Abstract – The present paper introduces tasks, challenges and solutions for the power management in power supplies employing energy harvesting technologies. Matching the energy transducers with the electronic circuit is discussed as well as the regulation of their output voltages. Furthermore control methods to decrease the power consumption of the application circuits are presented. Considerations to use energy storage elements are introduced. At last visions of combining several energy transducers to achieve universal power supplies, independent of the application, are outlined. A sensor module with thermo-electrical power supply, which works with human body heat, is demonstrated. It shows the practical implementation of the presented circuit and system techniques.

Index Terms – dc-dc-converter, energy harvesting, power management, power supply;

1 INTRODUCTION

The power consumption of electronic circuits and systems is decreasing more and more. On the other hand, the efficiency of energy transducers like thermo-generators (TEG), piezoelectric modules or solar cells is being further optimized. Thus the energy from the environment like heat, light or motion can be used to supply electronic devices. Typical application devices are sensors, wireless transceivers or displays. Every ambient energy source has its own challenge, which the user has to cope with (Table 1).

Besides the improvement of the energy harvesting transducers, high demands are made on the power management. The power management is the 'enabling technology' for the use of energy harvesting power supplies. With the improvement of the power management, the areas of application can be increased and new application fields are developed.

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Challenge</th>
<th>Estimated Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>Conform to small surface</td>
<td>10 µW – 15 mW</td>
</tr>
<tr>
<td></td>
<td>area</td>
<td>(Outdoors: 0.15 – 15 mW)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Indoors: &lt;10 µW)</td>
</tr>
<tr>
<td>Vibrations</td>
<td>Variability of vibration</td>
<td>1 – 200 µW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Piezoelectric: ~ 200 µW)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Electrostatic: 50 – 100 µW)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Electromagnetic: &lt; 1µW)</td>
</tr>
<tr>
<td>Thermal</td>
<td>Small thermal gradients</td>
<td>15 µW (10 °C gradient)</td>
</tr>
</tbody>
</table>

Table 1: Comparison between different ambient energy sources [1]

There are several duties the power management is responsible for in energy harvesting power supplies. The first task is matching the energy transducers voltage level with those of the electronic circuit or system to supply. The next function is the regulation of the supply voltage, to generate a constant voltage independent of source or load variations. Furthermore the power consumption of the application devices has to be minimized by the power management. So a maximum of functionality, performance and operation time is achieved with the minimum of energy provided by the energy harvesting module. Another task for the power management is the management of the energy and the required storage units like capacitors or rechargeable batteries.

The paper presents solutions and practical realization examples with measurement results for each of these tasks. Finally first approaches combining different energy transducers are reported. These combinations are designed to allow energy-autarkic operation independent of the environment or the application field. Strengths and weaknesses of the different energy harvesters have to be balanced with such approaches.

2 VOLTAGE LEVELS

The threshold voltages of semiconductor technologies are scaled down more and more due to technology development. Nevertheless there is a gap between the output of the energy transducers and the minimum required input voltage of state-of-the-art voltage converters like dc-dc boost regulators. The output voltages of thermo-generators (TEG) are proportional to the applied temperature gradient and are situated in the range of 50 mV per Kelvin, depending on the number of thermocouples deployed. Common versions of solar cells or fuel cells provide voltages of about 0.5 V. To use minimum amounts of energy in terms of small temperature gradients or little illumination, low-voltage semiconductor ICs have to be developed. In applications with limited board space, only a small number of units like thermocouples can be mounted. Due to the number of units connected in series determine the output voltage, you have to cope with low output voltage as well. Typical circuit techniques for boosting voltages are switched capacitor (SC) circuits, like charge pumps and inductor-based converters.
Commercial step-up (boost) dc-dc converters start with input voltages of 0.7 V, charge pumps with 1.5 V. The reason is the threshold voltage of the semiconductor transistors. If lower input signals have to be processed, special low-threshold transistors have to be used or dedicated dc-dc converters architectures have to be adapted. Two examples will be introduced here in further detail.

