An Energy-Adaptive MPPT Power Management Unit for Micro-Power Vibration Energy Harvesting

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Abstract— A batteryless power management unit (PMU) that manages harvested low-level vibration energy from a piezoelectric device for a wireless sensor node is presented. An energy-adaptive maximum power point tracking (EA-MPPT) scheme is proposed that allows the PMU to activate different operation modes according to the available power level. The harvested energy is processed by an ac-dc voltage doubler followed by on-chip charge pumps with variable up/down conversion ratios for higher efficiency. Interleaving technique is employed for the high-power output to reduce both current and voltage ripples. The PMU is designed using a 0.35 μ m CMOS process, and simulation results are presented to demonstrate its functions.

I. INTRODUCTION

Energy harvested from the environment could replace or extend the lifetime of bulky batteries in a wireless sensor network, and vibration is a promising source of energy. For piezoelectric materials at a given vibration status (magnitude and frequency), there exists an optimum output voltage at which maximum output power can be extracted [1]. An ultra-low-power maximum power point tracking (MPPT) scheme in a time-varying environment was discussed in [2] that tracked and held the maximum power point periodically using a very small duty cycle, and consumes only a fraction of the power required by prior MPPT schemes. All functional blocks are activated or shut down together. However, a sensor node consists of functional blocks with very different levels of power consumption. For example, signal processing may consume 20 μ W while RF power amplification and transmission may consume 1mW. The power management unit (PMU) should activate different blocks as the input power level changes. For example, at very low input power, the whole system may be duty-cycled; at medium input power the critical blocks work continuously while the rest are duty-cycled; and at high input power, all blocks are activated. To achieve energy-adaptive MPPT control, information on the absolute or relative amount of available power is needed. The problem is how to obtain and utilize this information without using power-demanding computational methods such as quantizing voltages and/or currents.

Prior research works focused on applications that consume power in the order of 100 μ W to 10mW or even higher [3]

[4]. Switch-mode power converters (switching converters) are often used due to its high efficiency. However, an off-chip bulky inductor is needed. Research in recent years has reduced the total power consumption of a sensor node to less than 1mW, and fully integrated small size solution becomes increasingly realistic and desirable in some cases. In addition, [5] shows that low-level vibration with available power of less than 100 μ W and fundamental frequency of less than 200Hz can be widely found in many situations. One challenge is to harvest energy efficiently from low-level vibration with low source voltage. Another challenge is to provide high power conversion efficiency over a wide range of source voltage without using switching converters. Furthermore, a fast power transfer rate is desirable such that the system could make the most use of short bursts of high-energy instants.

In this research, we propose an energy-adaptive MPPT power management unit for harvesting energy from very low level vibrations. Available power is measured by a simple "load perturbation" method that is basically a trial-and-error process. With this information the PMU could instruct the system to operate in different modes. A high-efficiency ac-dc doubler provides an adequate output voltage without resorting to additional step-up dc-dc converters for low vibration levels. Fully-integrated charge pumps with variable conversion ratios are used to replace switching converters. Fast energy accumulation and small input and output voltage ripples are achieved by time-interleaving techniques.

II. SYSTEM OPERATION

Fig. 1 shows the PMU of the sensor node with two types of load. (1) Baseband analog and digital circuits such as sensor front-end, A/D converters, computation logic and memory circuits consume about 10-20 μ W and should remain active if possible. (2) RF circuits consume about 1mW and should be activated if enough energy is accumulated for transmission. Due to size limitation the piezoelectric device may only provide a maximum of 100 μ W. Because the total power consumption exceeds the maximum power provided by the source, the transmitter has to work in a duty-cycled fashion. The energy for transmission is accumulated on storage capacitors C_{SRF1} and C_{SRF2} . The RF blocks are supplied by

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Fig. 1. System operation: (a) system diagram; and (b) voltage waveform of V_S and mode transition diagram for different available power.

