Electronic Interface for Piezoelectric Energy Scavenging System

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Abstract- **The paper focuses on an electronic interface for systems, called Piezoelectric Energy Scavenging Systems (PESS), which convert the energy of mechanical vibrations into electrical energy using a piezoelectric transducer. The output of the transducer is a strong and irregular function of time hence, to obtain a suitable supply source, an AC-DC conversion is needed. Classical rectifiers (half/full bridge or voltage doubler) with an output storage capacitor do not fit very well, since they work as peak detectors, converting only input voltages which are higher than their output voltage.**

The paper shows an electronic interface which is able to efficiently harvest the energy associated to the randomic voltage waveform delivered by a piezoelectric transducer. Its working principle is based on an inductive step-up converter; an active driving circuit is used to set the phases of the converter. The energy is stored into a capacitor which is also used to supply the active elements of the step-up converter, realizing a completely autonomous energy scavenging system. For this reason the whole circuitry has been designed with a very low-power consumptions, about 700 nA. A prototype was diffused in 5V CMOS STMicroelectronics technology and measurements showed its effectiveness.

I. Introduction

Energy scavenging systems are used to harvest the normally lost environmental energy and to convert it into electrical energy. This approach can be attractive where batteries are a bottleneck for the whole system (e.g. they have a finite life time and their replacement or recharge is not feasible or too expensive). An energy scavenging system, instead, is a theoretically endless energy source. In literature many papers describe methodologies to realize the energy-scavenger [1], [6], [8]. A lot of them focus on the conversion of the energy associated to mechanical vibrations since they can be easily found in many environments [1], [7]. This paper focuses on a piezoelectric transducer since it is one of the more efficient systems to convert the energy of mechanical vibrations [1]-[2].

The electrical output of the transducer is a strong and irregular function of time [1]-[4], [9] thus an AC-DC conversion is needed to realize a DC power supply. In literature many solutions are presented to realize this function, mainly based on classical topologies of AC-DC converters [1], [3]-[4], [9]-[11] (e.g. half/full bridge, voltage doubler) with a capacitance C_O connected at their output to store the harvested energy. The main limitation is that the energy associated to transducer output voltages lower than the voltage stored on C_O can not be harvested. This is a big drawback because in a real environment the mechanical vibrations and, consequently, the transducer output voltage, are often an irregular function of time. For example, Fig. 1 shows the measured voltage given by a piezoelectric transducer placed onto a car dashboard: there are few chances that the peaks following the one at 5 seconds could be harvested.

Anyway, even if the source is sinusoidal, after a transient a condition is reached when energy is no longer transfered from the transducer to the output. To realize an efficient energy scavenging system it is necessary to harvest the energy of the entire waveform.

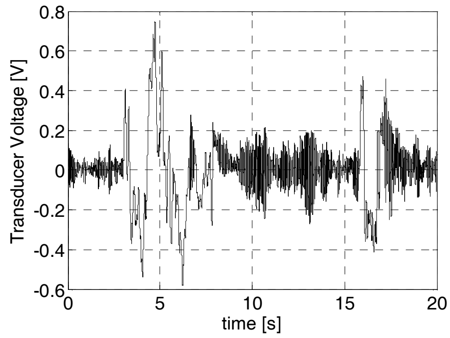

Fig. 1 Voltage supplied by a piezoelectric transducer, working in 31-mode, placed onto a dashboard.

The proposed solution is aimed at improving the efficiency of a PESS based on a cantilever-like piezoelectric transducer working in 31-mode. The front-end circuitry allows positive peaks of any amplitude to be harvested indipendently of the voltage across the storage capacitor C_O; while, for negative peaks, the behaviour of the circuit is the same as the standard voltage doubler.

A test chip was diffused in 5V CMOS STMicroelectronics technology and the measurements are presented.

II. Working Principle of the Proposed Solution

A piezoelectric transducer can be modeled as a current source, i_P, whose current is proportional to the derivative of cantilever strain, with a capacitor C_P in parallel [12]. Fig. 2a shows the block scheme of the proposed electronic interface while Fig. 2b is the working cycle obtained with

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an appropriate driving of the switches. Let us assume the cantilever starts from rest condition (no strain and no charge on plates) and it is then deflected from *a* to *b* (ref. Fig. 2b). If no load is connected to C_p, voltage v_P is the integral of current i_P and it reaches a local maximum V_{PMax} when the cantilever is at its maximum strain. At this point, C_P has collected the maximum charge, Q_{Pmax}, onto its plates and it stores an electrical energy equal to:

$$E = \frac{1}{2}\frac{Q_{Pmax}^2}{C_P} \quad (1)$$

Energy harvesting is maximally efficient if all of this energy is extracted. A classical rectifier does not comply to this requirement because it connects the transducer to the output storage capacitance as soon as the voltage v_P is higher than V_O [4, 10]. In this way the transducer has to produce a charge C_PV_O to reach the voltage V_O and from this moment on all of the extra generated charge is shared between C_P and C_O. Hence, all the cantilever deflections which produce a voltage lower than V_O do not transfer energy to C_O.

