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Low-power Methods of Power Sensing and Frequency Detection for Wideband Vibration Energy Harvesting

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Abstract. Power maximisation techniques in wideband vibration energy harvesting typically require the periodic sensing of input power or excitation frequency. This paper presents low-power circuits and sensing methods to obtain this information. First, an excitation frequency measurement circuit is presented that permits a reduced timer run-time compared to reported methods. Second, a power sensing method is presented, which extends the measurement range of reported techniques by adapting to the levels of the available power. Experimental results for the frequency measurement circuit tested in the range 35-51 Hz show a power consumption of 3.7 μW. The power-sensing technique is experimentally validated over a power range of 370-690 μW, and its power consumption is 7.5 μW.

1. Introduction

Maximum power point tracking and electrical tuning for wideband energy harvesting require the sensing of the extracted power or of the excitation frequency [1] [2]. Harvested power levels can span orders of magnitude, and in particular, at excitation frequencies away from the harvester resonance, the available power is low. Therefore the quiescent power consumption of the control and sensing circuitry should be as low as possible. This paper presents two low-power sensing methods: one for frequency sensing, and the other for power sensing.

Frequency can be determined from acceleration, velocity, or displacement. Direct acceleration sensing requires accelerometers which add to the total volume of the system and the power overheads. Displacement sensing can be implemented by means of a piezoelectric strip attached to the beam of the harvester as demonstrated in [1], which generates a signal without the need for a power rail. This alternating signal, however, requires adaptive filtering again with associated quiescent consumption. Phase shifting of the piezoelectric signal to align with the harvester voltage allows a reduction in power consumption of the measurement circuit because the same signal can be used for polarity detection and gate driving of the power conditioning circuit and the operation of the control circuit. This work uses a sensorless method that deduces frequency directly from the harvester output voltage. Since the mechanical structure of an electromagnetic harvester filters out excitation frequency components except those in the vicinity of the resonant frequency, the time interval between zero-crossings of the generated voltage can be used to determine the excitation frequency that is relevant for tuneable harvesters.

Power can be inferred from output current measurement in maximum-power-point-tracked energy harvesting systems, if the energy storage element is large enough to maintain a near output constant voltage between perturb-and-observe cycles. E.g. in [3], the authors present a power sensing method using a switched capacitor, where the output current of the power converter is determined by measuring the voltage rise on a small sensing capacitor during a short period during which the main storage and load are disconnected. A limitation of this method is that if the measurement range is large, as would be expected for a wideband excitation, then at the lower end of the range, the relative measurement resolution is poor. Here, a low-power system is demonstrated which adapts the resolution to the power level to obtain high accuracy over the whole measurement range.

2. Method

The energy harvesting system including the low-power methods for power sensing and frequency detection is presented in Figure 1. The system consists of an electromagnetic energy harvester, power converter, storage element, and measuring and control circuitry. The signals generated by the frequency measurement and the power sensing circuits are read by a low-power microcontroller MSP430. The microcontroller is enabled by an interrupt at the zero-crossing of the input voltage and is active for a short period during which all measurements and control actions are performed. The microcontroller then remains in sleep mode for the rest of a harvester half-cycle.

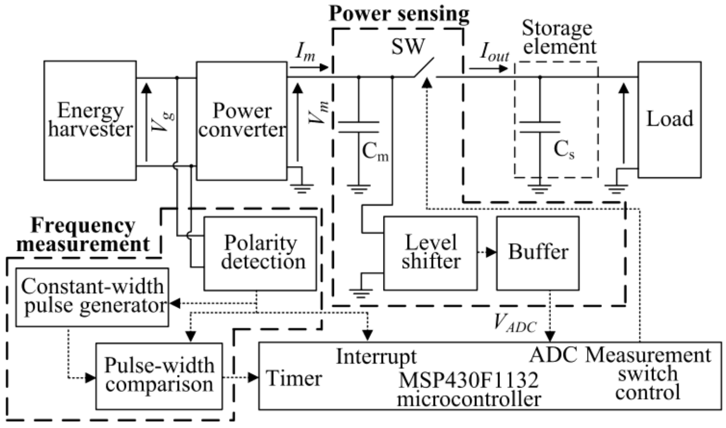

Figure 1. Low-power frequency detection and power sensing system.

