Micro Energy Harvesting: Research after the first decade*

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1. Energy-autonomous embedded systems: Prerequisites and general constraints

The energy-autonomous operation of an embedded system is under severe prerequisites and constraints: First of all, the most promising source of energy has to be identified and certified for every application scenario. This may be vibration, impact, heat, light or chemical energy. For all these forms of energy, measurement campaigns are essential to find the global feasibility and the most important design criteria for an optimized energy-harvesting concept. These may be vibration amplitudes and frequency spectra, temperature gradients, light irradiation levels and spectra or, in the case of a chemical conversion principle, the availability of a chemical fuel. As ambient energy is usually not constant over time, a temporal statistics of the potential energy input has to be matched with a temporal statistics of the power requirements set by the embedded system. This will give an idea about the feasibility of the whole concept. It will also define the necessity and required capacity of an intermediate energy storage used to cover brown-out phases of the ambient energy. Finally it will give a hint, whether the parallel use of two different conversion principles may be useful, e.g. to harvest energy from different resources.

Second, it is often neglected that additional influences act on all components of the embedded system, i.e. on the generator, energy storage and power management units as well as on the system hardware. While this is acceptable for a conventional power supply concept, the small power budget of a harvesting system enforces a more careful consideration. Temperature variations can, for instance, change the mechanical properties of a resonant vibration energy harvester and thus detune the generator, with detrimental effects on the harvested power. The same holds for the electrical storage capacity of batteries that is heavily influenced by temperature. A proper analysis of these influence factors is required to make, on one hand, a good choice of components-off-the-shelf. On the other hand, a robust design of components or, in addition, an active compensation of disturbing effects is desirable.

Third, the embedded system itself should, in an ideal case, adjust its functions to the level and delivery form of available ambient energy. For this purpose, the embedded system would require an internal knowledge base to calculate the level of available energy with a prediction for the near future. As a consequence, the on-time of the whole system or its power-relevant functionalities, e.g. sampling and transmission rates, are adjusted to guarantee a reliable, although reduced functionality. In any case, a low-power system hardware with an elaborated power-down capability is required for this kind of adaptivity.

In the following, a few examples of actual research are given that reflect these novel ideas in energy harvesting and energy-autonomous embedded systems, distributed into the categories energy conversion, energy storage, power management and system design. Also, examples are given on the suitability of components-off-the-shelf.

2 Energy conversion

2.1 Parallel and multiple harvesting

Parallel and multiple harvesting concepts represent a relatively novel area of research. The philosophy behind is to tap different ambient energy sources in parallel, as one source may show longer brown-out phases that can be bridged with energy from another, complementary source. Also, the use of different conversion principles for one type of resource (e.g. vibrations) allows for a more flexible design concerning the generator properties (source impedance, power and voltage levels) or the conversion ranges. Today, this idea is mostly followed by integrating individual generators into a hybrid design.

The so-called „power tile“ represents an example of a hybrid solar-thermoelectric generator for space applications [1]. The device combines a photovoltaic (PV) cell, a thermoelectric generator (TEG) and a thin-film battery in a flat multilayer stack (Fig. 1). The PV cell harvests energy from solar irradiation, while the temperature gradient between the illuminated cell surface and the shaded backside is converted via the TEG. Both generators feed into the thin film battery via an integrated power management circuit. The TEG is also intended to be used as a Peltier heat pump to keep the battery within its allowed temperature range.

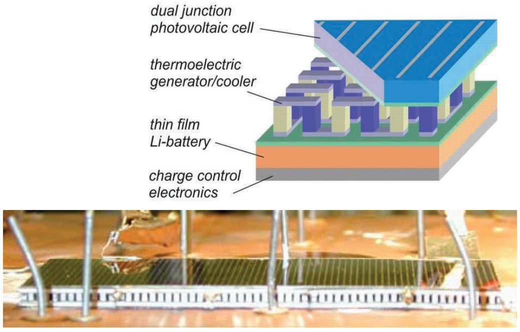

Fig. 1 *Solar-thermoelectric „power tile“ [1]: schematic (top) and photograph of the generator part (bottom).*

Fig. 2 shows a hybrid vibration energy harvester from our own laboratory that uses two conversion principles for the same source of energy [2]. Most vibration energy harvesters which are, e.g., mounted on the vibrating surface of a machine, contain a spring-mass-system [3,5]. Vibrations of an external host will set the spring-mass system into oscillation. The kinetic energy of the oscillating seismic mass is converted into electrical energy, e.g. via piezoelectric material integrated into the deformed spring [4] or via the movement of a permanent magnet in close vicinity to the cylindrical inductor [5]. The hybrid design combines both converters in one device (Fig. 2). A permanent magnet is used as a seismic mass for electromagnetic conversion while the mechanical spring is formed by a piezoelectric cantilever beam to extract energy from its deformation.