V_{DD2} and V_{DD3} such that noise-sensitive circuits and noisy circuits can be isolated.

The PMU starts with an ac-dc rectifying doubler followed by three charge pumps. The first charge pump QP₁ provides power for the baseband analog and digital circuits (BB). The charge pumps QP₂ and QP₃ charge up C_{SRF1} and C_{SRF2} instead of supplying current directly to RF circuits RF-A and RF-B. The outputs of all charge pumps are regulated by low dropout regulators (LDRs). The energy-adaptive MPPT control block generates the enable signal En_BB for QP₁, LDR₁ and baseband circuits, and the enable signal En_ES for controlling QP₂ and QP₃ for energy storage. A Power-Good block senses the voltage on C_{SRF1} and C_{SRF2} to decide whether the stored energy is adequate for the RF circuits.

A. Maximum Power Point

The piezoelectric thin film is modeled by an sinusoidal current source $I(t) = I_p \sin(2\pi ft)$ in parallel with the internal capacitance C_p . The amplitude I_p depends on the vibration magnitude and f is the vibration frequency. Using transistors as active diodes, the forward drop V_{dp} is close to zero [6], and the average rectifier output current I_{inavg} and the average harvested power P_{inavg} are

$$I_{inavg} = I_p / \pi - f C_p (V_S + 2V_{dp}) \quad (1)$$

$$P_{inavg} = [I_p / \pi - f C_p (V_S + 2V_{dp})] V_S \quad (2)$$

where V_S is the output voltage of the rectifier. Maximum power is obtained when V_S is

$$V_{S(opt)} = I_p / 2\pi f C_p - V_{dp} \quad (3)$$

From (2) and (3) the maximum power is

$$P_{avg(opt)} = f C_p (I_p / 2\pi f C_p - V_{dp})^2 \quad (4)$$

To obtain the voltage $V_{S(opt)}$, we use the MPPT method of [2], which disconnect the load by opening S_{IN} in Fig. 1 for a very short time and sense the open-circuit peak voltage of the piezoelectric source for control:

$$V_{p(open)} = I_p / 2\pi f C_p \quad (5)$$

It is approximately equal to the optimum voltage $V_{S(opt)}$ when the voltage drop V_{dp} is small.

TABLE I. OPERATING MODES

Input power range (assuming $P_{in} < P_{LRF}$)	Baseband & QP ₁ , LDR ₁ (P_{LBB})	Energy Accum. by QP _{2,3} (P_{LES})	RF circuits, LDR _{2,3} (P_{LRF})
$P_{in} < P_{LBB}$	Duty-cycled operation	Sleep	Sleep
$P_{LBB} < P_{in} < P_{LBB} + P_{LES}$	Continuous operation	Duty-cycled Energy Accum.	(low) Duty-cycled operation
$P_{LBB} + P_{LES} < P_{in} < P_{LRF}$	Continuous operation	Continuous Energy Accum.	(high) Duty-cycled operation

B. Energy-Adaptive MPPT

The value of $V_{S(opt)}$ is not adequate to tell whether the available power becomes higher or lower. This can be seen from (3) and (4). When both the current I_p and the vibration frequency f are doubled, the optimum voltage $V_{S(opt)}$ will remain the same but the available power $P_{avg(opt)}$ is doubled. To adaptively operate individual part in different modes, a method to detect the absolute or relative amount of available power is then needed.

Here we propose a simple "load perturbation" technique. The system always tries to operate all the blocks continuously, starting from the most critical block, and then responds to the change of V_S . Here the load itself is used as the yardstick against which the amount of available power relative to the load is measured. Fig. 1(b) shows the voltage V_S for different power levels and mode transition. As mentioned previously, the input power P_{in} is always less than the power dissipation of the RF part P_{LRF} .

