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# A Smart Load Interface and Voltage Regulator for Electrostatic Vibration Energy Harvester

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**Abstract.** This paper presents a new implementation in ams 0.35 $\mu\text{m}$  HV technology of a complete energy management system for an electrostatic vibrational energy harvester (e-VEH). It is based on the Bennet's doubler architecture and includes a load voltage regulator (LVR) and a smart Load Interface (LI) that are self-controlled with internal voltages for maximum power point tracking (MPPT). The CMOS implementation makes use of an energy harvester that is capable of producing up to 1.8 $\mu\text{W}$  at harmonic excitation, given its internal voltage is kept within its optimum. An intermediate LI stage and its controller makes use of a high side switch with zero static power level shifter, and a low power hysteresis comparator. A full circuit level simulation with a VHDL-AMS model of the e-VEH presented was successfully achieved, indicating that the proposed load interface controller consumes less than 100nW average power. Moreover, a LVR regulates the buffer and discharge the harvested energy into a generic resistive load maintaining the voltage within a nominal value of 2 Volts.

## 1. Introduction

The electrostatic vibrational energy harvesters (e-VEH) is a category of energy harvesters of which the vibrational energy is transduced into electric energy through an electrostatic transducer. The electrostatic transducer is usually a variable MEMS capacitor. In most of the implementations, such as [1, 2], the transducer is usually accompanied by a conditioning circuit (CC) where its role is to assist the energy conversion process and can be regarded as an autonomous form of maximum power point tracking algorithm (MPPT). In recently published e-VEH implementations, only the transducer and the CC are considered, with almost no form of energy management for the harvested energy to be interfaced with a load. In this paper we present a smart load interface that manages the extraction of the harvested energy from the CC and ensures the CC operating within its optimum region.

This paper is arranged as follows, first the e-VEH system blocks are introduced, then the CMOS implementation of each block is proposed, finally the simulations and conclusion are discussed.

## 2. E-VEH System Blocks

A smart e-VEH system is proposed that is formed of three main blocks - shown in Figure 1: a Bennet's doubler CC, followed by an intermediate load interface (LI), and load voltage regulator block (LVR). The load interface is a DC/DC converter like architecture. The load could be a low power sensor - such as in body sensor network (BNS) or a motion sensor. The requirements



of the load can vary from one application to another, yet it is not the main concern of this work. However, some load voltage regulation is proposed in this work for a generic load.

### 2.1. Bennet's Doubler CC

Conditioning circuits based on Bennet's doubler are one of the promising CC that were first introduced by A. Querioz et al in in 2014 [3]. Since then, it has gained the interest of the electrostatic energy harvesting community such as [4], [5] and [6]. It implements a rectangular QV cycle, with two main advantages on other QV cycles: First, It allows the accumulation of energy through self-increasing of the internal voltage. This allows a build up of energy even from small initial external biasing. Second, It allows synchronization of the charge flow with the movement of the MEMS capacitor plates through a network of diode, thus remove the need of extra controlling blocks.

However, Bennet's doubler CC has a fundamental characteristic of which the power of conversion is function of the instantaneous value of its internal energy. An energy management should achieves a smart control of this internal energy by setting the CC internal voltage within an interval maximizing the power of conversion. This is vital for circuits with self-increasing biasing, as Bennets doublers. Thus a load interface (LI) that separates the load from the CC while controlling that smart control is proposed. Moreover, high voltages are easily achieved with e-VEHs (up to tens of volts) while the harvested energy are typically within few micro watts, leaving  $1 - 2\mu W$  available for controller overhead at most. In consequence a mix of high voltage interface and low voltage low power controller is a must for proper operation of the e-VEH. The next subsection discuss in details this load interface.

### 2.2. Load Interface and Load interface Controller

The LI is formed of an inductor ( $L$ ), freewheeling diode ( $D_{LI}$ ), buffer load capacitor ( $C_{buffer}$ ) and a high voltage switch ( $SW_{LI}$ ). The  $C_{load}$  is a buffer low voltage storage capacitor. It is necessary for interfacing the harvester with the load, since  $V_{res}$  is usually too large to interface (up to 30V for some e-VEH) with the load. Moreover,  $V_{res}$  may experience slow variations, whereas the load voltage should be stabilized.