On the contrary the proposed solution is able to extract all the energy defined in (1) and to store it into storage capacitance C_O. This can be obtained in four phases. During phase 1 the transducer is strained (path *a-b* of Fig. 2b) and all the switches of Fig. 2a are open. In this way the whole interface circuit is not loading the transducer. When the maximum strain is reached, the transducer has generated the energy defined in (1), C_P stores it and voltage on node l_{x+} has reached the maximum. Driving circuitry senses this condition and starts phase 2: switch S2 is closed and a resonance between C_P and L takes place (path *b-c* of Fig. 2b). When the voltage on node l_{x+} reaches zero all the energy of the piezoelectric transducer has been transfered into inductance L. Driving circuitry senses this new condition and phase 3 starts: switch S2 is opened while switches S1 and S3 are closed (point *c* of Fig. 2b). When the current into L reaches zero the energy of L will be completely transfered to C_O and phase 3 ends. At this time switches S2 and S3 are opened.

If phases 2 and 3 are faster than the variation of the cantilever strain during these phases, in a first approximation the transducer can be considered motionless at the maximum deflection reached at the end of phase 1.

When phase 3 ends the cantilever starts to be deflected in the opposite direction and phase 4 can be started. Switch S1 is closed and path *c-d* of Fig. 2b is covered: current supplied by piezoelectric transducer recirculates through S1 and no charge is collected onto capacitor C_P, as in the standard voltage doubler topology. When the maximum deflection is reached (point *d*) phase 1 takes place again: differently from point *a* the cantilever is at a negative strain but still has no charges on its plates. Hence during the motion from *d* to *e* a positive charge is already collected on C_P corresponding to an energy that the circuit will be able to harvest. At the end of phase 1, when new maximum deflection is reached (point *f*), the charge increases further because of the positive deflection.

This demonstrates that this circuit recovers not only the energy of positive voltage peaks, but it is able to harvest

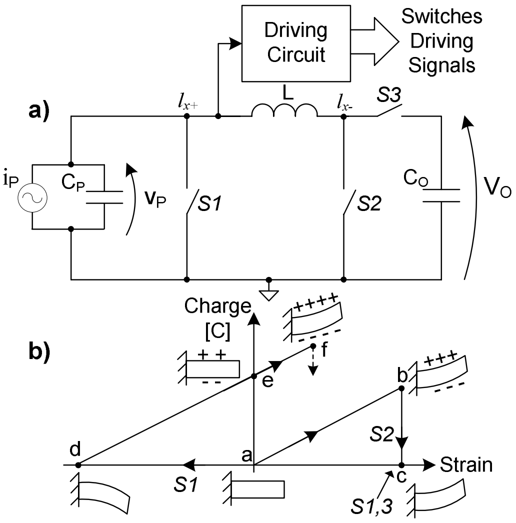

Fig. 2 a) Principle scheme of the proposed front-end circuit. b) Working cycle realized by the front-end circuit.

the energy corresponding to a whole deflection from negative peak to positive peak. This holds even if the amplitude of each deflection is different from the previous one.

III. Design Of The AC-DC Converter

Fig. 3a shows the circuitry designed to implement the conceptual scheme of Fig. 2a.

The driving circuitry has to be supplied only by the output voltage V_O, i.e. by the harvested energy, hence its power consumption should be as low as possible. Furthermore, since voltage V_O is variable in time, a supply independent bias circuitry [5] has been designed so to make the whole current consumption independent on the supply variations. Some modifications have been introduced with respect to [5]; in particular, to implement the start-up function, the leakage of two p-channel MOSFETs has been exploited. This solution allows us to avoid additional start-up circuitry, reducing the total power consumption.

Switch S1 has been splitted in two switches: S1' and S1" which are used during phase 4 and phase 3 respectively. In fact, the purpose of the prototype is to check the validity of this new approach and an attempt was made to keep the driving circuitry as simple as possible. In particular, switch S1" can be simply driven inverting phase 3, while a dedicated circuit drives switch S1' by sensing the voltage across it.

