Efficiently harvesting energy from temperature differences in order to power wireless systems

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Abstract— **Devices that generate electrical energy from a temperature difference are often used to provide energy autonomy. Since they normally deliver small voltages, the use of a step-up converter is required to get to the needed voltage for the electronics. Several such boosters exist on the market. In the practice, it is often difficult to provide enough energy when the temperature differences are small. It is well known that the impedance of the harvester can strongly influence the performance of the booster and therefore have an impact on the cost of the harvesting system. In this work, we present a booster architecture that allows a good impedance matching for existing TEG harvesters. The amount of energy harvested for a small temperature difference is high enough to allow the efficient use of small commercial TEGs. We show how the booster and associated power management system can be combined with very low power electronic to power loads such as sensors that communicate using Ble or other wireless protocols.**

Keywords—TEG; energy harvesting; low power; wireless; wearable; power management; Ble;

I. INTRODUCTION AND MOTIVATION

Energy autonomy is a well-established and recurring requirement in some embedded systems. The need is even more acute when dealing with wireless sensors. This is likely to be the same in fields that are gaining in importance, such as wearable electronics. Achieving energy autonomy by means of harvesting energy from the surroundings has fueled the imagination of many and has been hailed as "the solution". Although there are some practical realizations and commercial products, one is still far from the fulfillment of dreams and visions that were set before our eyes several years ago. Powering masses of consumer electronic devices without the need of batteries is not yet where we want to see it.

Among the important reasons for the slow deployment of systems that run on harvested energy are their cost and reliability, especially as consumers have been used to the comfort of small and very affordable batteries. Costs are strongly influenced by the price of harvesters and the associated power management circuitry. Energy availability issues are also present, linked to the nature and of the energy sources that

should be converted into electrical power. They often require complex, equally expensive and fragile storage technologies. Energy harvesting is likely to need more developments to become main stream. However, there are several efforts to deal with these issues. For instance:

- Harvesters are being developed to take advantage of existing and well established production techniques. This should help reduce their costs.

- Several firms have brought out products to help deal with the challenges provided by the different energy sources.

- Integrated circuits require less and less energy to do the same work. As the voltage needed by these circuits goes down, the difference between the voltages delivered by some EH devices and the voltage needed by the electronics is reduced. This helps improve the efficiency of some power management elements. Ultimately, this will influence costs and improve energy availability.

However, a lot of effort is still needed. This is especially true as one tries to find acceptable compromises for low cost harvesters. They might work at energy points where the efficiency of the PM elements is very small. This work is such an effort. A step-up that can allow the use of TEGs in situations where the temperature differences allow only small amounts of energy to be delivered is presented. The results of the discrete implementation show that it can well fill a void so help further the use of EH systems.

II. THE BOOSTER

It is well known that efficiency and low voltage start-up are important when using thermoelectric generators (TEGs) as power source. Beside these, impedance matching is also very important in order to maximize the output power. The proper loading of the energy storage and the control of an external system like a sensor when enough energy is available is important and too and also part of the power management unit.

In this work a circuit built up with discrete components and based on the DC-DC converter of [3] is shown. It can start-up and work with $10\mu W$ input power with TEGs from Micropelt and Greenteg which have an electrical resistance of more than 100Ω. Although we will concentrate on the unipolar version, there is also a bipolar variation that is briefly shown. It can work with positive and negative temperature differences on the TEG.
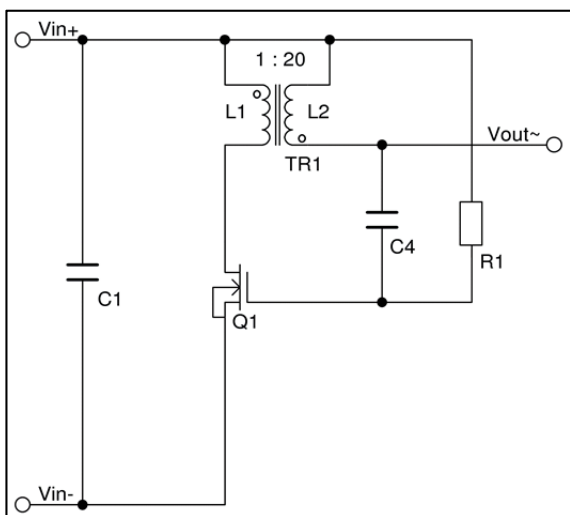

