

Signal-Powered Low-Drop-Diode Equivalent Circuit for Full-Wave Bridge Rectifier

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Abstract—Piezoelectric-device-based vibration energy harvesting requires a rectifier for conversion of input ac to usable dc form. Power loss due to diode drop in rectifier is a significant fraction of the already low levels of harvested power. The proposed circuit is a low-drop-diode equivalent, which mimics a diode using linear region-operated MOSFET. The proposed diode equivalent is powered directly from input signal and requires no additional power supply for its control. Power used by the control circuit is kept at a bare minimum to have an overall output power improvement. Diode equivalent was used to replace the four diodes in a full-wave bridge rectifier, which is the basic full-wave rectifier and is a part of the more advanced rectifiers like switch-only and bias-flip rectifiers. Simulation in 130-nm technology and experiment with discrete components show that a bridge rectifier with the proposed diode provides a 30–169% increase in output power extracted from piezoelectric device, as compared to a bridge rectifier with diode-connected MOSFETs. The bridge rectifier with the proposed diode can extract 90% of the maximum available power from an ideal piezoelectric device-bridge rectifier circuit. Setting aside the constraint of power loss, simulations indicate that diode drop as low as 10 mV at 38 μ A can be achieved.

Index Terms—Full-wave bridge rectifiers (FBRs), low-drop-diode equivalent (LDDE), piezoelectric devices (PZDs), synchronous rectifiers, vibration energy harvesting.

I. INTRODUCTION

AMBIENT vibration energy can be harvested and converted to useful electrical energy. The electrical energy can be used for powering low-power electronic systems such as sensors, microelectromechanical systems devices, or implantable medical electronics. Vibration energy can be harvested using various types of transducers such as electromagnetic, electrostatic, or piezoelectric. Electromagnetic-device-based harvesters employ a coil to tap energy from a moving magnetic field produced by magnets, which move in the ambient vibration [1]. In electrostatic energy transducers, vibration leads to a relative parallel motion between an electret and nearby metallic surface [2]. This leads to induced counter charge on the metal, with the charge simply following the relative motion of the electrets. This produces an electric current. Piezoelectric harvesters work by stressing a piezoelectric material in accordance with the vibration and tapping the generated electric charge from the material.

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Electrical energy from any vibration energy harvester device is converted to a load-usable form by an interface circuit, which is connected between the device and its load. The interface circuit consists of a rectifier–filter section for conversion of input ac to dc. The diodes in the rectifier conduct with a voltage drop, leading to power loss. The power loss due to diode drop is a significant fraction of the overall harvested power (10–100 μ W [3], [4]). It is, therefore, required for the diodes to conduct with minimum voltage drop. Hence, there is a need of a low-drop-diode equivalent (LDDE), which can be used to replace the rectifier diodes. In particular, the LDDE should be able to replace the four diodes in full-wave bridge rectifier (FBR), as FBR is the most common circuit reported in the energy-harvesting literature, sometimes referred to as the standard [5].

The LDDE should meet the following requirements;

- 1) it should have a very low forward conduction drop;
- 2) it should block any reverse conduction;
- 3) it should be able to replace the four diodes in FBR;
- 4) it should not use an additional external power supply;
- 5) it should be powered directly from input signal and not from harvested power. This is to use the available input power instead of the extracted output power;
- 6) it should not demand additional off-chip components;
- 7) the control circuit should draw minimum power.

We propose an LDDE, which meets all of the aforementioned requirements. The LDDE is based on mimicking a low-drop diode with a MOSFET operated in linear region. Such a MOSFET which is controlled such that it conducts in the deep triode region in one direction and goes into subthreshold region (OFF state) in the other direction is called a synchronous rectifier.

Previous implementations have also used synchronous rectifiers. However, their control circuit does not meet all of the aforementioned conditions 1–7. CMOS control rectifiers in [6] and [7] and the synchronous full-wave rectifier in [8] need an external power supply for powering up the comparator. Le *et al.*[8] also suggest a passive full-wave rectifier. It, however, requires additional off-chip capacitors. It is also less power efficient owing to the continuous conduction of two diodes by drawing power from the output and also due to reverse conduction by a transistor in saturation region. It also does not show the implementation in FBR.

In [9], a second piezoelectric patch is used to create two stable supply voltages to supply energy to a comparator. In [10], an additional input is required which is 180° out of phase with the input for full-wave rectification.

The proposed LDDE can also be used in voltage multipliers [5], [11] and charge pump [12]. A voltage multiplier with output-powered active diodes is shown in [13]. In [14], a

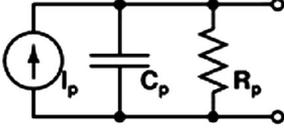


Fig. 1. Equivalent circuit of a PZD at resonance.

current-sensing approach is used for generating the gating signals of output-powered comparator of the MOSFET-based active rectifier. Being output powered, diodes in both [13] and [14] consume standby power. In [15], a MOSFET-based full-wave rectifier followed by a diode to block reverse current conduction is used. The diode is implemented as an active diode powered from the output. The circuit has greatly reduced the diode drop and improved the efficiency. However, the active diode consumes standby power. This issue has been taken care of, in [16] with an input-powered full-wave rectifier and active diode. In [5], the use of gate cross-coupled topologies of MOSFET-based FBR is indicated. This improves the power conversion efficiency. The ideas in [5] and [16] are specific to FBR implementation and are not of a stand-alone LDDE. The synchronous rectifier in [17] suggests a stand-alone LDDE. But it allows reverse conduction. Though the reverse current level can be made small, it cannot be neglected when used in low-power circuits like vibration energy harvesters. There is also a resistor–diode (diode-connected MOSFET) path which is continuously conducting leading to power loss. Work in [17] and [18] has not been suggested for low power (10–100 μ W) application.