Inductance L is an external component and its value has to be chosen so to obtain a resonant frequency with capacitor C_P faster than the dynamics of the mechanical strain. As it was said, this guarantees that during phase 2 and 3 the cantilever is almost motionless at its maximum deflection, thus the energy transfer from the piezoelectric transducer to the inductance is more efficient. In our case a value of 2200 μH was chosen while C_P was set to 220 nF (typical value for a practical piezoelectric transducer): this gives rise to a resonant frequency f_R of about 7.23 kHz. This frequency is significantly higher than the frequencies of typical environmental vibrations which are in the order of some tens of hertz [1].

During the start-up phase no energy is stored into C_O and its voltage is not enough to supply the actives elements, hence a passive path from the transducer to C_O has to be guaranteed. This function has been realized exploiting the parassitic body-drain diodes of switches S1', S1" and S3: they implement a passive AC-DC voltage doubler which works during the start-up. Inductor L does not interfere during the passive rectification.

Driving circuitry is presented in Fig. 3a as a block scheme, while Fig. 3b shows a picture of the diffused prototype; its area is equal to 320 x 360 μm^2.

During phase 1 driving circuit keeps all switches open.

Phase 2 has to start when v_P reaches its maximum value and it ends when v_P reaches zero. The first condition is detected by the Peak Detector while the second by comparator CMP1. The output signals of these blocks are routed to the SET (S) and RESET (R) input of a NAND based flip-flop which was designed to avoid the undetermined state.

Phase 3 has to start when the inductance current reaches its maximum value; since it is caused by the resonance between L and C_P, the current peak is reached when v_P is zero. This condition is detected by CMP1 which turns S2 off leaving node l_{x-} floating until the voltage v_2 gets higher than V_O. At this time CMP2 switches S3 and S1" on. The same comparator switches S3 and S1" off when the current which flows into inductance and into S3 crosses to zero.

Finally phase 4 has to start when i_P becomes negative. Solution described in [11] has been used: the loop implemented by operational amplifier OA1 and S1' forces the drain to source voltage of this switch to the input offset voltage of the operational amplifier, which was designed to be 20 mV.

An enable signal is used to improve the response speed of comparators CMP1 and CMP2 because they have to react to signals whose speed is in the order of f_R. The enable signal increases the bias current of CMP1 during phase 2 and of CMP2 during phase 3. This signal has the purpose to prevent an useless power consumption out of these phases.

The average current consumption of the whole driving circuit is equal about 700 nA.

IV. Experimental Results

Experimental characterization of the proposed circuit have been done with a function generator and a capacitance so to emulate the behaviour of the piezoelectric transducer. With respect to the equivalent circuit shown in Fig. 2a its Thevenin equivalent has been implemented. This was composed of a cascade of a function generator, which gives the equivalent output voltage of the transducer at no load condition, and of a capacitance which is the equivalent capacitance C_P of the transducer itself.

Fig. 4 shows the comparison of the output voltages obtained with the proposed front-end circuit and with a passive voltage doubler; this was realized with BAT86 Schottky diodes. Function generator supplied a sinusoidal input waveform with a peak amplitude equal to 1.5 V and frequency equal to 50 Hz. A load resistance equal to 650 kΩ has been connected in parallel with storage capacitance C_O.

It is possible to see that the proposed circuit works as a passive one until the energy stored into C_O is enough to supply the active elements, this condition is reached at t_1. From this moment on, an interval is needed to switch the bias circuit on. At time t_2 driving circuit is fully on and the output voltage reaches a value which is higher than the input voltage and is a function of the whole power consumption.

Fig. 5 shows a detail of the voltages V_O (blue trace), v_P (green trace) and v_2 (red trace): these were measured with the same input conditions defined in Fig. 4.

In particular it is possible to see that along phase 2 the voltage v_P is sinusoidal and it is due to the resonance between C_P and L. In the same phase switch S2 is closed and node l_{x-} is clamped at a voltage near to zero. It is possible to see also when S2 is opened because voltage on node l_{x-} gets higher than V_O: from this moment on CMP2 closes the switches S3 and S1". At the beginning of phase 4 an oscillation of v_P takes place: this is due to a resonance of the inductance L (which has not completely discharged into C_O) with parassitic capacitances. Fig. 5 shows that CMP1 was designed to open S2 before v_P reaches zero: in particular S2 is switched off when v_P is 400mV. This was done to prevent a delayed switching off of S2, due to the delay of the comparator.

Finally, Fig. 6a and Fig. 6b show the behaviour of the proposed solution and of the passive voltage doubler when the function generator delivers a variable amplitude signal. It is possible to see that the proposed solution is able to harvest the energy of peaks with amplitude lower than the output voltage stored into C_O.

