Piezoelectric Harvesting Circuit with Extended Input Voltage Range

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***Abstract*—A high efficiency energy harvester for a piezoelectric generator (PZG) was developed and tested experimentally. The proposed circuit is based on a non linear resonant rectifier that replaces the simple and less efficient diode bridge rectifier. The two stage harvester (rectifier and converter) extends the input voltage range capability and mitigates the dependency of the harvester on PZG output voltage. The second stage of the proposed circuit includes a low loss converter that stabilizes the output voltage. The paper presents a comparison and evaluation of two interface schemes connected to a step-down converter. One is based on a simple diode rectifier front end and the other one is the proposed non linear rectifier. It is shown that in a self powered mode, under same acceleration level of 0.38g, the improved harvesting circuit can increase the extracted power by 186% as compared to a conventional bridge rectifier interface. In addition, experimental results show that the proposed circuit can sustain output voltage regulation 3.4 times longer compared to direct connection bridge topology for 1.8mA load step.**

***Index Terms*—Harvesting, piezoelectric devices, resonant power conversion, AC-DC power conversion, comparators.**

I. INTRODUCTION

The development of ultra low power electronics makes possible the utilizing of alternative power sources to replace conventional batteries in remote sensor assemblies. Energy harvesting from solar, wind, thermal etc. to power wireless devices has been a focus of interest in the past few years. One promising power source is the piezoelectric generator (PZG) that extracts energy from surrounding mechanical vibrations which are found, for example, in an office air conditioning unit or a car engine. Practical ambient vibrations acceleration levels have been identified as varying from 0.02g to 1.2g at frequencies ranging from 60Hz to 200Hz [1], [2]. At resonance, piezoelectric generators with constant displacement amplitude can be modeled as a sinusoidal current source i_P in parallel with its electrode capacitance C_P (Fig. 1). In order to optimize the output power, it is required to match the load to the device properties [3]-[4] and to neutralize the capacitive output impedance [5]-[7]. In most applications, the AC signal produced by the generator needs to be rectified and to be fed to loaded DC-DC converter for maximum power tracking or voltage regulation. Previous studies have shown [8] - [10] that for each rectification interface scheme there exist an optimum load resistance R_{opt} for which the output power is maximized. Furthermore, placing a switched inductor across the terminal of the vibrating PZG has been suggested in the literature as a means for reducing the ill effect of the internal capacitor C_P of the PZT on its power output. For example, applying the rectifier interface shown in Fig. 1 as the first stage of a piezoelectric harvester, was shown to increase considerably the available power [5]-[7]. It was further observed that effective operation of the rectifier requires a comparator U_c (Fig. 1) to drive the switches. However, micro power comparators with relatively fast response time, as required in this application, are limited to low supply voltages. In a self powered mode, the supply voltages of the comparator are generated internally by rectifying the fluctuating output voltage of PZG. Consequently, the operation of the rectifier will be limited to the maximum ratings of the comparator's power supplies. In this study, a second stage converter is combined to the first stage resonant rectifier in order to alleviate this limitation.

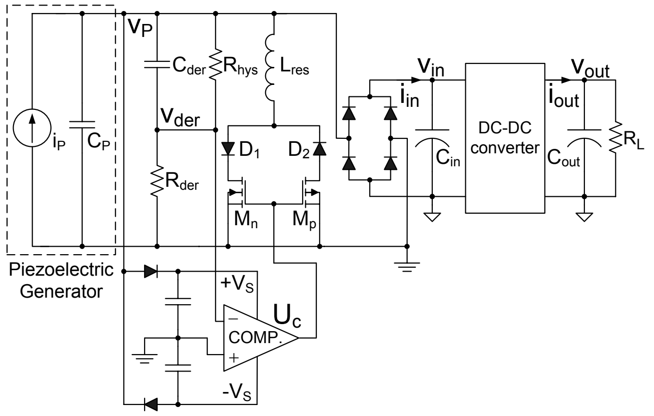

Fig. 1. A resonant rectifier interface connected to a DC-DC converter. The input voltage of the circuit is limited by the maximum ratings of the comparator's power supplies.