By using two conversion effects this design concept optimally uses the spring-mass system and its mechanical oscillation. The output voltage of both generators exhibits an inherent phase shift of 90°,which means that four evenly distributed energy maxima, instead of two, are gained within one oscillation cycle. Also, the high voltages (up to several Volts) available from the piezogenerator can be used to supply and control a synchronous step-up converter for the low-voltage electromagnetic generator. Vice versa, the AC voltage from the electromagnetic generator is usable as a synchronized trigger for a DC-DC converter (see e.g. [6,12]) that extracts maximal power from the piezogenerator.

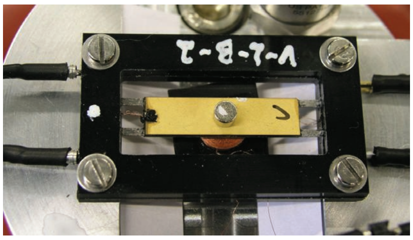

Fig. 2 *Photograph of a combined Piezo-electromagnetic vibration harvester [2].*

2.2 Adaptive generators

Ambient energy is a highly variable resource, concerning its general availability, achievable power level and conversion conditions. Most vibrating power sources, for instance, exhibit variable frequencies and amplitudes. The light levels and irradiation spectra for PV cells are different as a function of daytime, weather condition and in-door or out-door application. This calls for adaptive generators that are capable to follow such variable conditions.

Vibration generators may serve as an example here: With this kind of scavengers a good power output can be obtained as long as the ambient vibration frequency matches exactly the resonance frequency of the deployed spring-mass-system. Even a tiny mismatch between both frequencies will lead to a significant reduction of the output power (see Fig. 3). For this reason, the application field of inertial energy harvesters is by now restricted to vibrating environments with one constant frequency. In the past years, several attempts have been made to overcome this problem with frequency-tunable energy converters [7]. While several generator concepts have been studied in stand-alone tests, no truly self-sufficient and self-tuning systems are available today. The concept itself calls for energy-efficient actuators and control strategies as the supply power for the tuning operation has to be much lower that the total harvested power. Also, a thorough system design

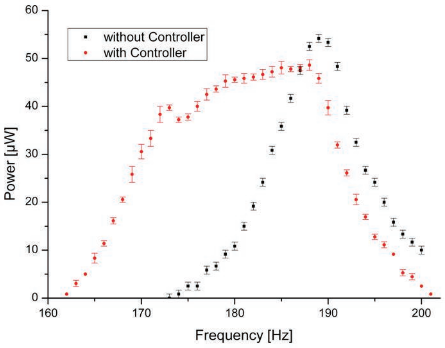

Fig. 3 *Output power of a frequency-adaptive piezogenerator system with and without adaptive tuning (sinusoidal excitation with an amplitude of 0.6 G).*

of the generator and the electronic control is mandatory for an optimal, energy-efficient interplay of all components. We have recently built such a piezoelectric energy scavenger system which is able to self-tune its resonance frequency in a completely energy-autonomous operation. The converter is based on multi-layered piezoelectric beams as described in [8]. While one part of these piezoelectric beams is used to generate electrical power, another part is employed as an actuator to change the stiffness and therefore the spring constant of the resonator. In combination with a low-power microcontroller, a self-sufficient frequency-tunable energy scavenger is obtained.

In Fig. 3 the power output of this scavenger, depending on the ambient vibration frequency, is shown with and without frequency tuning. The active tuning generates a nearly constant output power over a frequency range that is approximately 4 times wider than the power bandwidth of the un-tuned generator. The tuned peak power is slightly lower than the peak power of the static, un-tuned resonance curve, due to the fact, that a small amount of the harvested power is required to run the microcontroller and all associated electronics. This control circuit determines whether the scavenger is resonant or not and provides an appropriate tuning voltage for the actuator. A similar system is currently under development for the piezoelectric resonance-tuning of an electromagnetic harvester [9]. Within this parallel study it could be demonstrated that piezoactuators, once charged to a fixed voltage level, retain their strain, even under vibration, for a certain period of time. Therefore, it is sufficient - and power consuming - to activate the control system in regular time intervals only.

Compared to state-of-the-art in broad-band energy harvesters, this system allows to harvest over a wide frequency range, without suffering from a poor quality factor. It will also compensate other disturbing factors, e.g. the influence of temperature on the resonance behavior of the mechanical generator structure. Furthermore, the already present microcontroller can be used for other tasks, at the cost of a marginally higher power consumption.