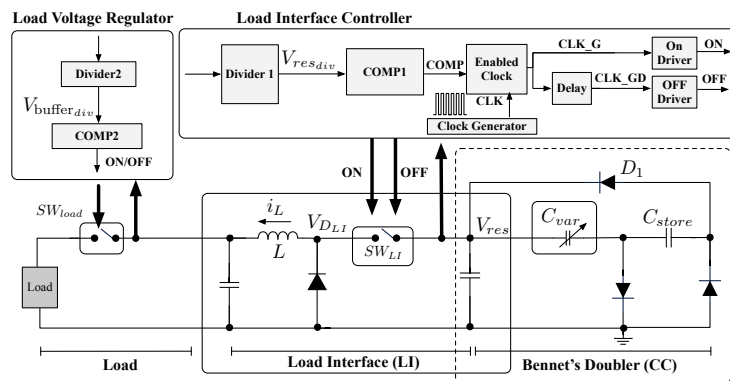
In general, the reservoir voltage ( $V_{res}$ ) has an optimum interval in which the harvesting power is maximized [7, 8]. If the voltage  $V_{res}$  exceeds this interval, then it should be forced back. The optimum interval is defined where  $V_{res}$  is within the two thresholds,  $V_H$  and  $V_L$ . The energy to be removed from  $C_{res}$  to drop its voltage from  $V_H$  to  $V_L$  is,

$$\Delta W = \frac{1}{2} C_{res} (V_H^2 - V_L^2) \quad (1)$$

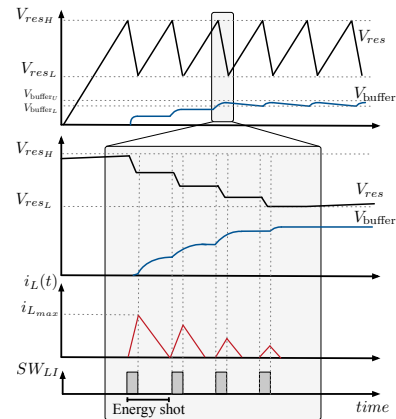
Extracting  $\Delta W$  is achieved by LI and is controlled by sensing  $V_{res}$  and controlling the switching order for  $SW_{LI}$ .

However, the technology of which the switch is implemented usually sets a fundamental upper limit on the allowed inductor current ( $I_{Lmax}$ ). In an effort to transfer the energy with a constrained current, the energy is transferred through number of energy-shots inspired from the well know burst-mode control. This burst-mode energy transfer process is repeated until  $\Delta W$  is extracted from  $C_{res}$ .

The proposed load interface controller is achieved by applying a scaled divided version of  $V_{res}$  to a comparator with a hysteresis as shown in Figure 3. The hysteresis gap is adjusted to the scaled version of the two thresholds  $V_L$  and  $V_H$ . The comparator output - COMP - controls an enable clock that precisely generates the switching decision for  $SW_{LI}$ . The transistor level implementation of the LI controller is discussed in the next section.



**Figure 1.** E-VEH with Bennets doubler CC, LI and LVR.



**Figure 2.** Multiple energy-shot transfer illustration of  $V_{res}(t)$ ,  $V_{buffer}(t)$  and  $i_L(t)$ .

### 2.3. Output Voltage Regulator

The LVR regulates  $V_{buffer}$  low voltage to maintain it between  $V_{buffer_U}$  and  $V_{buffer_L}$  while supplying the load with the required energy thus maintaining  $V_{buffer}$  within its average nominal value. The LVR controller senses a divided voltage of  $V_{buffer}$  using a second comparator (COMP2) as shown in Figure 4. It maintains  $V_{buffer}$  between  $2V < V_{buffer} < 2.2V$  by allowing the discharge of  $C_{buffer}$  into a load modeled by a resistor.