Fig.1 – self-starting low voltage oscillator

For low voltage start-up, a transistor based self-starting Meißner-oscillator similar to [1] and LTC3108 is used which is shown in Fig.1. A LC resonator is formed out of the inductance L2 of a 1:20 transformer, the parasitic parallel capacitance of L2 and the input capacitance of Q1 in series with C4. The oscillator can only work when Q1 is conducting and therefore a depletion MOSFET is used, which is biased with R1 for low-voltage start-up.
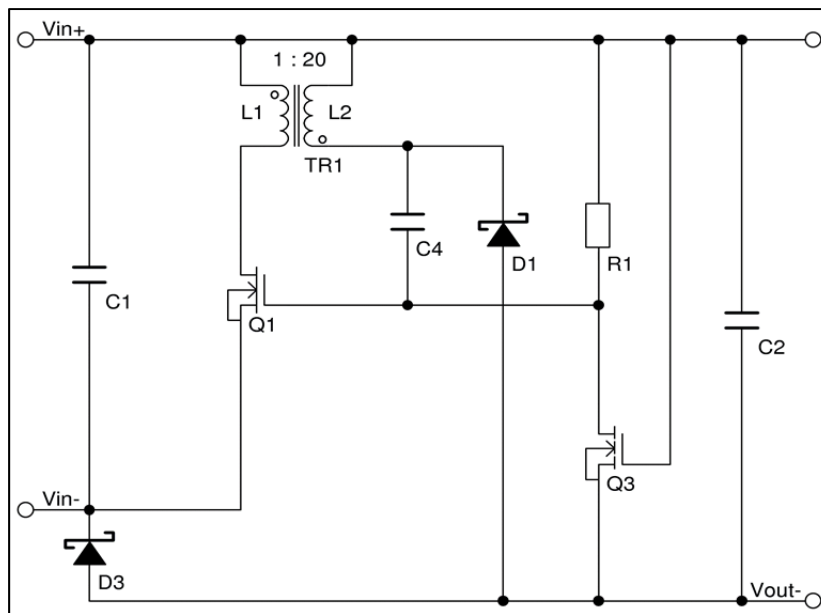
Fig.2 – self-stopping oscillator and rectifier

In Fig.2, a rectifier (consisting of Shottky-diode D1 and capacitor C2) is added. Every time Q1 is switched off, the energy stored in TR1coupled inductor loads C2. The voltage Vout is negative with respect to Vin. As the voltage at C2 approaches V_{th} of Q3, a negative voltage is also applied to the Gate of Q1 and the oscillator is stopped. The diode D3 is optional and loads C2 already before the oscillator starts and improves the start-up behavior.
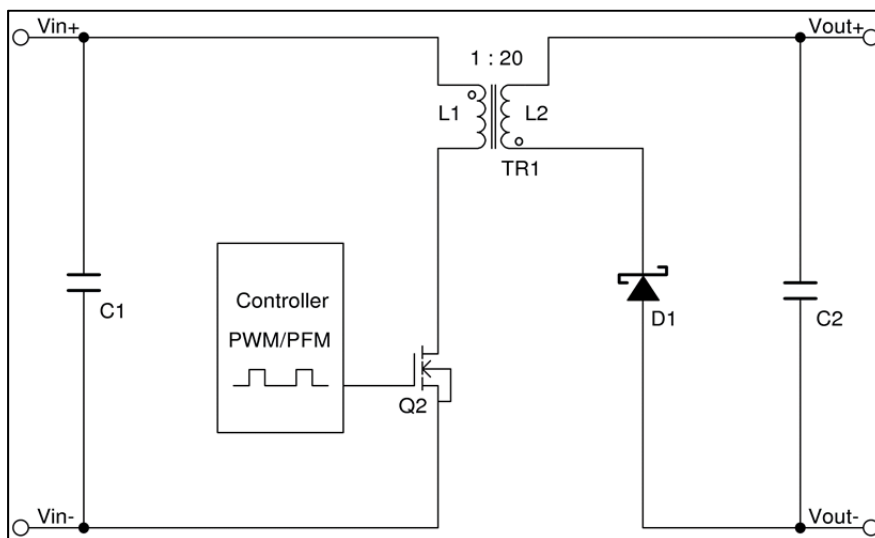