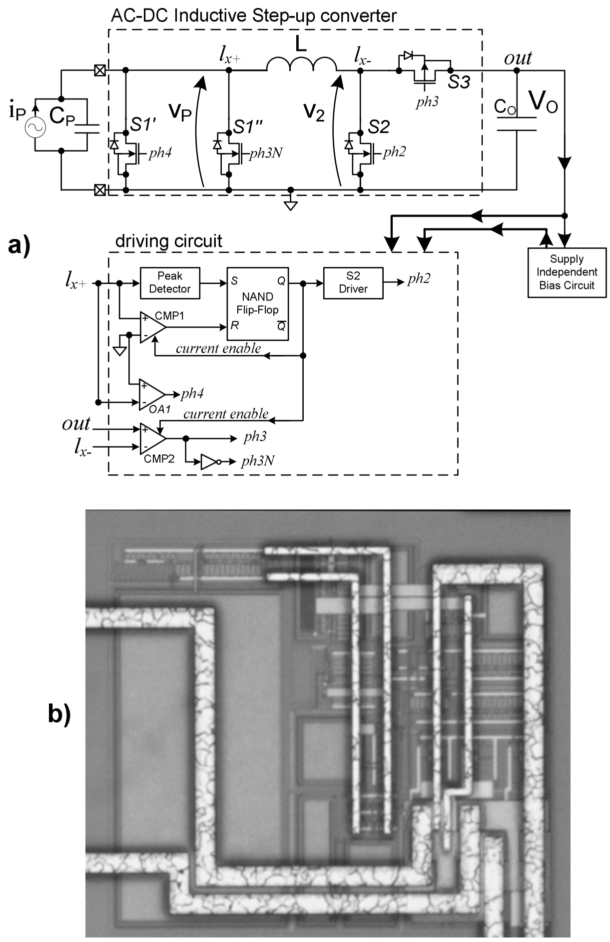

Fig. 3 a) Block scheme of the implemented front-end circuit. b) Picture of the diffused prototype.

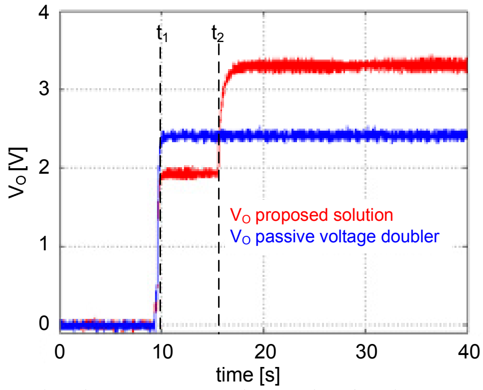

Fig. 4 Comparison between output voltages when function generator gives a sinusoidal signal.

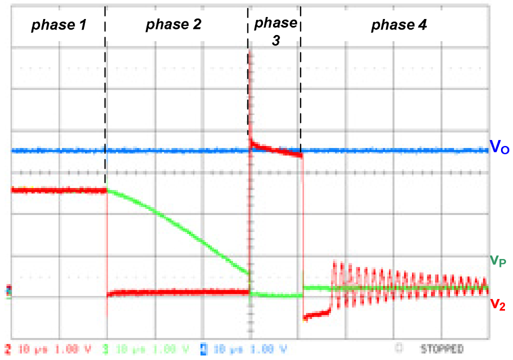

Fig. 5 Detail of the voltages V_O, v_P and v_2 during the four phases. Time scale: 10 µs/div; voltage scale for all traces 1 V/div.