3 Energy storage

3.1 Electrical capacitors

Depending on the power requirements of the embedded system electrical capacitors may be the best storage concept for a short to longtime power supply. In comparison to rechargeable batteries they exhibit a longer lifetime and a much higher flexibility concerning operational voltages and currents. However, the application of electrical capacitors in conjunction with a low-power microgenerator and a low-power embedded system requires a close attention to all potential power losses during charge, discharge and idle times. The result is somewhat surprising, as these effects are not important, predominant or visible at all in conventional applications:

For a long operational lifetime a solid-state dielectric capacitor would be an optimal choice over electrolytic capacitors. Today, multilayer ceramic capacitors (MLCCs) are available with a volumetric capacitance up to 12 µF/mm³. This has been achieved via a continuous shrinkage of the thickness of the ceramic dielectric layer, down to values in the range of 1 µm and below. However, together with this size reduction, the insulation resistance R_P of the dielectric material becomes important as a power loss factor. In general, the parasitic resistance of a dielectric capacitor is inversely proportional to its capacitance C and depends on the specific resistance ρ, and the permittivity ε of the dielectric material: $R_p \propto \frac{\rho \cdot \varepsilon}{C}$

In practice this means, that a 100 µF MLCC would already exhibit an insulation resistance of 5 MOhm [10]. For a typical embedded system with, e.g., a power requirement of 50 µW at a nominal supply voltage of 2.3 V, this insulation resistance would continuously draw a power of 1 µW. When the energy harvesting is stopped for a short period of time, the capacitor should bridge this brown-out phase. However, R_P alone would empty 50% of the stored energy within 173 s, i.e. the system will remain functional only for a very short period of time. This simple calculation demonstrates that highly miniaturized MLCCs, although regarded as small, long-tem stable and robust, may be not suitable as intermediate storage for ultra-low power embedded systems.

In comparison, a properly selected electrolytic capacitor turns out as a better choice. The leakage current I_L of electrolytic capacitors is falling rapidly from an initially high to a much smaller small continuous value. According to standardized test procedures [11], its typical basic data are described according to:

$$I_L(t = 2\,\text{min})[\mu A] < (\alpha \cdot U_R[V] \cdot C_R[\mu F]) + I_0\,[\mu A]$$
$$I_L(t = 5\,\text{min})[\mu A] < (\beta \cdot U_R[V] \cdot C_R[\mu F]) + I_0\,[\mu A]$$

The factors α and β typically take values around 0.01 and 0.001, respectively, while the continuous leakage current I_0 may be a few µA, all values depending on the electrical capacitance value C_R at the rated voltage. This calls for the application of low-leakage electrolytic capacitors with a reduced continuous leakage current. Taking the embedded system given above, a suitable 100 μF capacitor with a rated voltage of 10 V would show a much smaller continuous power loss in the range of 80 nW. A 50% energy drop in a fully charged capacitor does now happen within 2500 s, instead of 173 s. This calculation takes into account that the continuous leakage current of an electrolytic capacitor decreases, in addition to the temporal effects, with the applied voltage.

Finally, so-called “super-caps” or “Gold-caps” range at the upper scale of the capacitance range, with a power density close to rechargeable batteries. These capacitors use the build-up of electrochemical double layers at solid-electrolyte interfaces within liquid, organic or polymer electrolytes. A double layer thickness in the nm-range and electrode materials with effective areas up to 2000 m²/g allow for large electrical capacitances in the Farad-range.

However, it should be recognized, that these capacitors represent a bridge between electrochemical, rechargeable batteries and electrolytic capacitors. They may need a minimal charging current to accept power and will also show a higher leakage current, as they possess no insulating dielectric layer. This requires an energy harvester with a high-enough output current at a suitable output voltage level. As soon as the current drops below the values required by the capacitor, the “storage” system turns into a power dissipation system. Nevertheless, this type of capacitor is capable to deliver electrical power over long periods and with an acceptable leakage rate. With the 50 μW example system used here, a typical 0.15 F super-cap would show a continuous leakage around 0.5 μW and a 50% leakage power drop within 168 hrs, i.e. 7 days.

3.2 Rechargeable batteries

As already shown for electric capacitors, the choice of a rechargeable battery is governed by the special boundary conditions of an energy-autonomous embedded system. Most important are high variabilities of the power input from the energy harvesting system, the power demand of the embedded system, andthe state of charge (SOC) of the rechargeable battery. In addition, depending on the application, a high power density may be mandatory for highly miniaturized or light-weight systems as well as a high robustness, e.g. against temperature and pressure variations. Battery lifetime has to be considered in conjunction with the system’s operational lifetime. The requirements may range between several month, e.g. for an application in logistics, and 10 years, e.g. for a tire pressure sensor or an in-door light sensor.

