Interface Circuit Design for Energy Harvesting: State of the Art and Challenges

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Abstract - The Internet of Things (IoT) is going to contribute to highly efficient agriculture and industry, an aging society and so on. Energy harvesting powers up IoT devices to operate autonomously by harvesting energy from ambient without any battery or extends the battery life for the IoT devices. Therefore, it can eliminate or reduce the cost for replacing the battery which could be the largest cost for an IoT sensor network. Interface circuits convert electric energy generated by an energy transducer into electric power for IoT integrated circuits. In this paper, existing interface circuits and systems are overviewed. Design challenges are also discussed.

1. Introduction on interface circuits for energy harvesting

Energy harvesting (EH) [1] [2] is realized by a combination of energy transducer (ET) and interface circuits including rectifiers and power converters. ETs are categorized as shown in Table I. Fig. 1 illustrates how the ET is coupled with integrated circuits (ICs) such as sensor and RF circuits through a power converter, depending on the characteristics of the ET such as AC/DC, open circuit voltages and operation frequencies. DC power generated by photovoltaic cells and thermoelectric generators is up-converted by a DC-DC converter because the output voltages are lower than the operating voltages for ICs [3]. Fig. 1(a) shows a nominal configuration of the power converter including a booster, oscillator and regulator. The booster takes as input the output voltage of the DC ET and outputs the voltage V_{DD} for the IC building blocks with a clock generated by the oscillator. The regulator controls the oscillator so that V_{DD} is kept around a target voltage. AC power generated by electromagnetic waves [4] [5] and vibration [6]-[9] is transformed into DC power by an AC-DC converter. Based on the output voltages of the ET, up- or down-conversion is made by interface circuits. Figs. 1(b), (c) show two options for AC-DC boost conversion. AC power is input to the booster directly in Fig. 1(b), whereas it is input to a full bridge rectifier followed by the booster in Fig. 1(c). Electrostatic vibration ET has a larger output voltage and output impedance than the alternatives, which needs switched-capacitor voltage down-conversion (SC-VDC) as an example [10]. Even though the ET only generates electric power of an order of 1-100 µW, IoT edge terminals can work well as long as the duty ratio of the active time to the cycle time is sufficiently low, as shown in Fig. 2(a).

When a DC EH system functions so that the converter operates at a maximum-output-power condition of $V_{EH} = V_{OC}/2$, where V_{OC} is the open circuit voltage, half of the power generated by the ET is available for the remaining system of converter and sensor/RF chip(s). That is known as maximum power point tracking (MPPT) which is a fundamental design consideration [11]. The other half of power generated by the EH is wasted as heat on R_{EH}, the output impedance of the EH. One method of operation is measuring V_{OC} to determine the target voltage of $V_{OC}/2$ during non-operation period between power conversion operations. When the lower bound on V_{EH} to make the system functional is targeted as a design parameter, integrated charge pump circuits can be optimally designed [12]. Too many stages and too large capacitors can have much less output power due to the mismatching in impedance. When V_{EH} becomes higher than the minimum target voltage, the output power from the converter increases at a lower power conversion efficiency.

Table I Characteristic table for various energy transducer

	Energy transducer		Voltage up- or down-conversion	Nominal frequency	Block diagram
DC	Photovoltaic (PV)		Up	-	Fig. 1(a)
	Thermoelectric (TE)				
AC	Electromagnetic wave (RF)			100M-10GHz	Fig. 1(b) or (c)
	Vibration	Electromagnetic induction (EM)		10-100Hz	
		Magnetostrictive (MR)			
		Piezoelectric (PE)	Up or down		Fig. 1(c)&(d)
		Electrostatic (ES)	Down		Fig. 1(d)

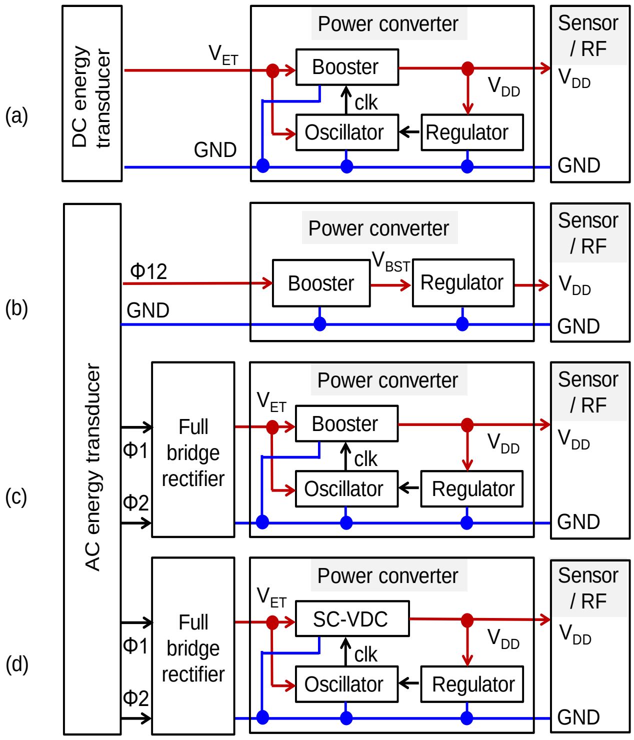

Fig.1 Interface circuit systems for energy harvesting: power converters for DC energy transducer (ET) (a), for AC ET with no rectifier (b), for AC ET with a rectifier (c), and for AC ET with voltage-down conversion.