Charge pumps collect small amounts of energy from the energy transducer on a capacitor and discharge it to another one. The polarity and timing of this discharge cycle determines the voltage of the second capacitor which works as output capacitor. Figure 1 is showing a charge pump connected as voltage doubler. Neglecting losses and the load resistor \( R_L \), and considering the charge \( Q = C \cdot V \) is equal in the two switching phases, it is found [2]:

\[
V_{\text{out}} = \frac{C}{C + C_{\text{out}}} \cdot 2 \cdot V_{DD}
\]

![Figure 1: Practical charge pump as voltage doubler (charging of C: switch S1 and S3 are closed; discharging C: S2 and S4 are closed)](image)

An IC from SEIKO [3] using SOI (silicon on insulator) transistors with low threshold voltages is available off-the-shelf. Input voltages of 300 mV are sufficient for this IC. Such a low-voltage (LV) charge pump can work as start-up circuit to deliver the required 0.7 V for a state-of-the-art boost converter.

When the output capacitor \( C_{\text{out}} \) of the low-voltage charge pump has reached a sufficient voltage level, it is used as an input source for a standard dc-dc regulator like a step-up converter. If the dc-dc converter has a sufficient input voltage from this capacitor for a first switching cycle, the circuit starts oscillating and is supplied by its own output. The charge pump can be short-circuited by the inductor of the step-up converter. Thus the charge pump works only as start-up circuit and their low efficiency is not a problem anymore.

A practical implementation of a voltage converter with a charge pump and a step-up dc-dc regulator (Figure 2) showed the measurement results in Table 2. The voltage \( V_{\text{in}} \) and current \( I_{\text{in}} \) are measured at the input of the circuit shown in Figure 2 at the terminals X1-1 and X1-2. The output parameters \( V_{\text{out}} \) and \( I_{\text{out}} \) are measured at the output terminals X2-1, X2-2. The start-up was achieved with input voltages of 250 mV. When the start-up has been carried out, the circuit is working with lower input voltages. The efficiency is improving with increasing input voltages.

The disadvantages of this approach are the high bill of material and the small availability of low-voltage charge pumps. The advantage is the possibility of a fully integrated realization as an IC with less external devices like capacitors or inductors.

The second approach is the application of coupled inductors in a step-up converter for voltage transformation [4]. Depending on the turns ratio of the device, large voltages are generated with smaller ones. The transformer is described by

\[
\frac{V_1}{V_2} = \frac{N_1}{N_2} = n
\]

Here \( V_1 \) is the input voltage on the primary winding \( L_1 \) with \( N_1 \) windings and \( V_2 \) is the output voltage at the secondary winding \( L_2 \) with \( N_2 \) windings. Neglecting losses, it is found

\[
P = I_1 \cdot V_1 = I_2 \cdot V_2
\]

and

\[
\frac{V_1}{V_2} = \frac{I_2}{I_1} = n
\]

For an inductor the relationship between voltages and currents is:

\[
V = -L \cdot \frac{dl}{dt}
\]

For the transformer the following equations are well-known:

\[
V_i(t) = L_i \cdot \frac{dl_i(t)}{dt} + M \cdot \frac{dl_2(t)}{dt}
\]
The key component in the circuit with coupled inductors is an always-on junction FET (JFET) like T1 in Figure 3. If a small voltage is present at the terminal \( V_{\text{in}} \) of the voltage converter, a current flows through the primary winding \( L_1 \) of the transformer \( T_1 \). According to the relationship between voltage and current for an inductor, the current follows an increasing exponential function and the voltage decreases with the same exponential function. The deviation of this current is positive, so a positive voltage is induced in the secondary winding \( L_2 \). The positive terminal of the inductor \( L_2 \), which is connected to the gate of T1, is driven to a fixed voltage level by the diode of the JFET T1. Thus with the positive induction voltage the negative terminal is shifted to a negative voltage level, charging the capacitor \( C_2 \) to a negative level.

