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# Ambient Energy Harvesting Chips for IoT End Devices: Review

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*Abstract*—***There are many existing energy harvesting (EH) chips on the shelf such as LTC3109, BQ25570, AEM10941, and LTC3588-1. This paper proposes suggestions on how to choose the right EH chips for different EH sources, to achieve fast activation on startup, and to design high charging efficiency requirements for Internet of Things (IoT) applications.***

***Keywords—Energy Harvesting Chip, Ambient Energy Harvesting, Supercapacitors***

## I. INTRODUCTION

The market for the Internet of Things (IoT) continues to grow rapidly and the number of connected IoT devices is expected to grow 9%, to 12.3 billion active endpoints in 2021 [1] and more than 27 billion IoT connections by 2025. Almost all exiting IoT devices need either batteries or power adapters to power and boot up IoT systems. Since IoT devices can be deployed almost everywhere, if there are no power outlets then batteries must be used, incurring manually replacing batteries problem [2]. Recycling or dealing with disposed batteries is another environmental issue in our greener world. Thus, self-sustainable standalone wireless IoT devices are always a critical and re-emerging research issue. This paper focuses on how to construct energy harvesters to support these self-sustainable standalone IoT devices.

There are many existing energy harvesting (EH) chips on the market such as LTC3109 [3], BQ25570 [4], LTC3588-1 [5], and AEM10941 [6]. How to choose the right EH chips for different energy sources is a hard problem because different energy sources require different matched EH circuits. This paper suggests important and practical suggestions for constructing EH circuits for ambient weak energy sources such as indoor photovoltaic, thermal gradient energy, Piezoelectric kinetic energy, and RF energy. How to design an EH system that provides fast activation and good charging efficiency is also studied in this paper. This paper focuses on ambient weak power energy harvesting.

The contributions of this paper are as follows: Firstly, we identify what commercial EH chips are suitable for different energy sources. Secondly, we discuss which chips may achieve fast activation by modulating the PMOS switch. Thirdly, we discuss how to deal with start-up power for IoT nodes and how to save power by using different diodes. Finally, we discuss and compare the charging efficiency of these chips.

## II. AMBIENT SOURCES FOR ENERGY HARVESTING

The ambient environment [7] has unlimited energies to be harvested, mainly including solar power, thermal energy, wind energy, salinity gradients, radio frequency (RF) energy, and kinetic energy. Some energy sources have strong power such as solar light or wind power in strong wind situations, others have only weak power such as indoor photovoltaic, Piezoelectric kinetic energy, and RF energy. Indoor photovoltaic [8] energies may come from indoor lightings such as LEDs or fluorescent lamps and the solar light through windows. The piezoelectric kinetic energy is the form of shocks or vibrations into electrical energy.

This paper focuses on ambient weak power energy harvesting, in particular, for Indoor photovoltaic energies, piezoelectric kinetic energy, and RF energies. Piezoelectric kinetic energy comes from vibrations and RF energies come from radio waves broadcasting from transmitters such as Wi-Fi access points and stations, Bluetooth central, and peripherals. The energy strength depends on the distance between RF transmitters and the EH receivers. Table 1 summarizes the comparison of the weak energy sources.

Table 1 Comparison of weak energy sources

| | Indoor PV | Piezoelectric | RF Energy |
|---|---|---|---|
| Energy Source | Light | Vibration | Magnetic Resonance |
| Power Density | 10 – 100 $\mu W/cm^2$ | 50 – 300 $\mu W/cm^3$ | 0.0002- 1 $\mu W/cm^2$ |
| Output Voltage | 2-5V | 1-15V | 20-500mV Depend on load |

### III. ENERGY HARVESTING TYPICAL SYSTEM

The block diagram of typical EH systems for the commercial EH chips is shown in Fig. 1, It consists of an energy source, an energy manager, a boost converter, a cold start unit, a buck converter, and a MOS switch.