This paper describes the development and realization of a self-powered system and its experimental evaluation compared to standard rectification technique. The solution presented here is based on discrete board level components. The electronic circuitry of the harvesting circuit was assembled using low power and off the shelf components. Overall system simulations were carried out to verify

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functionality and behavior of the system.

II. Analysis and Simulation

The basic idea behind the proposed rectification scheme shown in Fig. 1 is to initiate self commutation of the voltage across the output capacitor of the PZG. By proper timing, the external inductor L_{res} forms a resonant network with capacitor C_P and thereby causes the voltage of the PZG to flip polarity. The resonant rectification topology includes an inductor (L_{res}), two switches (M_n, M_p), two diodes (D_1, D_2), a differentiating circuitry (C_{der}, R_{der}, R_{hys}) that senses the slope of the capacitor's voltage (dv_p/dt), and a comparator (U_c).

As stated previously, the operation of the resonant rectifier of the configuration shown in Fig. 1 will be limited to the maximum ratings of the comparator's power supplies. As detailed below, this limitation was alleviated in present study by coupling auxiliary windings to the main DC inductor L_o of a buck converter. A step-down converter was selected because of the requirement for low regulated output voltage in broad range of applications. For example, 1.8V voltage level corresponds to the minimal working voltage of low power microcontrollers, accelerometers and RF circuits. In the proposed configuration, the power supply voltages of the comparator are approximately proportional to the regulated output voltage.

To compare the effectiveness of the proposed resonant rectifier and the conventional bridge rectifier, we first derive analytically the expression for the expected rectified output voltage (V_{in} in Fig. 1) for the two configurations. In the following analysis the damping effect of the generator is ignored. Namely, the amplitude and frequency of the generator is regarded to be constants rather than load dependent variables. The equivalent sinusoidal current source i_P is proportional to the velocity and as:

$$i_P(t) = \alpha \dot{u}_P(t) \qquad (1)$$

where, α is the piezoelectric force factor, and u_P is the displacement of the piezoelectric patch. Neglecting losses, the average input and output powers of the DC-DC converter are equal,

$$V_{in} I_{in} = V_{out} I_{out} \qquad (2)$$

where I_{in} and I_{out} are the average input and output currents of the converter, respectively (Fig. 1). The output voltage V_{out} is fixed at a defined regulated low voltage (1.8V). Hence, the average input resistance R_{in} of the converter that is also the equivalent resistance seen by the rectifier is proportional to the output load R_L as follows,

$$R_{in} = \frac{V_{in}}{I_{in}} = \frac{V_{in}V_{in}}{V_{out}I_{out}} = R_L \frac{V_{in}V_{in}}{V_{out}V_{out}} = R_L \left(\frac{V_{in}}{V_{out}}\right)^2 \qquad (3)$$

This relation holds regardless the converter type or operating mode (DCM, CCM). The average current that reaches the converter input for the standard rectifier (I_{in_SR}) and resonant rectifier (I_{in_RR}), is the integral of i_{in} over time (Fig. 1) [6],

$$I_{in\_SR} = \frac{2}{T_P} \int_0^{T_P/2} i_{in}(t)\,dt = \frac{2I_P - 4\omega_P C_P V_D}{\pi + 2\omega_P C_P R_{in}} \qquad (4)$$

where, I_P and ω_P are the amplitude and the resonant angular frequency of the current source i_P, respectively. The diode forward voltage drop V_D of the full bridge has been also considered in the analysis. Correspondingly, the average current of the resonant rectifier (I_{in_RR}), is [7],