When the current in the primary winding \( L_1 \) reaches saturation, the deviation and so the induced voltage in the secondary winding \( L_2 \) is zero, producing a drop in the secondary voltage. The sum of the voltage of capacitor \( C_2 \) and the secondary winding \( L_2 \) becomes negative, making the transistor T1 to switch off. So the current through the primary inductor is decreasing and a positive voltage is induced in the primary winding \( L_1 \), delaying the current decrease. Because the transistor T1 has a high resistance, the output capacitor \( C_3 \) is charged via \( D_1 \). When the primary current reaches zero, the induced voltage in \( L_2 \) becomes zero too and \( C_2 \) is discharged by \( R_1 \) to the level of the input voltage. Thus the JFET starts conducting again and the operation cycle repeats.

A feedback loop (not shown in the Figure 3) from output \( V_{\text{out}} \) formed by a voltage divider and some further devices controls the switching level of the JFET T1. Therefore the switching frequency is depending on the output voltage.

\[
V_2(t) = L_2 \frac{dI_2(t)}{dt} + M \frac{dI_1(t)}{dt}
\]

In Figure 4 and Figure 5 measured results of the voltage converter with coupled inductors are displayed. Figure 4 shows the input current and the output voltage as a function of the input voltage with no load connected to the converter. With 50 mV and 75 mV an output voltage of only 1.25 V is achieved. Increasing the input voltage, higher output voltages are possible. The input current is decreasing with increasing input voltage, due to the feedback loop from the output to the JFET T1. When a certain output voltage is reached and no load current is drawn, this feedback loop reduces the input current.

In Figure 5 the efficiency of the converter is displayed with respect to the output power. The switching frequency is in the range of 18 to 35 kHz. The length of the switching period determines the level of the current increase. Thus the higher the output power, the smaller the switching frequency. While the output power increases, the switching losses are decreased because of the reduced switching frequency. So the efficiency increases when the output power is scaled up.

### 3 POWER CONSUMPTION

In realising complete energy-autarkic systems, the energy from the transducers is often not sufficient when state-of-the-art application circuits, like sensors or wireless transceivers, are used. Thus the power management has to decrease the power consumption of the application devices. This can be accomplished through techniques like different standby modes, dynamic voltage and frequency scaling and using RSSI (receive signal strength indicator) and BER (bit error rate) measurements for transceiver-control.
Because the majority of harvesting applications employ wireless data communication, a method to reduce the power consumption in wireless transceivers is presented here. Control loops for automatic gain control (AGC) of amplifiers in the receiver chain are state-of-the-art (Figure 6). Most circuit techniques used in amplifier design, like source circuit, differential amplifier or the cascode decrease their current consumption with reduced bias or supply voltage. This is accompanied by a reduction of the amplifier gain. Communication receivers are always designed for worst-case conditions like minimum signal strength, maximum interfering signal and maximum noise. But these conditions do not occur permanently, so a reduction of gain could be tolerable. In combination with an AGC the power consumption can be reduced by controlling the bias or supply voltage when strong desired signals are present [5].

A power-efficient concept is mandatory when designing an amplifier gain control dependent on the signal-strength. The key component is the device for measuring the signal strength at certain points of the transceiver. The best method concerning power, board space and costs are the so-called rms-dc converters (rms: root-mean-square, dc: direct current). They produce a dc voltage depending on the rms value of the input signal, which is a measure for the signal strength. The regulation loop is completed by a state-of-the-art op-amp acting as controller and an adjustable dc-dc-converter or a simple MOSFET (Figure 7). A directional coupler can be used for coupling parts of the signal to the rms-dc converter. For evaluation purposes of the proposed control method to decrease the power consumption of a transceiver component, an increasing input signal RF_in was fed to the receiver input. Because of the control loop, the gain of the LNA is reduced with increasing input signal. This reduction of gain produced a decrease of current consumption I_LNA (Figure 8).

Practical implementation showed a current consumption of 2 mA for the control loop. Further a potential saving of 8.5 mA (73% of total consumption) for a LNA and of 13.8 mA (69 % of total consumption) for a LNA-mixer combination was achieved, when the maximum signal was applied.

