Novel Thermoelectric Energy Harvesting Circuit for Exploiting Small Variable Temperature Gradients Based on a Commercially Available Integrated Circuit

Martin Lenzhofer
Sensor Systems
Silicon Austria Labs GmbH
9524 Villach, Austria
martin.lenzhofer@silicon-austria.com

***Abstract*—Nowadays there is an increasing demand in generating electrical power out of ambient sources, such as light, wireless power, vibrations or heat, to supply low power electronics of self-sustaining sensor nodes. The main problem is that if dealing in harsh environments, or at places with very little energy budgets and additional varying environmental conditions, sophisticated harvesting circuits are necessary. In this work a novel approach for such a circuit is described that deals with thermal gradients. It bases on a commercially available integrated circuit, but with an external wiring scheme, according to the presented modified block diagram of a general harvesting system. A detailed description is given how to analyze the energy requirements. Additionally, the importance of adequate matching of the thermo-electric generator to the input impedance of the circuit is pointed out and at last the wiring of external components to override the internally fixed switching scheme of the build in blocks of the integrated circuit is described. Measurements verify the function of the low power thermal energy harvesting unit and demonstrate in detail the solutions to the key challenges to exploit maximal power out of thermal gradients and to supply a sensor node electronics over a certain time.**

Keywords-Harvesting circuit; thermal gradient; low power electronics; thermo-electric generator; thermal harvester; LTC3108.

I. INTRODUCTION

Recent developments in the field of wireless sensor technology and low power electronics enable an increase of the scope of applications in direction of self-sustaining sensor systems, even in harsh environments. Nowadays, most of the devices are generally powered by battery, but their drawbacks are that they increase the size of the devices and sometimes also their costs and pose an additional burden of replacement or recharging. Thus, there is an increasing effort in using other energy sources to supply the electronic circuits. The concept of energy harvesting describes the mechanism of exploiting energy from present sources in the environment of the sensor node. There are many ambient energy sources to exploit electrical power, but sophisticated circuits have to be developed to convert the small quantities of light emissions, wireless power transmitted by different devices, small vibrations or thermal energy into useful quantities that are sufficient to supply an electronic circuit [1]. A rough order of magnitude for the expected energy value for each energy source is given below.

Light energy is available almost everywhere and can be captured by photovoltaic (PV) cells, but it has to be considered that in average, levels between 10µW/cm² or just 10mW/cm² can be achieved indoor, depending on the location where the sensor node is used, meaning somewhere in the room or right beside a window, where the power levels are of course much higher, due to the fact of the sunlight influence. Of course, even higher values are achieved outdoor, if directly lightning the cell or photovoltaic module right adjusted to the sun, where values of up to 1.353W/m² [2] can be achieved, but these applications are not in the focus of the presented study dealing with energy harvesting solutions used in autonomous sensor nodes in a building or machine. To maximize the output power of the cell maximum power point tracking (MPPT) techniques must be applied. There are already commercial integrated circuits (IC) on the market with an implemented algorithm to continuously track the supply conditions and the corresponding load to maximize the transferred power, determined from the I-V curve of the solar cell.

Another omnipresent energy source is the radio frequency (RF) energy, due to the high number of mobile phones, WLAN networks, cell phone towers and every other kind of communication network. Beside the fact that the quantity of available power density level is very low, in the range of 0.1µW/cm² to 1µW/cm² [3], the energy levels additionally vary due to factors like terrain, number of users and many others. To achieve useful power levels also high gain and therefore big antenna systems are required and thus, often depict a limiting factor in being used in autonomous sensor nodes.

Also, the vibration energy source offers a great possibility to be converted into electrical power. There are many various forms - steady-state source, intermitted source and vibration source, where the last one is the commonly most often exploited one and being used to generate power, while for example human activity such as walking. While vibration amplitude can be quite large, like in the case of being exploited in civil structures ore railways, the expected levels, if being used under normal conditions, range between 4µW/cm² to 100µW/cm².