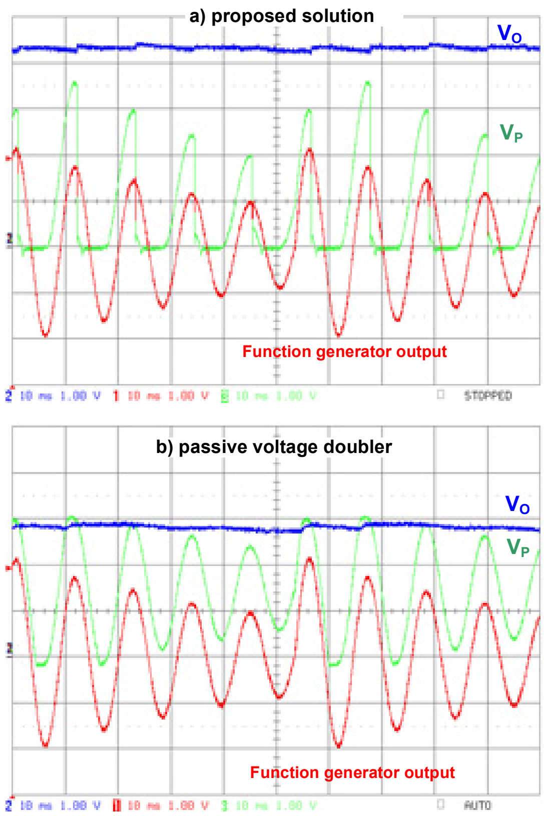

Fig. 6 a) V_O, v_P obtained with the proposed interface circuit; b) V_O, v_P obtained with a passive voltage doubler. Red traces are the function generator output. Time scale: 10 ms/div; voltage scale for all traces 1 V/div.

V. CONCLUSIONS

A novel front-end circuit for piezoelectric energy scavenging systems is presented. It is able to harvest the energy supplied by these transducers also when they are excited with randomic vibrations.

The main advantage of this solution, with respect a classical AC-DC converter, is that it is able to recover the energy associated to transducer output voltages lower than the voltage on storage capacitance C_O. It exploits the working principle of the inductive step-up converter.

A test chip was diffused using 5V CMOS STMicroelectronics technology. Experimental results show the effectiveness of this solution with respect to a classical AC-DC converter both when the mechanical vibration is sinusoidal and when it is randomic.

V. References

[1] S. Roundy, "Energy Scavenging for Wireless Sensor Nodes with a focus on Vibration to Electricity Conversion", PhD Thesis, The University of California Berkeley, Spring 2003.

[2] S. Roundy et al., "Improving Power Output for Vibration-Based Energy Scavengers", Pervasive Computing January-March 2005, pp. 28-36, Published by the IEEE and IEEE ComSoc.

[3] T. T. Le, Jifeng Han, A. von Jouanne, K. Mayaram, T. S. Fiez, "Piezoelectric Micro-Power Generation Interface Circuits" IEEE Journal of Solid State Circuits, pp. 1411-1420, Vol. 41, NO. 6, June 2006.

[4] E. Dallago, G. Frattini, D. Miatton, G. Ricotti, G. Venchi, "Self-Supplied Integrable High Efficiency AC-DC Converter for Piezoelectric Energy Scavenging Systems", International Symposium on Circuits and Systems ISCAS 2007, New Orleans LO, 27-30 May 2007, pp. 1633-1636.

[5] Z. Dong, P. E. Allen, "Low-Voltage, Supply Independent CMOS Bias Circuit", The 2002 45th Midwest Symposium on Circuits and Systems, 4-7 Aug 2002, pp. 568-570, Vol. 3.

[6] F. Peano, T. Tambosso, "Design and Optimization of a MEMS Electret-Based Capacitive Energy-Scavenger", Journal of Microelectromechanical Systems, pp. 429-435Vol. 14, NO. 3, June 2005.

[7] M. Renaud, T. Sterken, P. Fiorini, R. Puers, K. Baert, C. van Hoof, "Scavenging Energy from Human Body, Design of a Piezoelectric Transducer", The 13th International Conference on Solid-State Sensors, Actuators and Microsystems, Seoul, Korea, June 5-9, 2005, pp. 784-787.

[8] I. Stark, "Thermal Energy Harvesting with Thermo Life®", Proceedings of the International Workshop on Wearable and Implantable Body Sensor Networks, BSN 2006, pp. 19-22, IEEE Computer Society.

[9] J. Han, A. von Jouanne, T. Le, K. Mayaram, T. S. Fiez, "Novel power conditioning Circuits for Piezoelectric Micro Power Generators", APEC 2004, , February 2004, Vol. 3, pp. 1541-1546.

[10] E. Dallago, G. Frattini, D. Miatton, G. Ricotti, G. Venchi, "Integrable High-Efficiency AC-DC Converter for Piezoelectric Energy Scavenging System", IEEE Conference on Portable Devices, Orlando (FL), March, 2007.

[11] V. Bottarel, E. Dallago, G. Frattini, D. Miatton, G. Ricotti, G. Venchi, "Active Self Supplied AC-DC Converter for Piezoelectric Energy Scavenging Systems With Supply Independent Bias", Accepted for Lecture at IEEE International Symposium on Circuits and Systems, ISCAS 2008, Seattle, May 18-22, 2008.

[12] G. K. Ottman, H. F. Hofmann, G. A. Lesieutre "Optimized Piezoelectric Energy Harvesting Circuit Using Step-Down Converter in Discontinuous Conduction Mode", IEEE Transaction on Power Electronics, VOL. 18, NO. 2, March 2003, pp. 696-702.