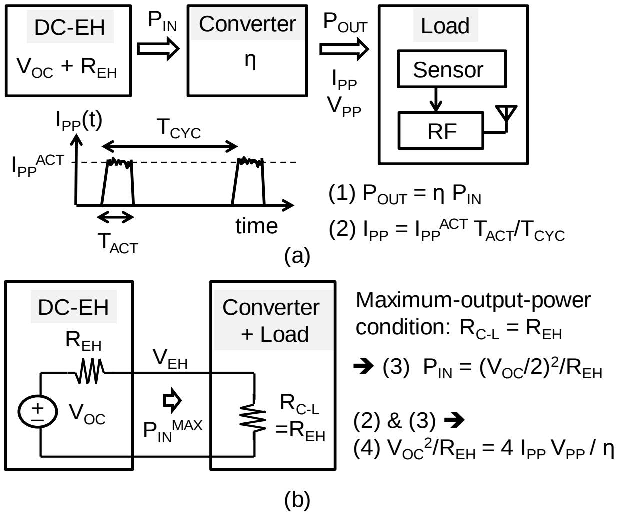

Fig. 2 (a) block diagram of an energy harvesting system with DC-EH, converter and sensor chip(s). (b) A maximum-output-power condition provides a relationship between ET generating power and load consuming power as (4) at $V_{EH}=V_{OC}/2$.

2. Building blocks

a) **Oscillator** The minimal V_{DD} of EH can be determined by oscillators. A fundamental limit of V_{DD} for an ideal CMOS inverter is shown to be $2V_T(\ln 2)$ ~36 mV at 300 K, where V_T is the thermal voltage [13]. However, actual ring oscillators under process variations need much higher voltages such as 200 mV. Hot carrier injection after fabrication mitigates random threshold voltage variation, resulting in a startup voltage of 80 mV for DC-ET [14]. One of the simplest oscillators is the Colpits oscillator which only has a single MOSFET with a few passive elements such as capacitors and inductor(s). The minimal V_{DD} is studied and demonstrated in [15], which shows a theoretical limit of 9 mV and an experimental limit of 86 mV. When the MOSFET operates out of a subthreshold region, it needs a higher V_{DD} to get a sufficient transconductance to compensate for an energy loss in the LC network. Based on a similar design parameter set for MOSFET and the passive elements, a realistic minimal V_{DD} is shown to be ~80 mV under a process variation of +/-50 mV and temperature range of 0-80 C [16] based on an EKV model [17].

b) **Booster** Voltage-up-conversion is realized with switching regulators [18], charge pumps [19] or transformers [20]. Switching regulators require higher current rather than higher voltage, which is suitable for energy transducers with relatively low output impedances such as electromagnetic induction and magnetostrictive for harvesting vibration energy. The charge pump operation is based on switched capacitors which can be integrated in sensor or RF chip(s). The transformers can have the functionalities of both the oscillator and booster with a relatively higher cost than the others [20].

c) **Rectifier** When RF power is high enough to generate a voltage for standard CMOS without boosting, a rectenna (rectifying antenna) can be used [21]. Otherwise, AC power needs to be converted into DC via a full-bridge rectifier, followed by DC-DC voltage multipliers. A low threshold voltage with low reverse leakage current is required for the rectifier across process and temperature variations.

d) **Regulator** In Figs. 1(a), (c) and (d), a divided voltage is compared with a reference voltage to stabilize the output voltage. The oscillator works depending on the output logic of the regulator [22]. In Fig. 1(b), V_{BST} is generated without control. The regulator regulates the voltage from widely varied V_{BST} to a stable V_{DD}.

3. Design challenges

To spread IoT devices everywhere, they must be produced at very low cost. Interface circuits should be fully compatible with standard CMOS technology at a minimal area overhead. Voc is likely determined by the minimum operating voltage of interface circuits. Circuit designers are requested to develop extremely low voltage building blocks. Switched capacitor voltage multipliers could be designed to work at a V_{DD} of 0.1 V under a specific temperature range with a tradeoff to the circuit area, i.e., cost and power conversion efficiency [23]. When the leakage current is relatively large, the capacitance per stage would need to be increased. An amount of the leakage current is highly temperature-dependent. Process variation also increases the leakage current. Thus, optimum design needs to be reconsidered for process and temperature tolerance. Optimum co-design of energy transducer and interface circuits is another challenge. Even though power conversion efficiency is degraded with an additional oscillator, the output power of a clocked AC-DC charge pump can be increased by a factor of two [24]. Flexible controller design is also required for an extreme variation in power generated by an energy transducer. It seems that numerous open research challenges remain unsolved, thus providing many areas for future designers to explore.

References

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