A closer look onto the rechargeable batteries available today reveals that no battery type exists that is capable to fulfill all requirements given above. Pb batteries show a high robustness and accept charging and discharging independent from their SOC. On the downturn they suffer from a low energy density, a high weight and severe environmental concerns. While the environmental concerns are also serious, NiCd systems are sufficiently robust and acceptable concerning their energy density. However, they are intolerant against frequent partial discharge and recharge due to their memory effect. NiMH batteries show similar properties with a double energy density and the advantage that the memory effect does not exist. Finally, the Li-Ion system offers the highest energy density and accepts charging and discharging under all SOC conditions. As a downturn these batteries require a tight control of the charging conditions and do not tolerate a trickle or overcharge.

As a consequence, there is no general suggestion for the “ideal” battery in an energy-autonomous embedded system. Nevertheless, the Li-ion system offers several advantages (light-weight, high energy and power density, SOC-tolerant) that comply with the operation conditions in an energy-autonomous embedded system.

One additional benefit of the Li-ion system is that the lifetime capacity, i.e. the product of the discharge level and the discharge cycle number, remains almost constant before the non-avoidable on-set of ageing and degradation. Therefore, 100 cycles can be performed with a 100% discharge and recharge rate, but also 1000 cycles with an only 10% discharge and recharge rate. Hence, a Li-ion battery with a sufficient over-capacity is a good choice for a long operational lifetime, as deep discharge is avoided during the usual brown-out phases of the energy harvesting system. In many cases this “too large” battery does not increase the size of an embedded system over acceptable levels. Low power systems are operable with coin batteries, whose total volume is dominated by packaging.

A rechargeable lithium microbattery with a nominal voltage of 3.0 V and a capacity of 11 mAh, in combination with the embedded system described above, may serve as an example. With a maximum allowable discharge of 10% as a guideline, the embedded system with 50 μW power consumption could be supplied from the battery over a time period of 50 hrs. With these parameters the total operational lifetime of the battery can be estimated to 1000 cycles x 50 hrs, i.e. 5.7 years.

In any case, the integration of batteries, capacitors and energy harvesters requires a specific power management circuit to distribute the harvested energy in an optimal way. This circuit would monitor the energy in-flow and out-flow, supply the embedded system with its required power, either from the battery or from the generator, and transfer all surplus energy into a long-term storage unit.

4 Energy management and system design

Energy-autonomous embedded systems require a specific energy management that is, in part, different from established concepts for portable and mobile electronic devices. The interface between the generator and the system may require step-up converters to supply the embedded system from low voltages, provided, e.g., from PV cells or thermoelectric generators. Systems with piezoelectric generator will benefit from special charge extraction techniques [6,12,13] that gain a maximum power output from the harvester. Finally, as already mentioned above, power distribution circuits are helpful for an optimal interplay between the generator, the intermediate storage (capacitor or battery) and the system electronics.

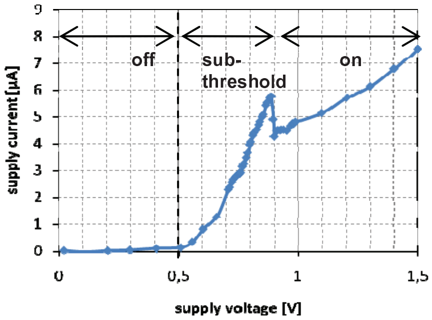

Fig. 4 *Current draw of a typical CMOS temperature sensor module during a linear increase of the supply voltage (slope: 12 mV/s) up to the nominal value (1.5 V).*

Another requirement that will be discussed in the following comes up for embedded systems that fall into an intermittent powerless mode. Many technical systems, like electrical and combustion engines or tire pressure sensors will only deliver relevant sensor data during their on-time. Their energy-autonomous embedded sensors are therefore allowed to fall into a powerless state as soon as the host is turned off. Other examples are energy-autonomous emergency detectors that draw their energy from faulty conditions, like unwanted vibrations, shock or undesired temperature levels. They are even requested to remain silent during the regular operation period of their host system.