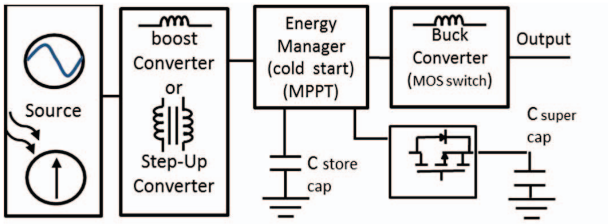


Fig. 1. Block diagram of typical EH system

#### *A. Cold Start*

The purpose of the cold start unit [9] is to provide enough operating voltage to start up the energy manager by a start-up oscillator circuit shown in Fig. 2. Note that not all of the commercial EH chips have cold start units, thus these chips cannot start up the attached IoT devices if the energy sources cannot provide high voltage power in the beginning. For example, indoor photovoltaic and piezoelectric energy sources do provide enough operating voltages to start the IoT devices but RF radio does not.

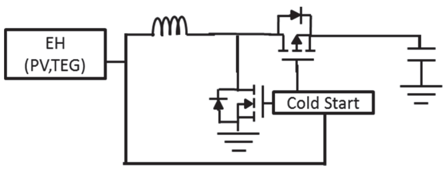


Fig. 2. cold start

#### *B. Maximum Power Point Tracking*

The MPPT unit is used by the boost converter, shown in Fig. 1, to find the best energy harvesting point which optimizes the match of the EH source and the storage capacitor ($C_{store}$) shown in Fig. 3 [10].

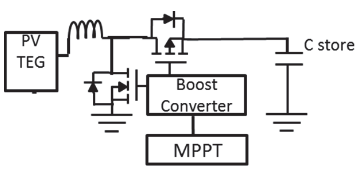


Fig. 3. MPPT circuit

### IV. COMMERCIAL ENERGY HARVESTING CHIPS

This section discusses the advantages and disadvantages of the commercial EH chips including LTC3109 [3] from Linear Technology, LTC3588-1 [5] from Linear Technology, BQ25570 [4] from Texas Instruments, and AEM10941 [6] from e-peas semiconductors. Major features such as the boost converter, the set-up converter, the buck converter, the quiescent current, the output voltage, and the activation time. The comparison table is shown in Table 2.

Table 2 Comparison of commercial energy harvesters

| | LTC 3109 [3] | BQ 25570 [4] | AEM 10941 [5] | LTC 3588-1 [6] |
|---|---|---|---|---|
| Boost Converter | No | Yes | Yes | No |
| Step-up Converter | Yes | No | No | No |
| Buck Converter | No | Yes | Yes | Yes |
| Quiescent Current (nA) | 200 | 488 | 500 | 950 |
| Output Voltage | Fix | Adjust | Adjust | Fix |
| Activation | Fast | Slow | Fast | Slow |

The first row shows that BQ25570 and AEM10941 contain boost converters but LTC3109 and LTC3588-1 does not. The reason is that LTC3588-1 only supports high voltage energy sources such as piezoelectric. The second row shows that only LTC3109 provides the set-up converter for ultralow voltage energy sources such as RF energy sources. The third row shows that only LTC3109 does not provide the buck converter and thus may suffer supplying power efficiency [11]. The fourth row shows that the quiescent currents of all these EH chips are quite low and thus may be ignored when designing EH systems. The fifth row shows that BQ25570 and AEM10941 may adjust the output voltage according to system load but LTC3109 and LTC3588-1 provide only fixed output voltages. The sixth row shows that LTC3109 and AEM10941 provide fast activation mechanisms. More detailed information is provided in the following subsections.

#### *A. BQ25570 EH chip*

BQ25570 chip consists of all the components shown in Fig. 1. An application note of the BQ25570 chip is shown in Fig. 4 with two inductors for the boost converter and the buck converter, one supercapacitor ($C_{sup}$) for storing backup energy when no input energy is provided, a small capacitor ($C_{out}$) for eliminating ripple noises, and a small capacitor ($C_{store}$) for storing basic energy for this chip.

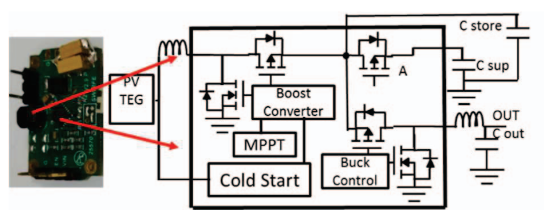


Fig. 4. An EH application using BQ25570 [4]

The boost converter raises small voltage from EH sources to enough voltage and then enables energy charging in the $C_{store}$ to start up the BQ25570 chip. Also, the output voltage can be adjusted from 1.3V to 3.3V. The PMOS switch, labeled by A, is used to charge energy into the supercapacitor ($C_{sup}$).