Fig.3 – Flyback Converter

Fig. 3 shows a flyback converter. When the enhancement MOSFET Q2 is closed, L1 is directly connected to the input voltage source. The primary current and the magnetic flux in the transformer increase, storing energy in the transformer. Due to the induced voltage in L2 the diode D1 is reverse-biased. When Q2 is opened, the primary current and magnetic flux drops. The diode D1 is forward biased by the secondary voltage, allowing current to flow from the transformer to charge the capacitor C2.
The advantage over a boost converter is a lower duty cycle which results in smaller secondary current, longer charging time of C2 and smaller switching losses. In the special case of TEGs which have a constant

electrical resistance, there is another advantage: In discontinuous current mode - where the current through L1 always starts at 0A - the input resistance of the flyback converter is constant with constant duty cycle:

$$I_{max,L1} = V_{in} * t_{on,Q2} \ / \ L1$$
$$I_{ave,L1} = V_{in} * t_{on,Q2}^2 * f \ / \ (2* L1)$$
$$R_{in} = V_{in} \ / \ I_{ave,L1} = 2*L1 \ / \ (t_{on,Q2}^2 * f)$$
(all calculations without losses)

R_{in} is independent of V_{in}, so it can be set once and no more measurements are necessary to work at the maximum power point (MPP).
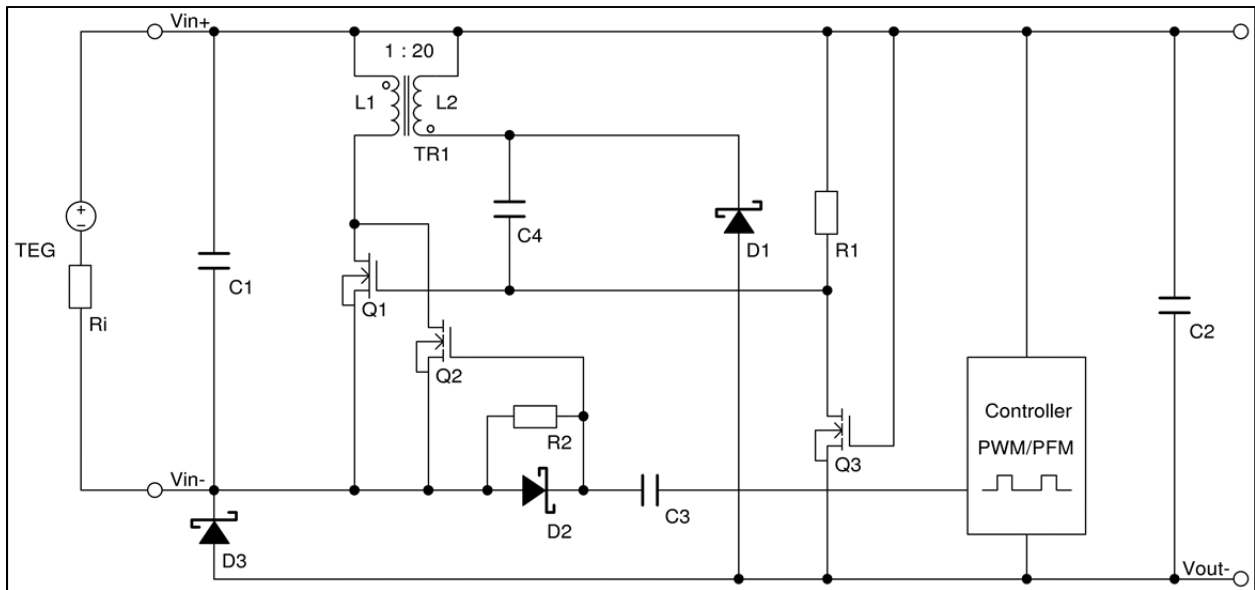

