Sensors and Actuators A 153 (2009) 222–229

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

# An ultra-low-power precision rectifier for biomedical sensors interfacing

Esther Rodriguez-Villegas[a,*], Philip Corbishley[a], Clara Lujan-Martinez[b], Trini Sanchez-Rodriguez[b]

[a] Department of Electrical and Electronic Engineering, Imperial College London, Exhibition Road, London SW7 2BT, UK
[b] Departamento de Ingenieria Electronica, Universidad de Sevilla, Camino de los Descubrimientos, 41092, Sevilla, Spain

ARTICLE INFO

*Article history:*
Received 20 January 2009
Received in revised form 1 April 2009
Accepted 15 May 2009
Available online 23 June 2009

*Keywords:*
Rectifier
Low-power
Wearable sensor
Breathing

ABSTRACT

This paper revisits the design trade-offs for low-power and low-voltage rectifiers required for sensor interfacing in a variety of biomedical applications. The paper discusses why most previously reported rectifiers are not going to be suitable in these emerging devices since design constraints are different from those in other more conventional applications. A novel rectifier topology is presented that meets the specifications required by a wearable breathing detector and is also suitable for many other devices described in the introduction. The novel rectifier consumes up to 90 nW of power, operates at only power supply voltages down to 1 V and achieves a dynamic range (DR) of 73 dB. The rectifier outperforms other previously reported topologies suitable for this kind of application.



## 1. Introduction

Low-power and low-voltage have become two of the most important drivers in the electronic industry in the last decade. Originally this was due to the strongly emerging consumer market for portable devices that needed to be lightweight and hence operate for a long period of time with a small battery. Recent advances in ultra-low-power circuit design made it possible to conceive electronic systems that could be worn by people, monitor physiological parameters, and even provide some kind of treatment. Wearability and comfortability impose tight constraints on size and hence on power since the smaller the battery the shorter its duration. For devices that, in most cases, have to operate continuously, battery duration is then the major issue. Much attention and resources are currently being put by both, industry and academia, into research on electronic circuit topologies that consume levels of power in the nanowatt range and are suitable for processing biological signals. The rectifier is one of the fundamental blocks that is required in a variety of wearable biomedical systems that incorporate online processing of a biological signal. Low-power/low-frequency rectifiers are needed in bionic implants for the deaf, hearing aids and speech recognition systems [1,2]. Functional electrical stimulation is becoming a promising technique to restore functions of paralysed body organs. As an example of this, an implantable microchip that rectifies bladder dysfunctions for spinal cord injury patients has been reported. Being implanted the amount of power available to operate this microchip is very limited. One of the important signal processing circuit blocks is the rectifier [3]. Important research is also being carried out on circuits that will be implanted near the brain for neural recordings. The data recovery circuitry requires a low-frequency, low-power half-wave rectifier [4]. Adaptive systems, incorporated into cuff electrodes to separate neural from electromyographic potentials have shown very promising results. Rectification again plays an important role. Nerve-cuff electrode recordings can be used to provide sensory feedback to artificial devices [5]. Also, it has been recently shown how intrauterine pressure can be predicted from electrohysterography and this could eventually remove the need for a catheter which increases the risk of fetal and maternal infection [6]. Intrauterine pressure could be measured in an even less invasive way by incorporating some kind of intelligence into the electrodes in the form of a microchip that processes the signal and then transmits the result to a base station or shows it in a small display, freeing the patient of restrictive cables. A low-power, low-frequency rectifier would be one of the constituent building blocks to implement the proposed algorithm. Other examples of systems that when developed will benefit from low-power rectifier blocks include portable surface electromyography systems and systems for sleep studies and treatment of obstructive sleep apnoea [7,8].

Many rectifier circuits have been proposed in the literature. However, very few have been reported that meet the power, voltage frequency and dynamic range constraints required by the above mentioned applications. This paper deals with the typical design issues associated with this kind of rectifier and proposes a novel circuit block that would meet the required specifications. The new rectifier circuit is one of the constituent blocks of a novel miniature breathing detector that has been recently reported [9]. The latter will be briefly introduced in Section 2 to familiarize the reader

* Corresponding author.
*E-mail address:* esther@imperial.ac.uk (E. Rodriguez-Villegas).

0924-4247/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2009.05.020

with the specific application. Section 3 will introduce the principle of rectification together with a review of the most popular circuit topologies that have been used to implement it. Section 4 presents the novel rectifier topology and analyses second order effects. The experimental results are presented in Section 5.