Assume initially all the loads are disabled and the capacitors C_{SIN1} and C_{SIN2} are charged from a very low level at t_0 . Four reference voltages V_{SR1} , V_{SR2} , V_{SR3} , and V_{SR4} are generated based on the detected optimum voltage $V_{S(opt)}$. These voltage levels are closely centered around $V_{S(opt)}$ and track the variation of $V_{S(opt)}$. V_S should be kept within V_{SR1} and V_{SR4} for (approximately) optimum power transfer. When V_S reaches V_{SR3} at t_1 , the analog and digital baseband (BB) will be activated. What will happen next depends on the available power levels:

- (a) $P_{in} < P_{LBB}$: If the input power P_{in} is less than the baseband power P_{LBB} , V_S will drop after t_1 . BB will be kept on until V_{SR1} is crossed at t_2 . Then BB will be

disabled. Since V_S is unloaded now it will rise again. At t_3 , V_S crosses V_{SR3} again and BB is re-enabled. The process will repeat.

- (b) $P_{in} > P_{LBB}$: If the input power P_{in} is larger than the baseband power P_{LBB} , V_S will continue to increase after t_1 . BB will be kept on. When V_{SR4} is crossed at t_2' , the energy storage (ES) process will be enabled. What will happen depends again on the available power levels:
- (b1) $P_{LBB} < P_{in} < P_{LBB} + P_{LES}$: If P_{in} is smaller than the total power dissipation of BB and ES, then V_S will decrease after t_2' . BB and ES will be kept on until V_{SR2} is crossed at t_3' . At this time, ES will be disabled but BB is still kept enabled. Because $P_{in} > P_{LBB}$, the V_S will rise again. At t_4' V_{SR4} is crossed again, ES will be re-enabled and the above process will repeat.
- (b2) $P_{LBB} + P_{LES} < P_{in} < P_{LRF}$: If P_{in} is greater than the total power of BB and ES but less than the RF part, V_S will keep moving upwards after t_2' . Finally, it will reach the limit value V_{lim} , which is very large and any voltage above it should be prevented. Whether or not the RF part will be activated does not depend on V_S reaching V_{lim} , but on whether the amount of stored energy is adequate, which may happen before or after the instant when V_S reaches V_{lim} .

It can be seen that by perturbing the load and watching for the level crossing events, we can obtain the information of the available power level relative to the load power level. At the same time, V_S fluctuates around the optimum point, providing maximum power transfer. Table I shows the operation modes for different input power.

III. CIRCUIT DESIGNS AND CONSIDERATIONS

A. AC-DC Doubler

Compared to full-wave rectifier with only one large capacitor, the two half-wave rectifiers in cascade needs two large capacitors C_{SIN1} and C_{SIN2} , but the output dc voltage is doubled. The two capacitors are 10 μ F and can be surface-mount capacitors which are very small. For low vibration levels, the doubler output V_S can be high enough to be used directly by the load, without using an additional dc-dc converter. The two diodes DA_1 and DA_2 are active diodes for higher efficiency [6]. The storage capacitors C_{SIN1} and C_{SIN2} should not be too large or too small. The lower limit is set by the minimum stored energy in a charge-discharge cycle to complete an atomic operation, and the voltage ripple has to be small enough to avoid disturbing the decision making of the comparators in the MPPT block. A large capacitor stores more energy and has less ripple voltage, but increases the system start-up time. A long start-up time will cause short bursts of energy to be missed, which is undesirable.

B. Energy-Adaptive MPPT Control Block

As shown in Fig. 2, the energy-adaptive MPPT control block consists of a Tracking Pulse Generator, a Refresher, and an Enable Signals Generation circuits. The pulse generator is used to recover the clock from the input and

Fig. 2. Energy-adaptive MPPT circuits: (a) tracking pulse generator and refresher and its timing; and (b) enable signals generation.

generates a pulse TP that is two cycles long for every 128 cycles. During these two cycles, the switch S_{IN} is open, putting the piezoelectric film into the open-circuit state. The two capacitors C_{F1} and C_{F2} are small enough to allow V_S to settle to $V_{S(opt)}$ within two cycles. The refresher circuit is to sample the present value of $V_{S(opt)}$ and discard the last one [2]. The last value has to be held for normal operation during the sampling period of the present one, so the refresher circuit consists of two time-multiplexed sample-and-hold (S/H) circuits. In practice, $V_{S(opt)}/2$ is generated instead of $V_{S(opt)}$, because the supply voltage V_S is close to $V_{S(opt)}$.