Fig.4 - Flyback converter for operation with very low input voltages

Fig.4 shows a combination of Fig.2 and Fig.3 with a TEG as power source. The circuit starts with the oscillator (self-start). When C2 is charged to around 0.8V, the controller is started and works in parallel until the oscillator is stopped at around 1.2V. For the Gate of Q2 an additional charge pump consisting of D2 and C3 is needed since Vout- is lower than Vin-. R2 is necessary to unload the Gate-voltage of Q2 after operation to make a new start-up possible. The efficiency of the flyback converter is much higher than the one of the start-up-circuit which is working with a much higher and uncontrolled switching frequency (changing with V_{in}).
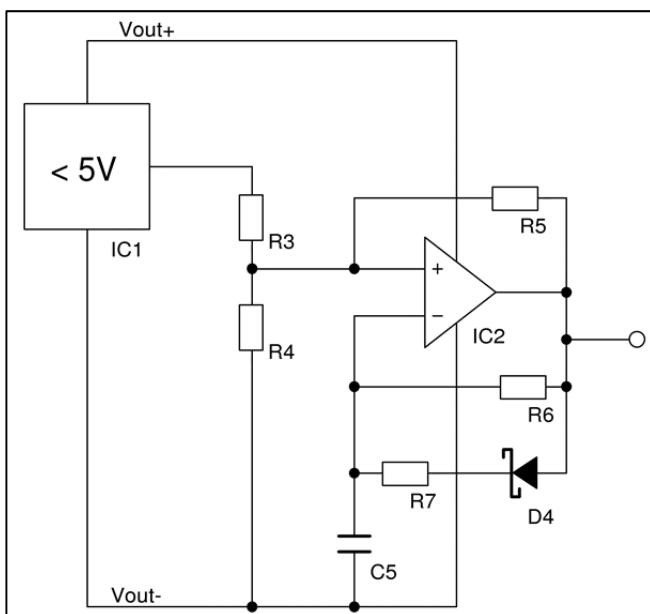

Fig.5 – Controller of the flyback converter

The controller shown in Fig.5 consists of a voltage detector and a comparator based oscillator. Both ICs (NCP300HSN47 and TS881) already work at 0.8V and have a current consumption of 300nA each. As long as the output voltage is smaller than 4.9V the oscillator works with a short on-time (R7||R6 ~

R7 charges C5) and a long off-time (R6 discharges C5) with constant frequency and therefore in pulse width modulation (PWM) with impedance matching.

When Vout is higher than 4.9V the oscillator is switched off until Vout goes down to 4.7V again. The controller thus works in pulse frequency modulation (PFM) where the frequency is load dependent.

This system was optimized for a Micropelt TGP-751 with an electrical resistance of 300Ω (R_{TEG}). It starts at an input voltage of 60mV and an input current of 170μA which equals an input power of 10μW and an input resistance (R_{in}) of about 350Ω . This is reached with a temperature difference of 1K on the TEG.

The Controller operates with t_{on}=5.8μs and f=4.35kHz.
(check: with L1 = 25μH: R_{in} = 2 * 25μ / ($5.8μ^2$ * 4.35k) = 342Ω)

Efficiency of impedance matching:
η_{im} = $P_{in}/P_{in,max}$ = 4 * R_{TEG} * R_{in} / $(R_{TEG}+R_{in})^2$ = 4 * 350 * 300 / $(300+350)^2$ = 99.4%
It turned out that an input resistance slightly higher than 300Ω maximizes $P_{out}/P_{in,max}$ since the impedance matching is nearly perfect and the electrical efficiency (η_{el}) with higher input voltages gets higher.
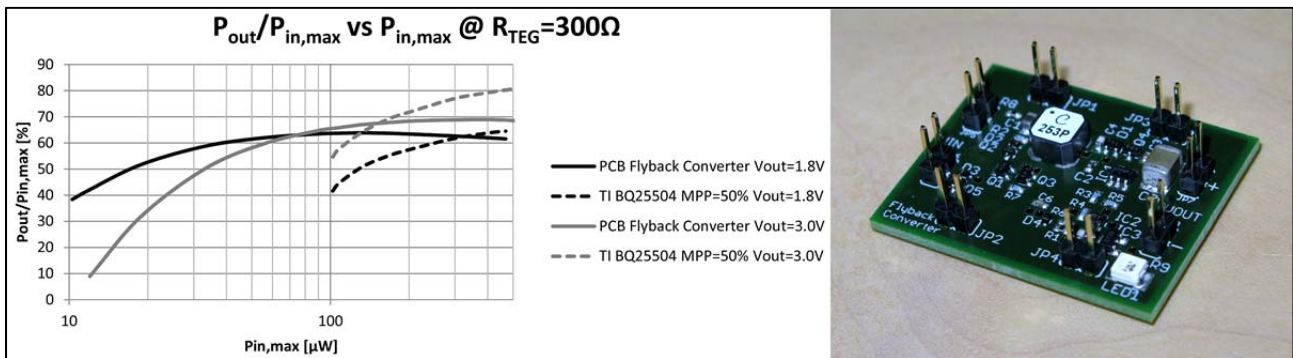P_{out} = η_{el} * P_{in} = η_{el} * η_{im} * $P_{in,max}$