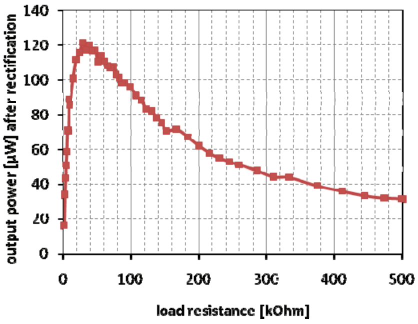

Fig. 5 *Output power of a piezoelectric impact-type generator as a function of the load resistance [14].*

As a benefit of this operation scenario, no long-term energy storage is required in the embedded system. A small capacitor will be sufficient to stabilize the system power and to deliver energy for a short over-travel time. As a drawback the system electronics, usually a CMOS circuit, has to start from zero power and zero voltage, while the ambient energy returns, usually with a slow increase of the available voltage and power. During this transition into an active state the CMOS circuit will pass through its sub-threshold voltage range, with a significant increase of power consumption.

This faulty condition may cause a deadlock when the energy harvesting system starts from a zero power state. During start-up the generator is loaded near short circuit with a small effective load resistance, as the voltage at the storage capacitor is small (Figs. 4 and 5). The generator may therefore not be capable to charge the capacitor and to supply the sub-threshold current at the same time.

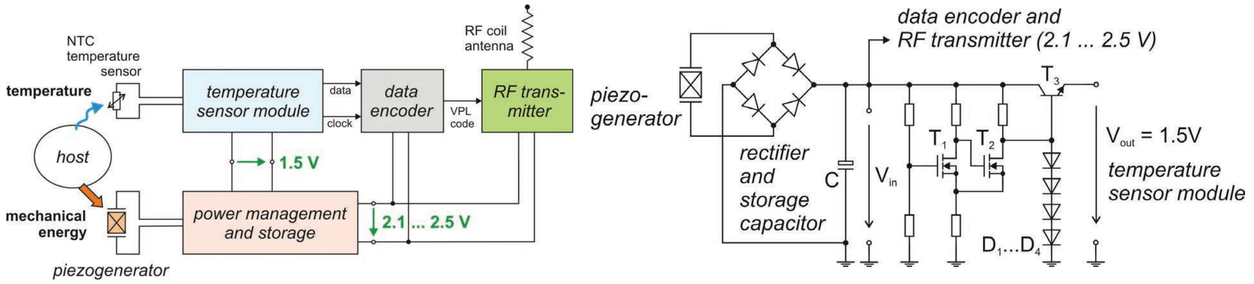

Fig. 6 *Schematic of an energy-autonomous wireless temperature sensor system (left) with its power management and storage (right), composed of a bridge rectifier, an energy storage capacitor and a low-power voltage regulator with Schmitt-trigger characteristics [14].*

In general it is advisable to choose a generator that is, under regular conditions, loaded with a resistance above the optimal load point R_{opt}. In this region, a decrease of the load resistance will increase the power output, with a moderate rate. On the contrary, when the generator is operated below or at its power maximum, a decrease of the load resistance will drastically reduce the available power. Fig. 5 illustrates these situations with the load curve of the piezoelectric impact-type generator developed for this study [14]. Additionally, an electronic start-up circuit is mandatory. This device monitors the voltage at the storage capacitor and turns on the embedded system electronics as soon as an acceptable voltage level is present. The power consumption of this circuit should be as small as possible and without any sub-threshold excursions. A “non-CMOS” device that fulfills these requirements with a minimum transistor count is depicted in Fig. 6. A linear voltage regulator (T_3 and diodes D_1 to D_4) and a “classical” Schmitt trigger (T_1 , T_2) are combined to generate a regulated output voltage V_{out} with well-defined turn-on and turn-off set-points, depending on the input voltage V_{in}. All other circuitry shows no sub-threshold effect and is directly supplied from the storage capacitor.

5 Summary and conclusions

Within this publication a brief outline of future research directions for energy harvesting and energy-autonomous embedded systems is given. In general, the focus shifts towards application-specific problems. A lot of basic research has been performed in the last decade concerning conversion principles. While this is, and has to be, an ongoing process, several harvesting concepts are now optimized to be more suited for a practical application. Two examples have been shown: Harvesting from different energy resources, using multiple conversion techniques, will increase the reliability of the energy supply. Adaptability of the generator to the level of ambient energy will provide a more robust energy source. Instead of “simply adding a rechargeable battery”, energy storage has to be addressed with respect to the requirements given by different conversion principles and embedded systems, to find an optimal solution for lifetime, storage capacity and the respective application scenario. Finally, a new type of power management electronics is slowly emerging, as the first commercial and experimental ICs become available. Here, the request for ultra-low-power electronics with low-voltage capabilities is identified, and, once again, dictated by the application.

6 Literature

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