$$I_{in\_RR} = \frac{I_P(1-e^{-\frac{\pi}{2Q_r}}) + I_P(1+e^{-\frac{\pi}{2Q_r}})\cos\delta - \omega_P C_P V_D (3-e^{-\frac{\pi}{2Q_r}})}{\pi + \omega_P C_P R_{in}(1-e^{-\frac{\pi}{2Q_r}})} \qquad (5)$$

where the phase lag δ defines as the time delay from zero crossing of i_P to the switching instant of M_n or M_p. $Q_r=\omega_r/2\alpha_r$ is the quality factor of the resonant branch, while $\omega_r^2 = \omega_{res}^2 - \alpha_r^2$, $\alpha_r=R_r/2L_{res}$ and ω_{res} is the resonant angular frequency during the voltage inversion process. R_r is the total resistance that includes $R_{ds(on)}$ of the switches and the resistance of the inductor R_{res}. The steady state average input voltage V_{in} of the converter for the two configurations can be found by multiplying equations (4) and (5) by the equivalent input resistance R_{in}. Applying (3) yields,

$$V_{in\_SR} = \frac{2I_P - 4\omega_P C_P V_D}{\pi + 2\omega_P C_P R_L \left(\frac{V_{in\_SR}}{V_{out}}\right)^2} R_L \left(\frac{V_{in\_SR}}{V_{out}}\right)^2 \qquad (6)$$

and

$$V_{in\_RR} = \frac{I_P(1-\gamma) + I_P(1+\gamma)\cos\delta - \omega_P C_P V_D(3-\gamma)}{\pi + \omega_P C_P R_L \left(\frac{V_{in\_RR}}{V_{out}}\right)^2 (1-\gamma)} R_L \left(\frac{V_{in\_RR}}{V_{out}}\right)^2 \qquad (7)$$

where $\gamma=\exp(-\pi/2Q_r)$.

The solutions of (6) and (7) for V_{in} are depicted in Fig. 2 as function of R_L for the following parameters: i_P=0.5mA, V_D=0.5V, C_P=60nF, ω_P=2π·185rad/s, δ=π/3, γ=0.692. The results of Fig. 2 show that the input voltage of the resonant rectifier is higher than the input voltage of the standard rectifier for all possible loads. This is due to the fact that the

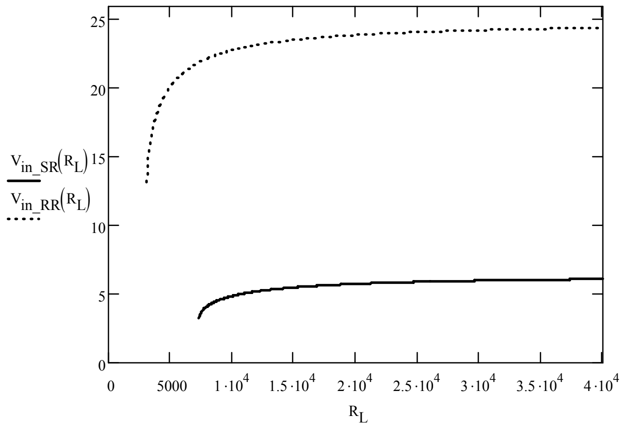


Fig. 2. Analytical comparison between average output voltages (V_{in} of converter) of the resonant rectifier interface and the standard interface versus output load R_L.

switched inductor neutralized the capacitors' C_P current in the resonant rectifier, increasing thereby the impedance seen by the PZG. This would boost the piezoelectric output voltage of the PZG (v_p) to higher levels for same i_P. Hence, the rectified voltage V_{in}, which is the input voltage of the buck converter will increase as well. Higher input voltage implies a higher input power and a larger stored energy on the input capacitor of the converter.