Fig.6 – Measurement results and picture of PCB "Flyback Converter"

A couple of PCBs called "Flyback Converter", shown in Fig.6, were produced. Both the PCBs and the international patent application of [3] were financed by AWS – Austria Wirtschaftsservice which is now looking for a cooperation partner for a chip integration of the circuit.

The measurements results show the superior performance in the very low power range against the best in class IC BQ25504 which needs 330mV to start-up (this would require three TGP-751 in series to start-up with a 1K temperature difference on the TEG). The LTC3108 which can start-up with lower voltages is not included since it has a very low input resistance. That resistance will lead to η_{im} < 30% and $P_{in,max}$= 320μW for start-up with R_{TEG} = 300Ω.

Due to the simplicity of the flyback converter circuit the efficiency decreases with higher input power. The reason is the increasing voltage drop on D1. It is very small in order to achieve low capacitance and high efficiency at low input power. In an integrated solution, a synchronous rectifier (say a N-MOSFET parallel to D1) and the use of a higher switching frequency for higher input power would increase the efficiency. The power consumption of the controller would be reduced, improving the efficiency at very low input power higher.

The large transformer shown in the picture is not necessary. It is simply the smallest 1:20 version we could find on the market for this work.

We also designed a flyback converter variation optimized for small single cell solar cells. That circuit can work with a tiny 1:3 coupled inductor. It was also tested successfully.
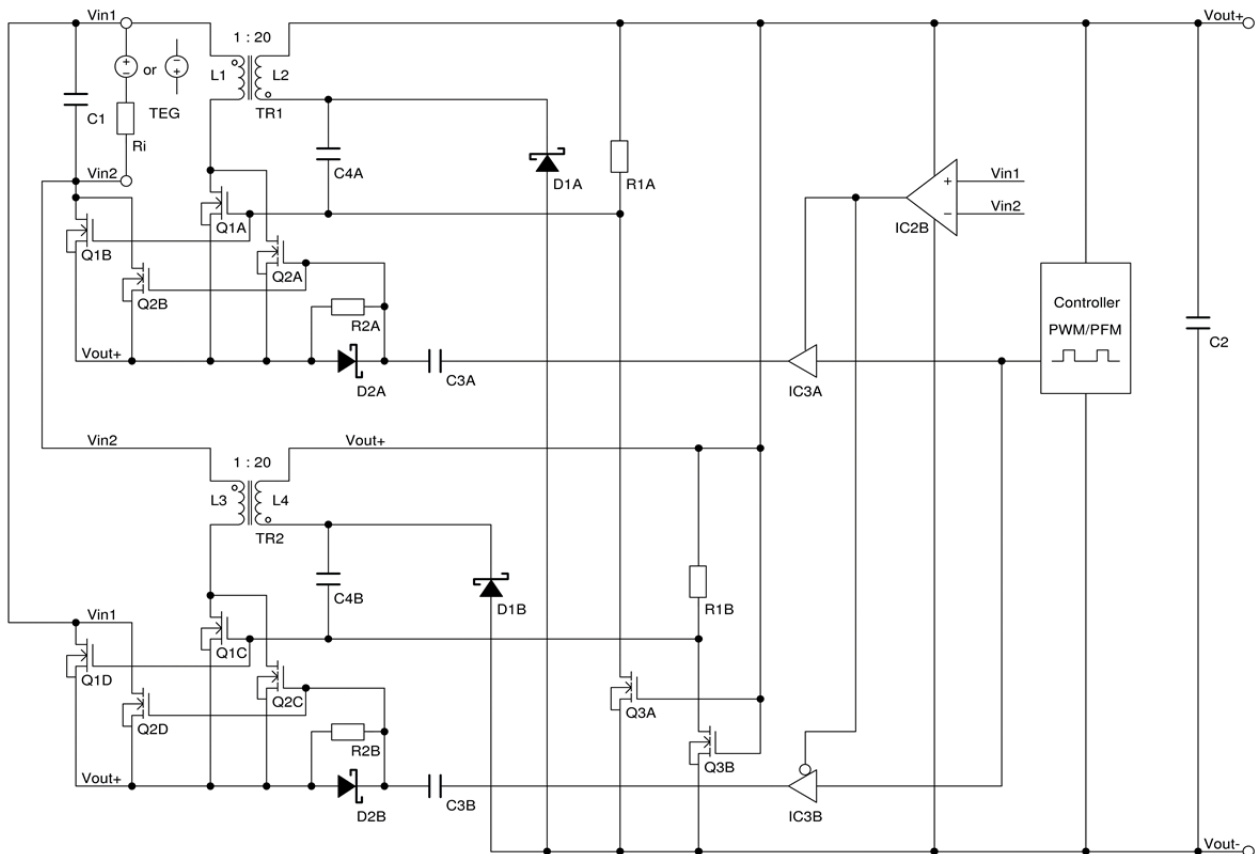
Fig.7 – Bipolar flyback converter for operation with very low input voltages