## 3. CMOS implementation and simulation

The load interface and the voltage regulator are implemented in ams 0.35  $\mu m$  HV (50V) technology. It makes use of the energy harvester presented in [9], which is capable of producing up to  $1.8\mu W$  at harmonic excitation, given  $V_{res}$  is kept within its optimum. The intermediate LI stage and its controller, shown in Figure 3, makes use of a high side switch with zero static power level shifter [10], and a low power hysteresis comparator (COMP1). The LI controller was previously presented in details in [11] with average power consumed of less than  $100nW$  (excluding the switch and the voltage divider). The optimum  $V_{res}$  interval is set between 15V and 13.5V. The  $C_{buffer}$  is allowed to discharge into a light resistive load of ( $525\Omega$ ) by a LVR, shown in and Figure 4. It makes use of a low power hysteresis comparator (COMP2), similar to the one used for the LI controller. The system simulation depicting the behavior of the load interface proposed system is shown in Figure 5. With the reservoir capacitor initially charged with 20V, simulation shows the evolution of both the harvester internal voltage ( $V_{res}$ ), LI buffer voltage ( $V_{buffer}$ ) and Load voltage ( $V_{Load}$ ) with successful regulation of load voltage and maintaining  $V_{res}$  within its optimum interval.

## 4. Conclusion

This paper presents a complete energy management interface for vibrational energy harvesters. It is capable of regulating high internal voltage of the conditioning circuit while maintaining maximum energy harvested. This is achieved by a mix of high and low voltage design. The controller design takes into account low energy constraints, as the whole system should be able to operate within low power generated from the harvester. The proposed e-VEH system also offers an output load voltage regulation of a resistive load and is capable of periodically supplying a generic load with a 2V for a period of 1ms.

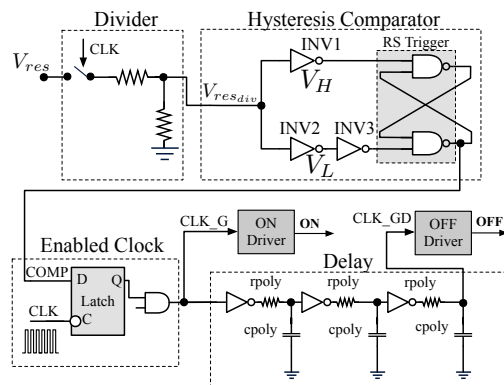


Figure 3. Load Interface Controller.

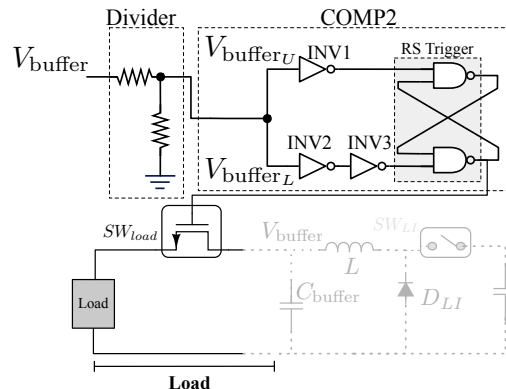
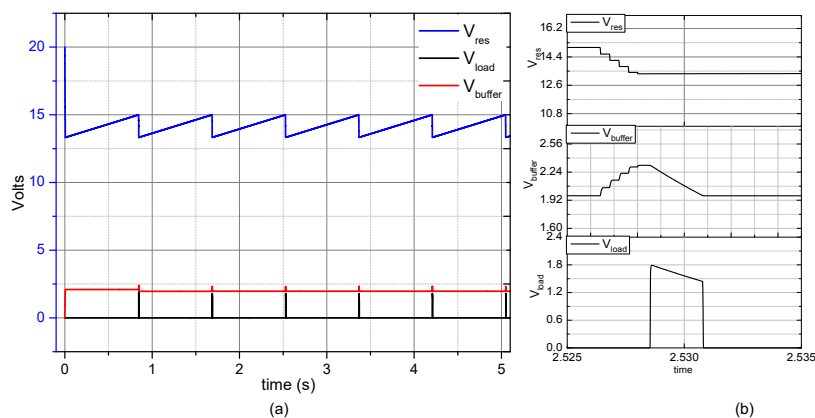


Figure 4. Load Voltage Regulator.

Figure 5. E-VEH LI simulation  $0s < t < 5s$  (a) zoom-in at  $2.525s < t < 2.535s$ (b).

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