Four reference voltages $V_{SR1}/2$, $V_{SR2}/2$, $V_{SR3}/2$, and $V_{SR4}/2$ are generated by the circuit shown in Fig. 2(b). Four comparators each with a current consumption less than 100nA are used to compare the reference voltages with $V_S/2$. The outputs of the comparators are used to set the operating mode of the PMU. The comparators should have large input devices to reduce the standard deviation of the random offset voltage to a very small fraction of the difference between two neighboring reference voltages.

C. Charge Pumps

The output voltage of the ac-dc doubler is in the range of 1.4V to 5V and the targeted supply voltages for baseband (V_{DD1}), RF Circuit A (V_{DD2}) and RF Circuit B (V_{DD3}) are 0.85V, 1.55V and 2.45V respectively. To make the efficiency comparable to a switching converter, the charge pump has to be highly reconfigurable according to the input voltage V_{CSIN} [7]. The conversion ratios (M) are dynamically configured as shown in Table II.

Fig. 3 shows the schematic of the charge pump QP_2 for RF-A. The control logics for the corresponding power switches are shown in Fig. 4. For example, the switch S_7 has a control logic of $r_1|\phi_1(r_2)$, meaning that S_7 will be turned on when M is 1X ($r_1="1"$) or during ϕ_1 when M is 2X ($r_2="1"$). It will be kept off for other cases. Similar schematics and control logics are developed for the other charge pumps.

As mentioned before, QP_2 and QP_3 are used for accumulating power for circuits RF-A and RF-B. It should be noted that the charging priority of QP_3 is higher or QP_2 has to "wait" until QP_3 has charged C_{SRF2} to above 2.6V. This high voltage is used to drive some switches in QP_2 such that their sizes could be much smaller. To accelerate the power conversion process and reduce the I/O current/voltage ripples, interleaving technique is employed for QP_3 , as shown in Fig. 5. The schematics of $QP_{31} \sim QP_{34}$ are the same and their driving signals $\phi_1 \sim \phi_4$ are from the ring oscillator.

Table II Conversion Ratio Management

Blocks	V_{CSIN}	QP _i M=	V_{CPi}	V_{DDi}	I_{max}
RF-B (i=3)	4.2V ~ 3.6V	1	>2.6V	2.45V	10 mA
	2.6V ~ 1.8V	3/2			
	1.8V ~ 1.4V	2			
	1.4V ~ 0.9V	3			
RF-A (i=2)	4.2V ~ 3.6V	1/2	>1.7V	1.55V	1 mA
	3.6V ~ 2.4V	3/4			
	2.4V ~ 1.8V	1			
	1.8V ~ 1.44V	5/4			
	1.44V ~ 1.2V	3/2			
	1.2V ~ 1V	7/4			
	1V ~ 0.9V	2			
BB (i=1)	4.2V ~ 3.6V	1/4	>0.9V	0.85V	20 μ A
	3.6V ~ 2.7V	1/3			
	2.7V ~ 1.8V	1/2			
	1.8V ~ 1.2V	3/4			
	1.2V ~ 0.9V	1

Fig. 3. Schematic of charge pump QP₂ for RF-A.