Fig.7 shows a bipolar version which can work with positive and negative input voltages. It consists of two anti-parallel circuits and the start-up is similar to [2] (which is used in LTC3109).

2 MOSFETs are always used to switch the primary winding to the power source. This prevents a current flow via the parasitic bulk diode in case of negative input voltage. The gates of the depletion devices are biased with 0V, which is nearly the same situation as in Fig.4, since the input voltage is very small. Only the oscillator with positive input voltage starts, but after start-up both are turned off and there is no current in the unused converter, which is an additional advantage over [2].

When working as flyback converter, a second comparator (TS882) is used to decide which input voltage is higher and therefore which driver of IC3 (74AUP2G241) should be enabled.
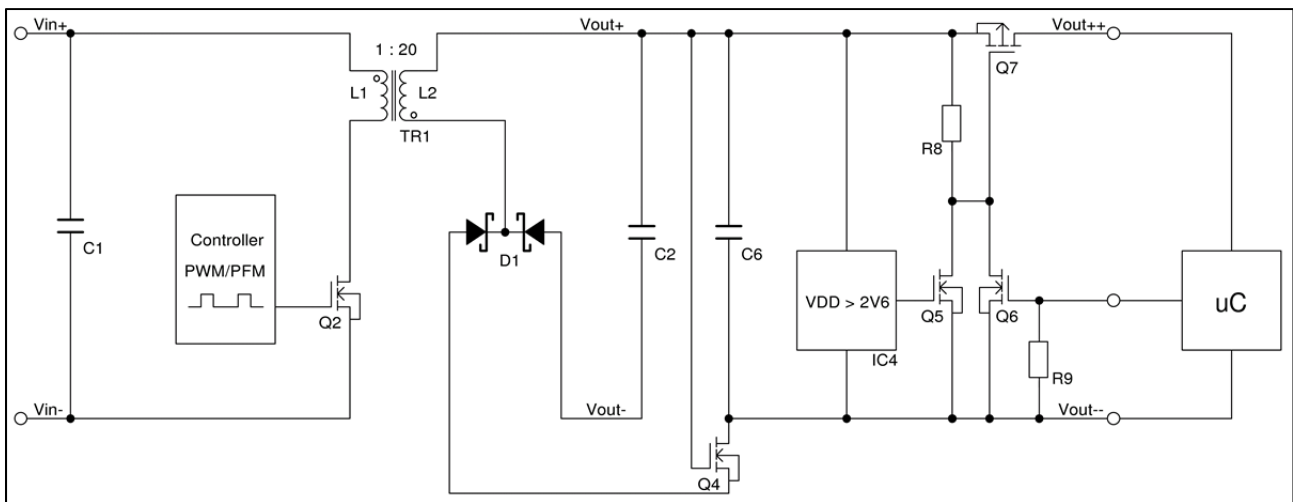
Fig.8 – Load connection

In applications where the power consumption of the external system is much higher than P_{out} , the system can only work with very low duty cycle. A storage element (C6) which is only loaded after start-up is needed. This is realized by taking advantage of the V_{th} of Q4 and by using a dual common cathode diode (D1). Energy can only be transferred in one direction, the controller is never supplied from C6 and also a cyclic heat source can be used.