## 2. The rectifier in a low-power breathing detector

The rectifier block presented in this paper was designed to meet the specifications of the wearable breathing detection system reported in [9]. A simplified block diagram of this system is shown in Fig. 1 for illustration purposes and to put the specifications into context. The breathing signal is sensed with a microphone inserted in a conical bell. This signal goes through a bandpass filter with a passband of 500–900 Hz which attenuates signals outside of this range. It has been shown how within this band the ratio between the signal and the combined effects of noise is greatest [9]. Below the passband the ratio between the signal and the myo-acoustic noise, external speech and heart sounds is reduced, making breathing detection less reliable. Above 900 Hz the breathing signal attenuates more so than the noise, reducing the SNR at higher frequencies and reducing the reliability of breathing detection. A sixth order filter is used to attenuate out-of-band signals sufficiently. There are, however, transients due to noise sources, such as myo-acoustic transients and swallowing. The noise artefacts caused by myo-acoustic effects and swallowing create transients that have a broadband frequency response which is not attenuated in the passband of the filter. The system then rectifies the signal and a lowpass filter provides the acoustic envelope signal. The cutoff frequency of the lowpass filter is 2 Hz to capture the fundamental harmonic of the acoustic breathing envelope signal, the period of which relates to the inhalation and exhalation cycle. The bandwidth of interest is from 0.2 Hz to 2 Hz. The amplitude of the differential input signal to the rectifier varies between 340 μV and 348 mV when a small coin cell battery providing 1.4 V is used. In practical terms this means that the rectifier must have a dynamic range of over 60 dB, with noise and dead-zone levels below the minimum signal of 340 μV. It can be seen from these numbers that the main design constraints for this kind of application were the power consumption (since this was designed for a wearable medical device), the power supply voltage and resolution, as opposed to the bandwidth in other different applications. Systematic DC-offsets in the rectifier would not be a problem for the system as long as they do not bring the signal outside the input range of the lowpass filter. However, it is easy to accommodate the filter to account for up to a few mV of offset (which is much lower than the maximum input signal it will have to necessarily process). The feature recognition block will later on account for all the systematic offsets carried by the signal.

## 3. Rectifier circuits

The simplest conceivable form of rectification is diode rectification using a single diode connected with a resistor, as shown in Fig. 2(a). A signal voltage, $V_{in}$ is applied and ideally, the half-wave rectification function is achieved, i.e.:

$$V_{out} = \begin{cases} V_{in} & V_{in} > 0 \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

However, in reality, a voltage across the diode needs to be applied before it conducts, creating a "dead-zone", thus the rectification function is distorted and the resolution compromised. A refinement is to use the diode in the feedback path of an opamp, Fig. 2(b). When the input of the opamp is greater than zero the opamp's output swings and the "dead-zone" effect is minimised by the feedback. When the input of the opamp is less than zero, the diode prevents feedback operation and isolates the rectifier's output from the output of the opamp. A clamp diode may be added to control the voltage at the output of the opamp when the opamp is prevented from being in negative feedback, the phantom in Fig. 2(b). The dead-zone of the rectifier is reduced. However, active diodes are limited by the slew-rate of the opamp. As the diode changes from off to conduction a sudden change in voltage is necessary at the output of the opamp to overcome the dead-zone effect. Sudden voltage change is limited by the slew-rate and over this time period the diode's response has a dead-zone. This causes the dead-zone effect to become frequency dependent because, as frequency increases, the proportion of the waveform affected by the dead-zone increases. If the clamp diode is biased in such a way that the output of the opamp is close to its initial voltage when diode conduction occurs then slew-rate effects are minimised.

A frequency improvement may be achieved over the opamp–diode circuit by using a transconductor–diode circuit, Fig. 2(c) [10,11]. The transconductor circuit drives the diode with a current rather than a voltage. This improves the frequency response as the transconductor is used in an open loop configuration. The maximum frequency of the circuit is now controlled by the parasitic capacitance found at the output of the transconductor and the transconductance value of the transconductor. Rectifiers based on transconductor–diode circuits may operate well into the MHz region [12,13].

Other current mode approaches are also found in the literature, taking advantage of performing voltage-to-current conversion outside of a feedback loop increasing the maximum frequency of operation. One technique is a current mode precision rectifier that does not use a diode. An opamp is connected in an unity gain configuration and the current through the power supplies is measured and subtracted from one another, Fig. 2(d) [14]. In principle this should increase the operational frequency of the system as all the opamps are always in negative feedback, although simulated results within the paper only show results up to a few tens of kilohertz. The currents from the two supplies of the first opamp are then, via resistors converted to voltages, measured by opamps, before a final opamp subtracts the two currents. Although this solves the problem of the dead-zone of the diode, the problem of mismatch occurs, reducing the benefit of this topology. Mismatch between these two differential halves may cause slightly different delays which limits performance. A further extension of this work uses an opamp without feedback to drive bipolar transistors to create a rectifier, Fig. 2(e) [15,16]. This again removes the need for feedback and improves performance over opamp–diode designs. A topology using current conveyors and four diodes may also be used for rectification, Fig. 2(f) [17,18]. This consists of two current conveyors and four diodes for full-wave rectification. This topology may be considered as a fully differential transconductor made from the two current conveyors followed by a diode bridge and is thus no differ-

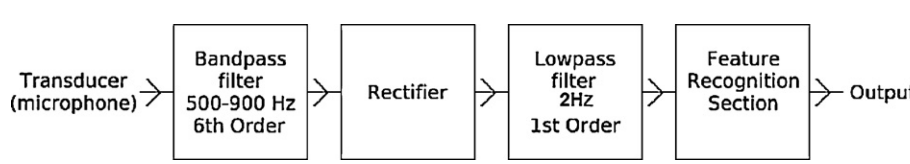


**Fig. 1.** Block diagram of the breathing detector system in which the rectifier is used.