A simulation was carried out by LTspice using model of micro-power LTC3588-1 controller used in this study (Fig. 3). The internal capacitance of the piezoelectric generator C_P was estimated to be 60nF using the technique of [11]. The PZG current i_P used in the simulation was estimated experimentally using the relation $V_P=I_P/C_P\omega_P$, where V_P is the piezoelectric open circuit peak voltage. The PGOOD signal of the controller can be used for estimating and comparing the ability of the two configurations to support peak power load demand. According to the specification, PGOOD pin remains high until V_{out} falls to 92% of the desired regulation voltage (1.8V). Fig. 4 shows the simulated waveforms of the two configurations for a current step of 1.8mA. As evident from Fig. 4, the resonant interface configuration is able to sustain regulation 6.4 times longer compared to the standard connection. This hold up time is of course dependent on the value of the capacitor connected at V_{in} (10µF, in the simulated case).

III. Experimental Setup and Results

The configurations under study were investigated in order to evaluate their performance in self powered mode under different conditions. Fig. 5 shows the schematic diagram of the experimental setup for testing the two configurations. The prototype implementation for this setup and the harvesting circuit are shown in Fig. 6. Piezoelectric bimorph with free end was used as the piezoelectric generator (RBL1-006 model, Piezo Systems, Inc). The other side of the bimorph is clamped to the PCB harvesting circuit. The whole system is

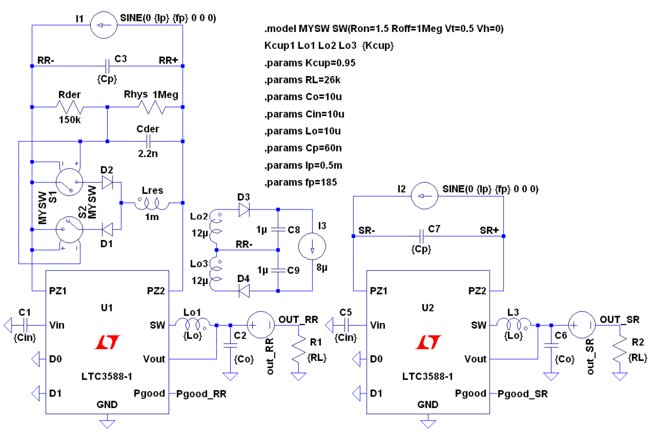


Fig. 3. Simulation diagram of the standard rectifier (right side) and the resonant rectifier (left side). The auxiliary windings (L_{o2} and L_{o3}) are coupled to the main DC inductor (L_{o1}) and used to feed the comparator by an approximately constant voltage. The average current drawn from the power supplies of the comparator (8µA) is an overestimated current consumption of the comparator.

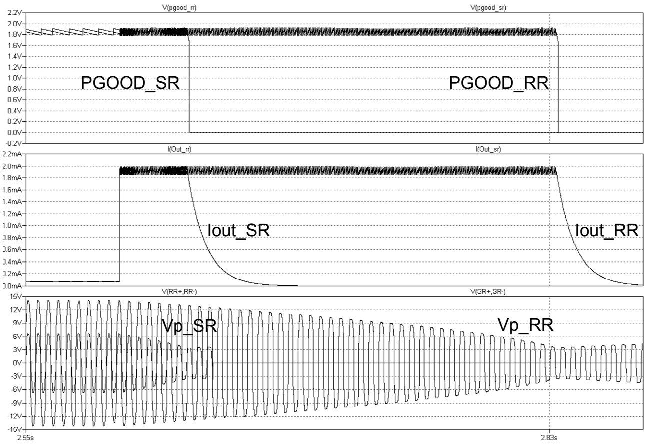


Fig. 4. Simulation waveforms of 1.8mA load step response of the two configurations. See Fig. 3 for notations.

screwed on an electromagnetic shaker [12] which simulates vertical ambient vibration across the z-axis. The shaker was sinusoidally excited by a function generator signal that was amplified by a power amplifier. As a result, the piezoelectric device was forced to vibrate in a bending mode at a frequency imposed by the shaker.

