage b) block 2-the integrator and the RMS-DC converter for i_{AC2}, c) block 3-the RMS-DC converter for i_{AC1}, and d) block 4-the current divider.

RMS-DC converters and current dividers, the bipolar devices can be replaced by subthreshold-operating MOSFETs, and the integrator can be implemented with CMOS-based operational transconductance amplifier (OTA), with wide input range. We will now discuss details of circuit blocks used to implement the proposed wirelessly tunable LDO.

FIC: Input stage-The schematic of the input stage is shown in Fig. 3-a. This stage converts the input AC signal into a current that will be fed into next stages. The DC level of the input voltage is first adjusted via two PNP-based level shifters. An AC current with DC offset is then produced with node "A" being set as a virtual ground. After proper DC cancellation, the AC current will go into the current buffer. Transistors M_{P1}-M_{P6} are biased by external DC voltages V_{B1} and V_{B2} to generate DC currents. Transistors M_{N1}-M_{N2} are self-biased to include both DC and AC components. The $DC{+}AC$ current is then mirrored through transistors M_{N3}-M_{N6} into two different branches. By proper DC cancellation, two AC outputs i_{AC1} and i_{AC2} are generated to go to the subsequent blocks.

FIC: Integrator stage-The integrator is shown in Fig. 3-b and consists of transistors M_{P7}-M_{P12}, M_{N7}-M_{N10}, Q_2-Q_5, one capacitor C_1 and two DC voltages V_{DC1} and V_{DC2}, to execute the integration operation on the current [16].

FIC: RMS-DC converter stage-The RMS-DC converters are shown in both blocks 2 (Fig. 3-b) and 3 (Fig. 3-c). Note that accurate RMS-DC conversion is achieved through the precise controlling of the current sinks [17].

FIC: Current divider stage-The current divider circuit shown in Fig. 3-d consists of two "biased current cancellation" circuits and the core divider. The output currents in blocks 2 and 3 both contain the biased DC current and the generated DC current from the corresponding AC inputs. For example, transistors M_{P25} and M_{P26} mirror the output current from block 3, and subtract the biased DC current I_{DC1} and feed the remaining DC current I_{AC1_RMS} to the divider. Similarly, the DC component $I_{AC2\_INT\_RMS}$ from block 2 is extracted, and finally, the output current $I_{DIVIDER}$ becomes proportional to the input frequency.

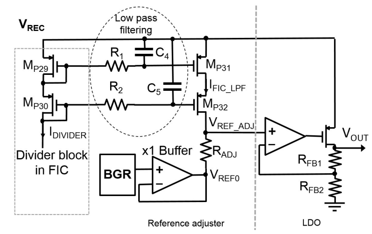


Fig. 4. Schematic of the reference adjuster and the LDO.

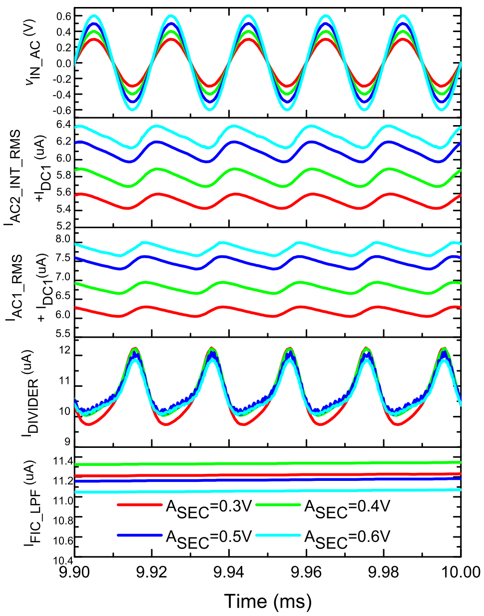
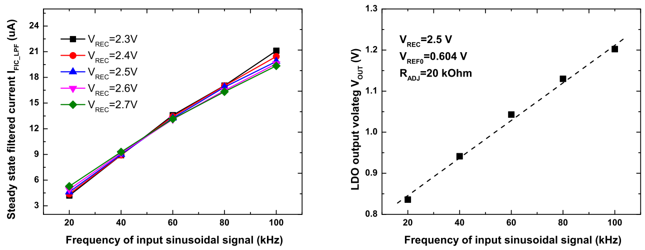


Fig. 5. Steady state simulation results for $I_{DC1}{+}I_{AC2\_INT\_RMS}$, $I_{DC1}+I_{AC1\_RMS}$, $I_{DIVIDER}$ and I_{FIC_LPF} as the input signal amplitude varies from 0.3 V to 0.6 V.