2.1. Frequency detection

In digitally controlled systems, time intervals between two events are usually measured by running a timer on a microcontroller for the duration of the interval. Thus by timing the half-cycle period of the input voltage the excitation frequency can be measured [2]. However, the continuous operation of a timer, even on the low-power MSP430, requires 28 µW to run continuously at 85 kHz clock frequency. Here we demonstrate a method where the timer runs for only part of the harvester half-cycle. Figure 2 illustrates the principle: A polarity detector determines the beginning of the harvester cycle, upon which a pulse is generated, whose fixed width T_{rc} equals the half-cycle period of the excitation at the upper limit of the harvester frequency band. At the end of the fixed-width pulse, the timer is started in order to measure the remainder of the half-cycle. Therefore timer's on-time T_m approaches zero at the upper limit of the frequency band and is highest at the lower limit. The derived harvester frequency can be expressed as

$$f_h = \frac{1}{\frac{1}{f_{max}} + 2T_m}\ , \qquad (1)$$

where $f_{max} = 1/2T_{rc}$ is constant and equals the highest frequency in the measurement range and T_m is the timer value.

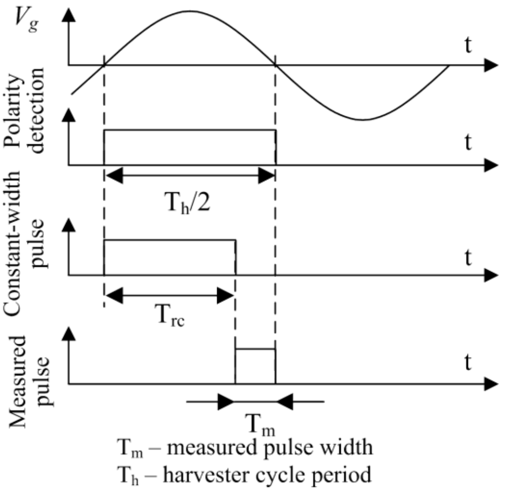

Figure 2. Waveform of the main pulses in the frequency measurement circuit.

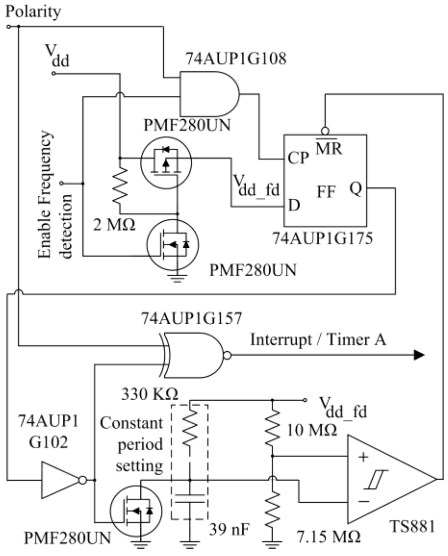

Figure 3. Low-power implementation of the frequency detection circuit.

The fixed-width pulse is generated by an RC circuit, a comparator, and a reset circuit (Figure 3). At the beginning of the positive half-cycle the voltage across the capacitor starts to increase from zero. When a pre-set threshold voltage is reached, the comparator generates a reset pulse for the flip-flop, the MOSFET switch is closed, and the capacitor is discharged to zero and remains zero until the beginning of the next positive half-cycle. The falling edge of the constant-width pulse sets an interrupt flag in the microcontroller and activates a 16-bit timer. The timer runs until a second interrupt is generated by the falling edge of the polarity detection circuit. The measured period T_m can be calculated as

$$T_m = \frac{K + K_{init}}{F_{clk}} \tag{2}$$

where K is the final timer value, K_{init} is a constant denoting the number of clock cycles between the interrupt and the start of the timer, and F_{clk} is the clock frequency of the oscillator used by the timer. In order to reduce the power consumption during the operation of the timer, the clock frequency is reduced from 5 MHz nominal to 85 kHz, and the CPU. Additionally, the low clock frequency ensures that the register that stores the timer value will not overflow. Nevertheless, decreasing the clock frequency reduces the resolution of the measurement. At 85 kHz the frequency resolution varies between 14 mHz at the lower limit of the bandwidth and 36 mHz at the upper limit.