The 1mH inductance of the resonant inductor L_{res} was built around a EFD 15 core (Philips) on which 35 turns of AWG #24 were wound. The series resistance of the inductor was measured by a LCR meter to be 0.24Ω at a frequency of 1kHz. The comparator U_c was an ultra low power MAX921 IC (Maxim, USA) drawing 4µA supply current I_Q. The supply voltage range of the comparator is from ±1.25V to ±5.5V and the typical propagation delay is 12µs. It should be noted that other commercial ultra low comparators are also compatible with the requirement of the proposed harvesters, such as Linear Technology's LTC1440 IC. As pointed out above, since the piezoelectric voltage v_p can be higher than ±5.5V, the supply voltages of the comparator were generated by two auxiliary windings. The main DC inductor L_o of a buck converter and the auxiliary windings were also built around a EFD 15 core (Philips). A micro-power LTC3588-1 IC with internal diode bridge and switches was chosen as the step-down converter. Two 10µF tantalum storage capacitors were connected at the input and output terminals of the converter. In some practical applications supercapacitor would be beneficial to increase the hold up time.

The vibrating frequency of the system was fixed at 185Hz (corresponds to the fundamental resonant frequency of the PZG). The input acceleration level was monitored using Analog Devices ADXL325 accelerometer. The sensitivity and output bandwidth of the device across the z-axis, at supply voltage of 3.3V, are 192mV/g and 500Hz, respectively.

The experimental results of the piezoelectric output v_p under two different loads driven by a vibrations of 0.38g acceleration magnitude are given in Fig. 7 for comparison. This vibration magnitude of 0.38g is within the range of practical vibration sources [1]-[2], and thus can be considered a representative case. Fig. 7 reveals that the amplitude of the resonant rectifier is higher than the standard rectifier

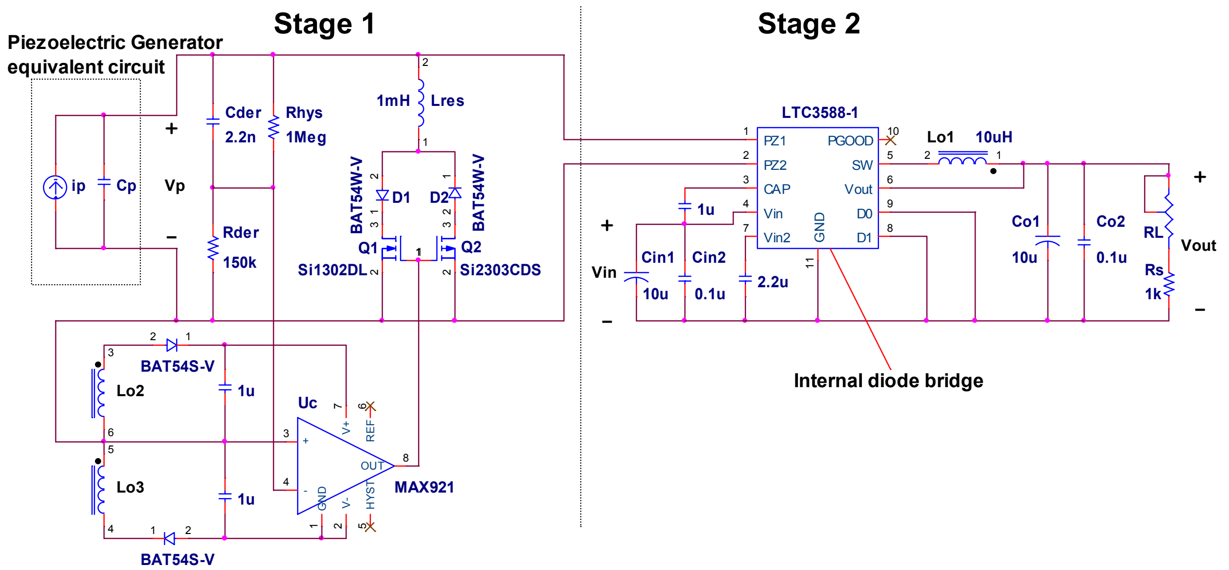


Fig. 5. Proposed self powered resonant rectifier circuitry with auxiliary windings and regulated output voltage.