Reference level adjuster-Ideally, the output current is expected to have negligible ripple. However, due to the nonlinear operation of the current divider, the AC ripple in the current $I_{DIVIDER}$ may still be observable. One solution to reduce the AC ripple is to introduce a low pass filter (LPF). As shown in Fig. 4, two RC LPFs (resistors R_1, R_2 and capacitors C_4, C_5) are added at the gate terminal of transistors M_{P29} and M_{P30}. As a result, the mirrored and scaled current I_{FIC_LPF} will be a current with negligible AC ripple. This current is buffered through the transistor M_{P32} to generate the adjustable reference level V_{REF_ADJ}, and consequently, the output voltage of the LDO V_{OUT} [15].

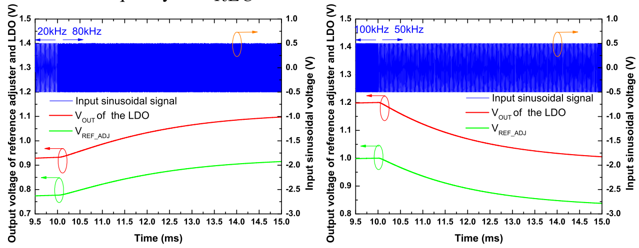
IV. Simulation Results

The proposed technique was implemented and extensively simulated in IBM's *0.13-*μm BiCMOS technology. The circuit was designed to operate with V_{REC}=2.5 V. The input frequency range was varied between 20 kHz to 100 [1]. For realizing the references and the LDO, we followed the structures in [3]. With $V_{REC} = 2.5\ V$, the total power consumption of the circuits shown in Fig. 3 and Fig. 4 is around 400 μW, when f_{sin}=50 kHz.



(a) (b)

Fig. 6. Simulation results for a) steady state output current as a function of frequency at different values of V_{REC}, b) output voltage of LDO as a function of frequency at $V_{REC} = 2.5\ V$.



(a) (b)

Fig. 7. Transient simulation results for V_{REF_ADJ} and V_{OUT} when input frequency varies a) from 20 kHz to 80 kHz, and b) from 100 kHz to 50 kHz at $V_{REC} = 2.5\ V$.

Fig. 5 shows steady state simulation results for currents in different parts of FIC for four different amplitudes of the input sinusoidal signal (A_{SEC}=0.3 V, 0.4 V, 0.5 V and 0.6 V) at f_{sin}=50 kHz. As shown in Fig. 5, variations in the input amplitude result in variations in the amplitude of the output currents of the two RMS-DC converters ($I_{DC1} + I_{AC2\_INT\_RMS}$ and $I_{DC1} + I_{AC1\_RMS}$), however, negligible variation is observed at the output current of the FIC ($I_{DIVIDER}$). After applying the LPFs, the variation in the current I_{FIC_LPF} that goes to the reference adjuster stays below 0.4 μA, with the nominal value sitting at 11.2 μA. Therefore, I_{FIC_LPF} has high stability to the variations in the amplitude of the input signal.

To validate the functionality of the proposed solution and evaluate the line regulation, different values for V_{REC} (2.3 V to 2.7 V) with input frequency ranging from 20 kHz to 100 kHz were considered, and results for I_{FIC_LPF} are plotted in Fig. 6-a. As can be seen, good linearity between the frequency of I_{FIC_LPF} and the input frequency is achieved for different values of V_{REC}. Furthermore, to probe the relationship between the input frequency and the LDO output, simulations were run at $V_{REC} = 2.5\ V$. The results are plotted in Fig. 6-b. The output voltage is linearly dependent on the frequency of the input signal.

Figs. 7-a and 7-b show simulation results for the adjustable reference level (V_{REF_ADJ}) and the output of LDO (V_{OUT}) when the frequency of the input signal transitions from 20 kHz to 80 kHz, and from 100 kHz to 50 kHz, respectively. The observed smooth transition of both V_{REF_ADJ} and V_{OUT} as the frequency varies, validates the dynamic voltage scaling capability of the proposed technique.

V. Conclusion

In this paper, a design technique for implementing wirelessly tunable LDOs was presented. Based on the frequency of the signal at the primary side, the output voltage level of the LDO at the secondary side can be controlled. Simulation results confirmed the functionality and the reliable operation of the proposed technique for different scenarios. The proposed wirelessly tunable LDO can be used as a stimulator for iEAPs in the next-generation muscle prosthesis with the advantage of enabling immediate movement restoration following implantation. Future work include the integration of the proposed LDO with iEAPs and investigating the *in vivo* capability of the subcutaneous prosthesis.

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