One drawback of this application note is that activating the IoT device may take a long time for the normal 1F or 0.47F supercapacitor ($C_{sup}$). For example, under an indoor PV energy source with 28uA and 1F supercapacitor, it takes 17.8 hours to charge up to 1.8V.

### *B. LTC3109 EH chip*

LTC3109 chips are a much simple design compared to the typical EH system shown in Fig. 1, which does not contain the boost converter and the buck converter, instead, a set-up converter is employed to raise ultra-low-voltage such as RF signals. The distinguishing feature of this chip is that the RF signals such as Wi-Fi, Bluetooth, and TV broadcast signals can be harvested.

An application note of the LTC3109 chip is shown in Fig. 5 with two high turns ratio transformers (i.g. 1:100 transformer) to step up high voltage and a supercapacitor ($C_{sup}$) to store backup energy. The output voltage is fixed at 2.35V, 3.3V, 4.1V, or 5V.

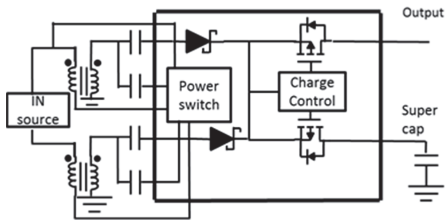


Fig. 5. An EH application using LTC3109 [3]

### *C. LTC3588-1 EH chip*

LTC3588-1 chips are also a simple design compared to the typical EH system shown in Fig. 1, which does not contain the boost converter or the step-up converter, the MPPT, and the cold-start unit. An application note of the LTC3588-1 chip is shown in Fig. 6 with a supercapacitor ($C_{sup}$) to store backup energy, a small capacitor ($C_{out}$) to eliminate ripple noises, and a buck converter to output 1.8V, 2.5V, 3.3V, and 3.6V for IoT devices. Note that this chip needs to raise to 4V, which takes a very long time, to activate the buck converter.

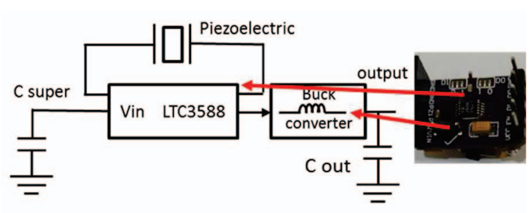


Fig. 6. An EH application using LTC3588-1 [5]

### *D. AEM10941 EH chip*

AEM10941 chip consists of all the components shown in Fig. 1. An application note of the AEM10941 chip is shown in Fig. 7 with a primary battery to start up IoT devices in the beginning even there is no power is harvested, and a secondary storage element which can be supercapacitors or batteries.

There are three voltage outputs: a low voltage supply, labeled as LVOUT, that provides 1.2-1.8V to drive IoT, a high voltage supply, labeled as HVOUT, that provides 1.8 V-4.1V to drive a radio transceiver such as Wi-Fi or Bluetooth signals, and a buck output (not shown in Fig. 7) at 2.2V which may enable fast activation.

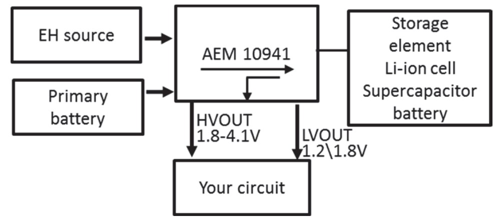


Fig. 7. An EH Simplified schematic view using AEM10941 [6]

### *E. Test chip for fast activation*

Use an indoor photovoltaic with 28 µA current source, 4.8V output voltage as EH source to test LTC 3109, BQ25570, AEM10941, and LTC3588-1 which with 22 µF output loader for fast activation testing. The LTC 3109, BQ25570, AEM10941, and the LTC3588-1 output voltage is 2.35V ,2.21V,2.2V and 2.5V. The storage supercapacitor is 0.022 F. The position of the supercapacitor is according chip datasheet. The comparison of the energy harvesters is shown in Table 3. The LTC3588-1 takes a long time to charge the supercapacitor to 4.13V then the chip turns on the buck converter. This chip is suitable for high EH sources. The LTC3109, AEM10941 have fast activation functions, can quickly activation in a short time.