S_1	$r_1 \phi_1(r_2)$	S_7	$r_1 \phi_1(r_2)$	S_{113}	$\phi_1(r_{34} r_{74})$
S_2	$\phi_2(r_{54} r_{32} r_{74} r_2)$	S_{81}	$\phi_1(r_{54} r_{32} r_2)$	S_{114}	$\phi_1(r_{34} r_{74})$
S_3	$r_{12} r_{34} r_1 \phi_1$	S_{82}	$\phi_1(r_{54}) \phi_2(r_{34} r_{74})$	S_{12}	$r_1 \phi_1(r_2) \phi_2(r_{12} r_{34})$
S_4	$r_1 \phi_1(r_{12} r_{32} r_2)$	S_9	$r_{12} r_1 \phi_1(r_{54})$	S_{Q1}	$r_1 \phi_2(r_{12} r_{54} r_{32} r_2)$
S_{51}	$\phi_2(r_{54} r_{32} r_2)$	S_{10}	$r_1 \phi_1$	S_{Q2}	$r_1 \phi_2(r_{12} r_{54} r_{32} r_2)$
S_{52}	$\phi_1(r_{12} r_{54} r_{32}) \phi_2(r_{34} r_{74})$	S_{111}	$\phi_2(r_{54} r_{32} r_{74} r_2)$	S_{Q3}	$r_1 \phi_2$
S_6	$r_1 \phi_1(r_{34} r_{74} r_2) \phi_2(r_{12})$	S_{112}	$\phi_1(r_2)$	S_{Q4}	$r_1 \phi_2$

Fig. 4. Control logic of power switches in Fig. 3.

Fig. 5. Interleaved QP₃.

Fig. 6. Reference and clock generator.

D. Ref & CLK Branch for Start-Up

The reference voltage used to determine the conversion ratios of charge pumps does not need to be very accurate, and can be implemented by using MOS-only topology shown in Fig. 6. Diode M_5 and M_8 operate in sub-threshold region and M_2 , M_3 , M_6 , and M_7 act as a clamping opamp. V_{ref} varies by 6mV across the whole operation range (V_{CSIN} : 0.9V ~ 4.2V; Temperature: -20° ~ 100°). A 5-stage ring oscillator could generate all driving signals with a frequency that ranges from 1.6MHz to 2.5MHz. The total current consumption for this block is around 400nA with $V_{ref} = 758mV$ and $f_{osc} = 2MHz$ at $V_{CSIN} = 2V$ and $T = 25^\circ$. The start-up circuit is not shown.

Fig. 7. Simulated voltage waveforms of V_{SIN} for different power levels.

IV. SIMULATION RESULTS

Fig. 7 shows the simulated voltage waveform of V_{SIN} for three cases: (1) $I_p = 15\mu A$, $f = 30Hz$ and $P_{avg(opt)} = 8.54\mu W$. (2) $I_p = 30\mu A$, $f = 60Hz$ and $P_{avg(opt)} = 17.08\mu W$. (3) $I_p = 50\mu A$, $f = 90Hz$ and $P_{avg(opt)} = 31.63\mu W$. Both the load power P_{LBB} and P_{LES} are equal to $10\mu W$. The first two cases have the same $V_{s(opt)}$ of 3.578V. It can be seen that, for case 1, V_{SIN} fluctuates between 3.652V and 3.431V, with an average of 3.541V. For case 2, V_{SIN} is between 3.725V and 3.507V, and the average is 3.616V. For both cases, the average voltage is very close to the optimum value. The input power for case 3 is larger than the sum of P_{LBB} and P_{LES} so V_{SIN} stays at 4.234V, which is above the optimum value of 3.976V.

V. CONCLUSIONS

In this paper, an energy-adaptive MPPT power management unit for harvesting energy from very low level vibration is proposed. By a simple control method, it sets the system in different operation modes depending on the available power level. Fully-integrated time-interleaved charge pumps with variable conversion ratios are used to replace the switching converter, eliminating the need of an external bulky inductor. A very low power voltage reference is used to generate the reference voltages for start-up. The functionality of the MPPT scheme is verified by simulations.

VI. REFERENCES

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