**Figure 6: Example for AGC in a wireless transceiver**

**Figure 7: Control loop for LNA to reduce the power consumption**

**Figure 8: Current consumption I_LNA of a LNA as a function of the input signal strength RF_in**

### ENERGY STORAGE

Considerations have to be made about using energy storage elements, like batteries or supercaps. These elements are needed to provide large peak currents for mobile communication systems because they work in so-called time-division multiple-access or burst mode. That means the power consuming blocks of the electronic device are enabled only in very short time-slots in the range of micro- or milliseconds. This feature makes the use of energy transducers much easier, because time is left to store the required energy for a transmission burst.

To use these storage elements as efficient as possible, care must be taken when choosing the properties of them. Important are the supply voltage level of the application circuits in comparison to the voltage level of the storage element. Especially when using batteries, high battery voltages together with low supply voltages of the circuits should be avoided. Considerations have to be made also about the numbers of charge-discharge cycles and lifetime of batteries, because they are limited to some hundreds or thousands cycles, especially in maintenance-free systems.

Additional circuitry is required for charging the batteries to generate the appropriate charge profile like constant-current constant-voltage (CC-CV) for lithium batteries. Energy transducers like thermo-generators and solar cells provide only a minimum load current, thus a current limiting regulator may be not necessary. A simple
diode for limiting the voltage may be sufficient and makes the circuit less complex. In any case, care must be taken to the leakage currents of the regulator or the diode.

5 THERMO-ELECTRICAL POWER SUPPLY FOR WIRELESS TRANSCEIVERS

A thermo-electrical power supply is designed to show the practical implementation of the previously introduced circuit techniques. The thermo-generator uses the body heat and delivers about 2 mW of electrical power to a rechargeable battery. The application module is a temperature sensor and a wireless transceiver, which transmits the measured data to a base station. For demonstration purposes, the base station is connected to a laptop to display the measurements, which are temperature, voltage, and current from the thermo-generator (see Figure 10). The power management has been accomplished by means of a low-voltage charge pump and a boost converter. There was no charge regulator, but only a diode for voltage limitation because of the low currents from the thermo-generator. A second dc-dc-converter was used for the supply voltage of the transceiver [6].

Figure 9: Block diagram of the wireless transceiver for sensor signals with thermo-electrical power supply

The system is self-powered by the body heat, which produces a temperature gradient of about 5 Kelvins to the environment. Measurement results with the human hand as heat source are shown in Table 3. The voltage $V_{in}$ and current $I_{in}$ are measured at the input of the power management shown in Figure 2 (X1-1, X1-2) directly after the thermo-generator. The output parameters $V_{out}$ and $I_{out}$ (X2-1, X2-2) are measured at the battery.

The results show an electrical output power of about 1 mW from the heat of the human hand. Depending on the duty cycle of the wireless transmission, fully self-powered operation is possible. In the demonstrator a transmission rate of one value per second was used. This is sufficient for many kinds of sensors and enables a power supply by only a thermo-generator.

<table>
<thead>
<tr>
<th>$V_{in}$ (mV)</th>
<th>$I_{in}$ (mA)</th>
<th>$V_{out}$ (V)</th>
<th>$I_{out}$ (µA)</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>246</td>
<td>9.76</td>
<td>2.077</td>
<td>646</td>
<td>65.38</td>
</tr>
<tr>
<td>254</td>
<td>10.00</td>
<td>2.12</td>
<td>645</td>
<td>62.87</td>
</tr>
<tr>
<td>265</td>
<td>10.16</td>
<td>2.13</td>
<td>695</td>
<td>64.28</td>
</tr>
<tr>
<td>236</td>
<td>9.88</td>
<td>2.142</td>
<td>550</td>
<td>58.71</td>
</tr>
</tbody>
</table>

Table 3: Measurement values of the power management module for the power supply with a thermo-generator

Figure 10: Graphical user interface of the wireless transceiver for sensor signals with thermo-electrical power supply

6 COMBINATION OF ENERGY TRANSDUCERS

To realize universal power supplies, independent of the application environment, several transducers have to be combined to balance their strengths and weaknesses. There are some approaches on the way to be developed at different research institutes like combining thermogenerators with solar cells and battery or combining piezo-materials with supercap and battery.