When loading C6, the only load is the Supervisory IC4 (TPS3839L30) which consumes 150nA. When the threshold of 2.65V is reached, NMOS Q5 and PMOS Q7 are turned on and the microcontroller (µC) of the external system is started. Due to the hysteresis of IC4, it is possible to turn on NMOS Q6 with a "1" and hold Q7 low ohmic until the job is done (in case of a sensor the measurements and transmissions) . After that the µC-output is set to "0" and Q7 is turned off again.

C6 needs to be large enough, so that the voltage is still within the system specification at the end of operation without any additional input power. On the other hand, the load has to be high enough, so that the voltage of C6 is below the hysteresis of IC4 with the highest possible input power. If this is not the case, an extra load can be connected by the µC after the important operation in order to "burn" the surplus energy. If both conditions are fulfilled, IC1 of the controller is not necessary. For over-voltage protection a Zener diode is recommended.

The booster was demonstrated in an application. The human body acts as heat source for a TEG. The harvested energy is used to power a temperature sensor. The measured data is sent to a smartphone using Bluetooth smart compatible wireless frames. The block diagram and the software layers needed are shown in Fig.9 and Fig.10. The low power microcontroller starts when enough energy is available, makes the needed measurements and sends data in ADV mode. It sends data as long as there is energy, leading to a discharge of the storage capacitor. Once the voltage is lower enough, the system is switched off automatically, and the storage is recharged. Alternatively, the microcontroller can also turn itself off with the appropriate signal.

The temperature tag is similar to one that has been described at previous conferences [4,5]. The interested user is advised to consult the associated documentation.
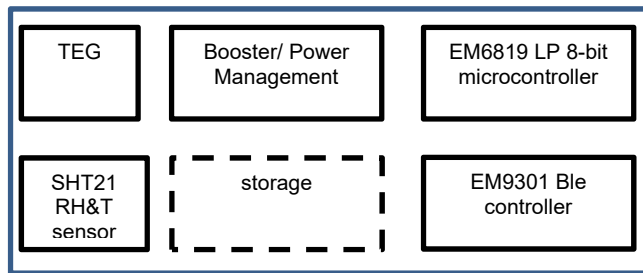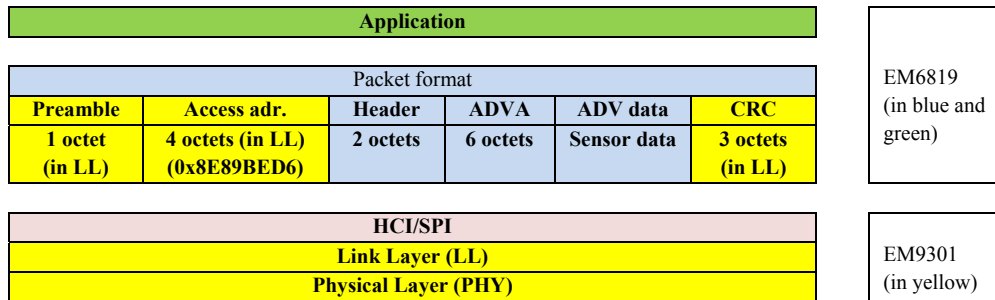
Fig.9 – Block diagram of the system

Fig.10 – Communication layers of sensor

IV. CONCLUSIONS

A step-up converter optimized for work at low voltages and energy levels has been described. Thanks to the good impedance matching, that device allows operations with low-cost TEGs in a power segment where current devices are not as efficient. The device has been successfully tried in a discrete configuration. Better results are expected for an integrated solution.

REFERENCES

[1] Low voltage driven oscillator circuit, John E. Bohan Jr., US4734658, 1987

[2] Polarity independent step-up converter capable of operating under ultra-low input voltage condition, David Charles Salerno & John Bazinet, EP2575248, 2010

[3] Flyback converter for operation with very low input voltages, Harald Dillersberger, WO2014060241, 2013

[4] Indoor battery-less temperature and humidity sensor for Bluetooth Low Energy, M. Meli, U. Beerli, Wireless Congress 2011, Munich

[5] Using Bluetooth Smart with Energy Harvesting, M. Meli, Embedded World 2013 Nuremberg