In this paper, we have proved the efficacy of the proposed LDDE in a piezoelectric device (PZD)-based vibration energy-harvesting system. The electrical equivalent of a PZD [3] when it is vibrated at its resonance frequency is shown in Fig. 1. I_p is a sinusoidal current source with amplitude equal to $I_{p\text{peak}}$. $I_{p\text{peak}}$ depends on the amplitude of vibration and the frequency f_p of the current source is equal to the frequency of vibration. Resonant frequency of the PZD is assumed to match with f_p . From Fig. 1, it is seen that the maximum available power from the PZD with conjugate matching of load is given by

$$P_{\text{PZD}(\text{max})} = \frac{I_{p\text{peak}}^2 \cdot R_p}{8}. \quad (1)$$

When the rectifier–filter section is introduced at the output of PZD, it sets a further limit on the maximum available power to the load. Let this limit on the maximum available or extractable power be represented by $P_{\text{EXT}(\text{max})}$. Then, $P_{\text{EXT}(\text{max})} \leq P_{\text{PZD}(\text{max})}$.

The proposed LDDE can replace the diodes in various architectures of rectifiers used for PZD-based harvesting. These architectures include conventional FBR, switch-only rectifier [3], [19], bias-flip rectifier [3], series synchronized switching harvesting with inductor (SSHI) [20], [21], synchronous charge extraction circuit [20], [22], voltage doubler [3], resonant rectifier [23], and pulsed-resonant micropower converter [24]. Makihara *et al.* [25] suggest SSHI with two rectification diodes instead of four. Series SSHI with magnetic rectifier [26] uses a transformer to reduce the effective diode drop by a factor equal to

TABLE I
 $P_{\text{EXT}(\text{max})}$ OF VARIOUS RECTIFIER ARCHITECTURES

Rectifier Architecture	$P_{\text{EXT}(\text{max})}$ [3]
FBR	$C_p \cdot (V_p - 2V_D)^2 \cdot f_p$
Voltage Doubler	$C_p \cdot (V_p - V_D)^2 \cdot f_p$
Switch Only Rectifier	$2 \cdot C_p \cdot (V_p - V_D)^2 \cdot f_p$
Bias Flip Rectifier	$2 \cdot C_p \cdot (V_p - \frac{V_D}{Q})^2 \cdot Q \cdot f_p$
V_p is the open circuit voltage amplitude at the output of PZD. V_D is the rectifier diode drop. R_p is ignored in the derivation of $P_{\text{EXT}(\text{max})}$ of the first 3 rectifiers. Q is qualitatively the parallel combination of the Q-factors of PZD and that of the resonant path of C_p and inductor of bias-flip rectifier.	

the transformer ratio. The $P_{\text{EXT}(\text{max})}$ is dependent on the architecture of rectifier. The SSHI and resonant architectures provide a high $P_{\text{EXT}(\text{max})}$, as compared to the conventional FBR. Table I gives the $P_{\text{EXT}(\text{max})}$ of different architectures. From Table I, it is seen that for all rectifier architectures, $P_{\text{EXT}(\text{max})}$ increases as the rectifier diode drop decreases.

The remainder of this paper is organized as follows. Section II covers the working principle and power considerations of the proposed LDDE. Section III gives the design considerations and the simulation results in 130-nm technology. Section IV describes the detail of an experiment with the proposed LDDE, implemented with discrete components. Finally, Section V concludes this paper.

II. WORKING PRINCIPLE OF THE PROPOSED LDDE

A MOSFET operated in linear region (deep triode region) exhibits a very low value of dc resistance. It can conduct with lesser voltage drop for the same current, as compared to a diode or a diode-connected MOSFET (DCMOS). This property of MOSFET is exploited to use it to mimic a low-drop diode. It may also be noted that a DCMOS cannot be used as a low-drop diode, because of a minimum drop across it which is equal to the threshold voltage of MOSFET.

In the proposed LDDE, MOSFET is controlled such that it conducts only in one direction (call forward direction) and in linear region in the forward direction. The control circuit is designed such that it draws power directly from the input signal, so that no external supply is required.

A circuit diagram of the proposed LDDE is shown in Fig. 2. Source of PMOS (M_1) acts as the anode and drain of M_1 acts as the cathode of LDDE. The emitter–base junction of p-n-p transistor (T_1) is across (in parallel with) the source–drain of M_1 . Substrate of M_1 is kept connected to drain to block reverse conduction.

To illustrate the LDDE operation, the following step-by-step description is given:

- 1) When LDDE sees a voltage in the forward direction (positive signal voltage), the emitter–base junction of T_1 is forward biased and T_1 begins to conduct.
- 2) When T_1 conducts, it provides the base drive current to n-p-n BJT (T_2) and T_2 enters into conduction.
- 3) The gate–source capacitance C_{gs} of M_1 gets connected across the PZD through T_2 and C_{gs} starts getting charged in the negative direction.

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