In [7] a thin film organic or hybrid solar cell connected to a polymer-Li battery is reported. The so-called "EURO-PSB" shows characteristics like low weight, small thickness and mechanical flexibility. Thanks to a smart interconnection between the two units, the battery is always charged with optimized voltage, independent of the illumination conditions.

In [8] a combination of a thermo-electric device, a solar cell and a battery together with a charge-control circuit is reported. Called "Power Tile", the system is packaged in a less than 2 mm thick volume. The thermogenerator can harvest some of the thermal energy incurred when solar radiation raises the temperature on the photovoltaic cell. It can also work as heat pump to keep batteries within a desired temperature range. The integrated circuit includes dc-dc converters, battery-charging circuit, thermo-electric heater driver and the required sense and control circuits. In full sunlight, the photovoltaic cell delivers 125 mA at 2.1 V. The thermogenerator generates 20 mA at 0.8 V, when a temperature difference of 35 °C is present.

A German research project called "PiezoEn" addresses the combination of a piezo material with a lithium battery, a supercap and a power management chip. The capacitor is required in each application, dealing with vibration energy and piezo materials, to filter the current peaks from the transducer. Because large capacitors are difficult to integrate on ICs, it is reasonable to integrate it...
7 SUMMARY

In this paper power management tasks in energy harvesting applications are introduced. Ways of converting the output voltage of energy harvesting transducers like thermo-generators, solar cells or fuel cells are explained. Results of practical realizations are presented. Furthermore approaches to reduce the power consumption of electronic systems in energy harvesting applications are summarized and an example is explained in detail. Considerations about energy storage elements and their circuitry are made. Finally a look in the future towards autonomous self-powered systems is outlined.

8 CONCLUSIONS

Regarding the power management in energy harvesting applications, the requirements are changing in comparison with the solely battery driven systems. Voltage levels and sensitivity have to scale down and current consumption must be decreased to assure performance with small amounts of energy available from the environment. A certain intelligence to adapt to different operation modes is required to maintain minimum power consumption and so self-powered operation by energy harvesting transducers. Due to these small amounts of energy being processed, the power consumption in blocks like step-up converters or regulators has to be minimized, to arrive at an acceptable efficiency. Furthermore leakage currents approach the range of the output current of the energy harvesting transducers, so they have to be handled carefully. Circuit functionality like charge regulation and monitoring or data rate must not be “overspecified” to achieve minimum complexity and so minimum power consumption. Only this way, self-powered energy harvesting systems could be realized.

ACKNOWLEDGMENT

The authors would like to thank Franz-Xaver Arbinger, Ortwin Beier, Harald Böttner, Alfonso Carrera, Cosmin Codrea, Dirk Ebling, Frank Förster, Javier Gutiérrez, Alexandre Jacquot, Jan König, Nestor Lucas, Loreto Mateu and Jürgen Schmidt for their technical support.

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Markus Pollak studied Electrical Engineering at the University of Erlangen/Germany and graduated with Dipl.-Ing. degree in 2000. Since February 2001 he works at the Fraunhofer IIS, department of power efficient systems. He was working in the design of integrated circuits for RF-transceivers and power management circuits. His recent projects are concerned with dc-dc converters for energy harvesting applications and programming of microcontrollers for wireless transceivers.

Günter Rohmer received his master degree in 1988 and the PhD in 1995 from the technical university of Erlangen, Germany. In 1988 he joined the Fraunhofer Institute for Integrated Circuits working in the field of analogue IC-Design. In 1996 he changed to the telecommunication department and started the navigation activities at the institute. Since 2001 he is head of a department dealing with the development of components for satellite navigation receivers, indoor navigation and microwave localisation systems. Other activities of this department are techniques and modules for power and battery management and interface technologies like transceivers or transponders.