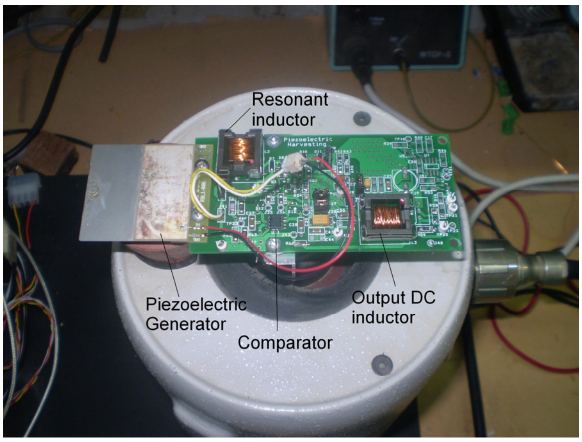
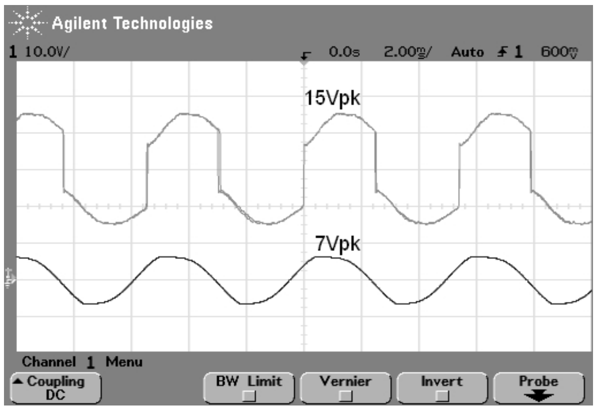
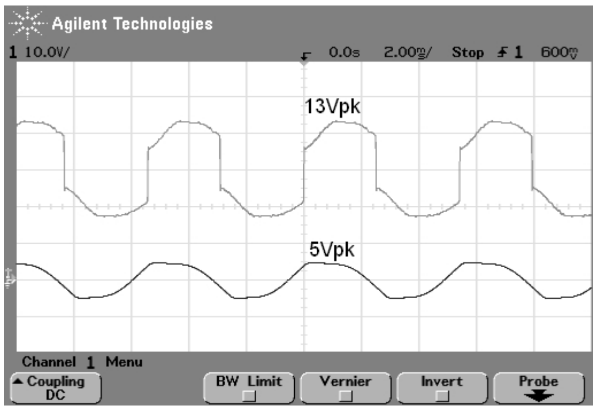


Fig. 6. Experimental setup and circuit prototype. Piezoelectric generator (with free end) is clamped to a PCB. The whole system is mounted on a shaker that provides vertical (z-axis) sinusoidal vibration.



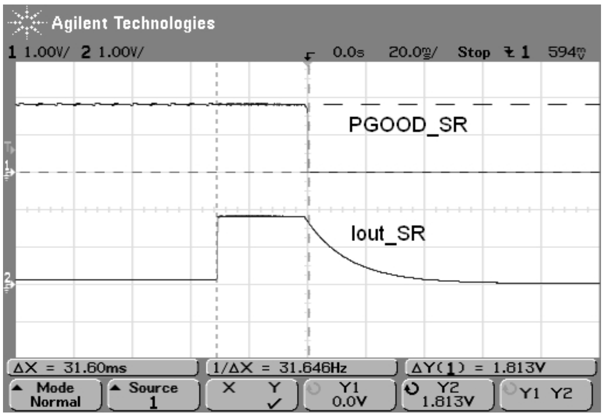
(a)