Table 3 The comparison of the energy harvesters

| | LTC 3109 [3] | BQ 25570 [4] | AEM 10941 [5] | LTC 3588 [6] |
|---|---|---|---|---|
| Activation Seconds | <4 | 2160 | <4 | 4580 |

## V. SUGGESTIONS FOR AMBIENT EH TECHNOLOGIES

This session proposes suggestions for constructing energy harvesters with ambient weak power energy.

### *A. Low voltage energy harvesting*

RF signals are everywhere such as Wi-Fi or Bluetooth devices. To the best of our knowledge, only LTC3109 EH chips that use two compact step-up transformers may capture RF signals efficiently.

### *B. Fast activation*

LTC3588-1 and BQ25570 EH chips cannot have fast activation because the supercapacitor is directly connected to the storage capacitor. Since there is not enough voltage to turn on the buck converter, in the beginning, these chips need to take a long time to charge the supercapacitor and storage capacitor up to a certain activation voltage (e.g. 2V).

LTC3109 and AEM10941 EH chip use modulating circuits to periodically turn on/off the PMOS to connect/isolate the connection between the supercapacitor and the storage capacitor. Since these chips can temporarily turn off the connection, the storage capacitor will have enough energy to support the operation of IoT devices, resulting in fast activation.

Note that the input voltage of IoT devices needs to connect to the buck pin of the AEM10941.

### C. *Buck converter for higher charging efficiency*

The energy that is impossible to transfer from one capacitor to another capacitor without losing energy is called the two capacitor paradox [11]. This is because capacitors have an internal resistor that may consume energy when two capacitors are connected. Note that the LTC3109 chips suffer from the two capacitor paradox problem, and the LTC3588-1, BQ25570, AEM10941 do not.

### D. *Low Leakage Storage Capacitor*

Electrostatic double-layer capacitors (EDLC) are commonly used in EH systems, but due to the high leakage current compared to that of lithium-ion capacitors (LIC) [12]. Thus, LIC is a better candidate to use in weak EH. Fig. 8 shows the self-discharge voltage with time to prove that the leakage current of LIC is much smaller than that of EDLC.

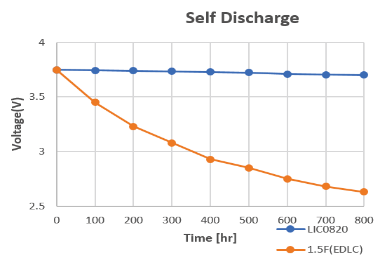


Fig. 8. Self Discharge EDLC vs LIC

### E. *Replacing Disposable and Rechargeable battery with LIC*

Disposable and rechargeable batteries are commonly used in IoT applications. But there are two major disadvantages, firstly, when the batteries are running out of energy, a manual replacement is required; secondly, these disposed of batteries cause environmental pollution. Since LIC supercapacitors can have up to 750F capacity with extremely low current leakage, this capacitor is very suitable for IoT applications. Thus, we strongly recommend using LIC instead of batteries and EDLC for IoT applications. Note that LIC has extremely high capacity and thus is hard to charge quickly when the LIC has no energy at all in the beginning. One possible solution is to fully charge the LIC before using it.

### F. *Diode Selection*

A rectifier diode is commonly used to prevent the current of the storage capacitor from flowing into EH sources as shown in Fig. 9. There are two considerations for selecting the diode: low forward voltage which prevents energy loss during EH and low reverse leakage to prevent further energy loss. The surface-mount Schottky barrier diode BAT54 [13] has a small forward voltage (about 0.15V under 30μA charging current) and a small reverse leakage (i.e. 0.3μA) and is a good candidate for diode selection.

## VI. CONCLUSION

Constructing an EH system for ambient weak energy sources is a hard problem due to so many different energy sources which require so many different matched EH circuits. This paper suggests important and practical information for shorting the development time and effort to design EH systems for ambient weak energy sources. We also show how to design an EH system that provides fast activation and good charging efficiency. The AEM10941 and LTC3109 are better to achieve a fast activation from Table 3.

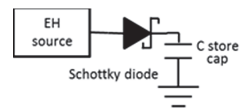


Fig. 9. A rectifier diode for EH source

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