The power consumption of the proposed frequency detection circuit is evaluated by comparison with the case where the microcontroller timer runs for the whole half-cycle period. The power measurements are performed at the resonant frequency of the harvester. The reduced timer operation has reduced the total average power consumption from 4.3 µW to 3.7 µW, 1.05 µW of which is consumed by the microcontroller and the remaining 2.65 µW by the components in the frequency detection circuit. It should be noted that the improvement the frequency detection circuit offers increases with the increase of the excitation frequency.

2.2. Power sensing

A small change in environmental factors such as excitation frequency and amplitude can result in significant change in the amount of extracted power. For example, for the harvester used in this work, a decrease of the frequency by 1.5 Hz from the resonance, 44.3 Hz, reduces the maximum extractable power by 70 %. The method proposed here aims to enable accurate operation of MPPT algorithms at a wide range of the excitation frequency and low quiescent overhead. In [3], a switched capacitor current sensing technique is deployed, as described in Section 1. The voltage rise ΔV_{C_m} on the measurement capacitor C_m is proportional to the output power:

$$\Delta V_{C_m} = \frac{\overline{P_{out}}_{\Delta t}\,\Delta t}{C_m \cdot V_{out}} \,. \tag{3}$$

Since the output power P_{out} averaged over Δt is a function of extracted power, large variations in the extracted power result in large variations of the measured voltage. As the range and the resolution of the ADC are fixed, these variations affect the overall sensitivity and range of the measurement.

The improved power sensing technique described here increases the measurement sensitivity and range by adaptively changing the duration of the measurement period Δt according to the output power (Figure 5). The method relies on the measurement being synchronised with the harvester half-cycle, and the operational cycle of the MPPT control algorithm being much longer than the measurement period M. This allows the measurement period to be increased in steps equal to the period of the harvester cycle without affecting the voltage range across the storage element significantly. An algorithm for implementation of the method on a low-power MSP430 microcontroller is presented in Figure 4.

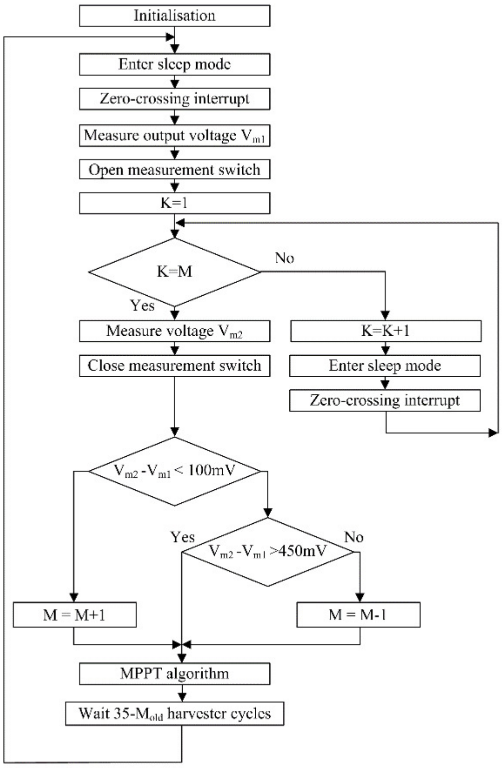

Figure 4. Algorithm for adaptive power sensing; M – number of harvester cycles during which the measurement switch is open; Vm1, Vm2 – measurements of the converter's output voltage at the beginning and at the end of the measurement period.

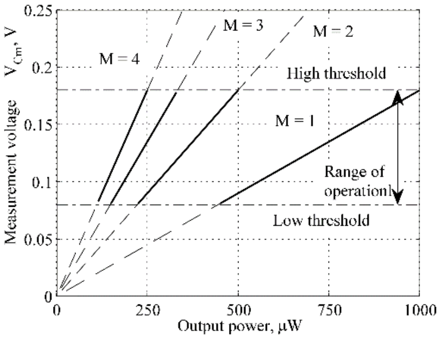

Figure 5. Theoretical measurement voltage ΔV_{Cm} as a function of the output power. If one of the threshold is reached, the duration of the measurement period M is changed. The measurement capacitor is 39 μF and the output voltage is 2.5 V.