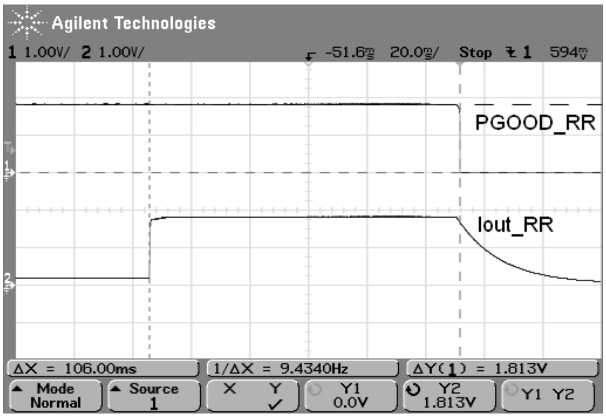
(b)

Fig. 7. Experimental waveforms of the piezoelectric output voltage v_p for direct connection (lower trace) and the resonant interface (upper trace) under 0.38g acceleration excitation: (a) I_{out}=100μA, V_{out}=1.817V, (b) I_{out}=200μA, V_{out}=1.817V. Vertical scale: 10V/div., horizontal scale: 2ms/div..

configuration. This outcome confirms that the rectified input voltage of the converter V_{in} is indeed behaving as predicted theoretically. The maximum output power for the two configurations at the same applied acceleration amplitude of 0.38g was recorded by decreasing the load resistances until the system collapsed. The maximum output power were found to be 743μW and 400μW for the resonant rectifier interface and the direct connection topologies, respectively. This implies that the resonant rectifier configuration improves the power harvesting by 186% as compared to the direct connection scheme. In order to evaluate the behavior of the system in a case of sudden increase in output current demand, a load step was applied to the topologies. These experiments mimic a realistic scenario in a wireless sensor system in which the radio will typically turn on for short period of time in order to receive and transmit data, and then go again into sleep mode. Typically, wireless sensors consume peak powers of several mW for short period of milliseconds durations. Fig. 8 illustrates 1.8mA load step response of the two systems under study for input acceleration magnitude of 0.26g. As expected, the captured waveforms (Fig. 8) show that the time interval from the load step event to the loss of regulation (measured by PGOOD signal) is 3.4 times longer for the resonant rectifier



(a)



(b)

Fig. 8. Experimental waveforms of PGOOD signal (upper trace) and I_{out} current (lower trace) for 1.8mA load step under 0.26g acceleration excitation: (a) direct connection with load step between 70µA and 1.8mA, (b) resonant interface with load step between 100µA and 1.8mA. Vertical scale: 1V/div., horizontal scale: 20ms/div..

interface than that of the direct connection topology. As already pointed out, these hold up times can be extended by using a larger capacitor at the input of the converter.

IV. Discussion and Conclusions

This study presents a self powered and output voltage stabilized PZG based harvesting system. The improvement of this modified configuration over previous published approaches is the stabilization of the comparators' voltages and the output voltage by a low power, monolithic DC-DC step down converter. Experimental measurements validate the proposed concept, showing good operation of the harvesting circuit over wide range of voltages. The proposed circuit was also tested in response to peak load current demand by applying 1.8mA load step to the circuits. Simulation results predict that for this stepped load, the proposed interface will sustain regulation 6.4 longer than direct connection (Fig. 4) while the experimental results validated an improvement of 3.4 in regulation time as compared to direct connection (Fig. 8). The discrepancy between simulation and experimental results is mainly due to the fact that the simulation was derived for constant displacement model while the experimental system was actually driven by constant force (acceleration) amplitude. In such a case, the damping effect of the electrical load will reduce the amplitude of the PZG vibration. Nonetheless, the results clearly confirm the conclusion that the resonant rectifier interface helps to maintain the rectified voltage of a PZG above the UVLO threshold of the DC-DC converter for broader load range as compared to bridge rectifier.

The results obtained in this study show that the resonant rectifier interfaced with an efficient buck converter, that includes coupled inductors to stabilize the comparator's voltage, form a robust energy harvesting solution, optimized for piezoelectric sources.

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