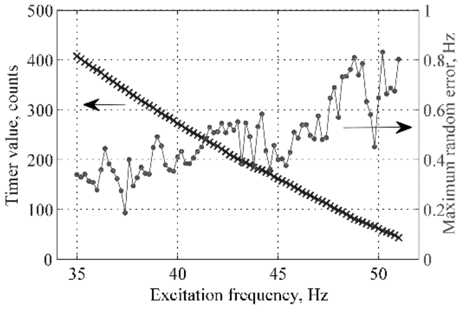

Figure 6. Measured timer value as a function of the excitation frequency and calculated maximum random error.

3. Experimental results

3.1. Frequency detection

To test the performance of the frequency detection method experimentally, the excitation frequency is swept between 35 Hz and 51 Hz at step size of 200 mHz. The length of the fixed-width pulse is T_{rc} = 9.09 ms, which corresponds to an upper limit of the harvester frequency of 55 Hz.

3.2. Power sensing

Figure 5 demonstrates how the measurement period is changes with output power. The excitation frequency and amplitude are held constant and the power is changed by sweeping the duty ratio of the switching converter. The measurement voltage reaches a threshold where the measurement period changes in steps of one harvester half-cycle, for example from 2 cycles (M=2) to 2½ cycles (M=2.5).

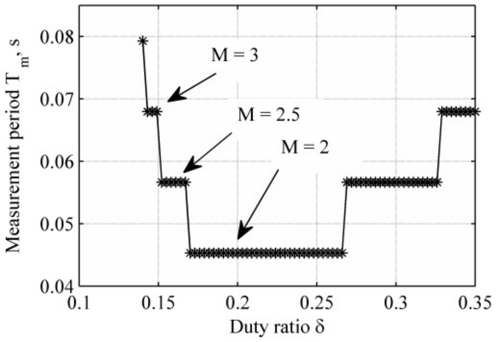

Figure 5. Measurement period against duty ratio.

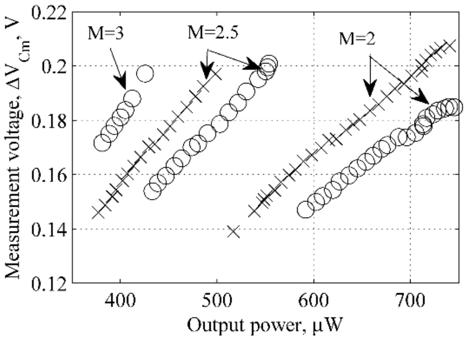

Figure 6. Measurement voltage and measurement period against power. (Output voltage: ○ - 4 V, × - 3.5 V).

The relationship between the measurement voltage $\Delta V_{C_m}$and the output power at output voltages 4 V and 3.5 V is shown in Figure 6. When a decrease in the power causes the measurement voltage to fall below a threshold of 140 mV, the measurement period is increased by a half-cycle. Since the relationship between the value of the analogue-to-digital converter and the measurement voltage is constant, this results in increased measurement resolution, which is necessary at low power levels. If however the measurement voltage reaches the upper threshold at 210 mV the measurement period is reduced to prevent saturation of the ADC. The measurement voltage is thus kept between these two threshold limits, resulting in M being varied between 2, 2.5, and 3. At lower output voltage levels, due to higher output currents, the same range of measured power can be achieved with fewer steps. For example, at $V_{\text{out}=}$3.5 V M takes on only two values: 2.5 and 2. The results show that if the measurement period were kept constant at M = 2, then the sensitivity of the measurement circuit would be 3.75 mW/V whereas the adaptive system reaches sensitivity of 1.88 mW/V. The measured standard deviation for the power range between 370 and 750 µW at 3.5 V output voltage is 0.6 mV. The average power consumption of a discrete component implementation of the proposed method is 7.5 µW in a system which performs measurement once every 35 harvester cycles.

4. Conclusions

In this paper, two low-power methods for frequency detection and power sensing are demonstrated. The frequency detection method uses the harvester output directly, and has a total power consumption of only 3.7 µW. The method is compared with the case where a microcontroller timer is used to measure the frequency of the excitation, and reduction in the power consumption by 14 % is demonstrated. The power sensing method uses 7.5 µW, and is validated over a power range of 370 µW to 750 µW extending the operational range by 26 %. The results show that the proposed methods are suitable for application in MPPT for wide-band sub-milliwatt energy harvesting.

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