At last, thermal energy can be obtained either present in the ambient or generated during several processes. The most common way to generate electrical power to supply an electronic circuit of the available source is to use the Seebeck effect [2]. To extract energy from a thermal source a thermal gradient is required, where the conversion efficiency is directly related to the achieved temperature difference (hot and cold side) of the Peltier element or thermo-electrical generator (TEG). As it is described later in this paper, dependent on the application it is not always possible to achieve big gradients, leading in investigating novel design approaches however, to ensure the possibility of suppling an electronic circuit [3]-[5]. The expected energy output by exploiting thermal variations ranges between 10μW/cm² to about 60W/cm² [6]. As the temperature gradients are usually low, also the conversion efficiency and the output voltages of the systems are low, which afford special converter circuits. There are many applications, which focus on the usage of thermoelectric devices exploiting stable and continuous temperature differences, but there are rarely any of them dealing with harvesting energy from temperature gradients [7]-[10]. There are two main reasons for that: on one hand, the little energy potential within a gradient does not seem to be very attractive and, on the other hand, it is a reliability issue for stable operations of autonomous systems. Nevertheless, there are a plenty of applications that show small temperature gradients, for example, in wearable systems and in systems for environmental and infrastructure monitoring.

Referring to [1], the presented paper describes the functionality of the developed thermal harvesting circuit in more detail and additionally, demonstrates the possibility of exploiting energy from just a thermal gradient with a start-up procedure for an electronic circuit. Furthermore, the theoretical investigations point out the importance of matching the generator to the load impedance, as well as quantify the theoretical potential of a temperature gradient.

Section I describes the building blocks of a common energy harvesting system and the modified one. Section II deals with the development of the harvester circuit, based on the extended block diagram and Section III presents real measurements, verifying the functionality of this novel approach.

II. Building Blocks of an energy Harvesting System

Referring to the literature [11], commonly a conventional energy harvesting system is built up by several blocks, shown in Figure 1.

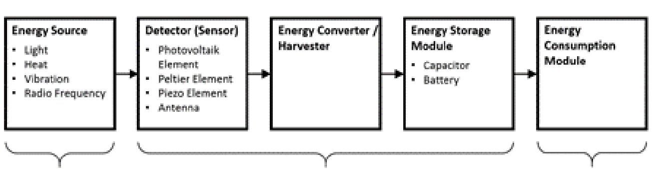

Figure 1. Block diagram of a conventional energy harvesting system.

At the input of the system the residual energy from the ambient environmental source is captured by the detector. There it is converted into the electrical domain and afterwards stored to supply different loads (circuit blocks). Optionally, as it was already mentioned in the introduction, some conditioning circuits can be developed to achieve a higher efficiency and output power. The storage module ensures continuous energy supply even under varying environmental conditions or also in the case, if the source is not available anymore.

This simple block diagram, shown in Figure 1, of an energy harvesting system is in general valid, but must be modified and extended, if dealing with not stable environmental conditions. Also, if working in the RF domain, where accumulation of energy is necessary, a more sophisticated system is needed. Referring to the described challenge of extracting energy from varying temperatures or its gradients, a similar approach to RF systems must be realized, to even have the ability of supplying any electronics. Figure 2 illustrates the modified block diagram for a system that is even able to address the previously mentioned challenges. Just a single reference could be found that describes this modified block diagram [12].

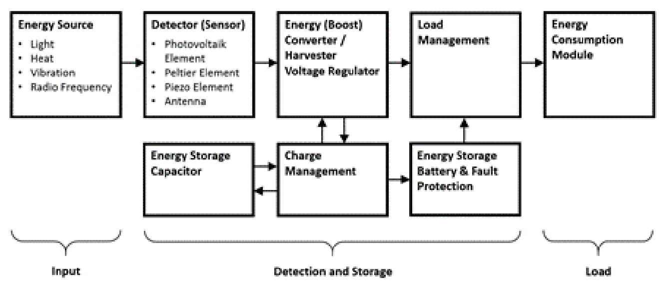

Figure 2. Modified block diagram for a general valid harvester system that is also able to deal with RF sources and thermal gradients.

Similar to Figure 1 the system includes a detector, represented by the TEG in this dedicated case, the voltage regulator working as energy converter, the charge management circuit to realize the energy storage block and additionally before connecting to the load the so important load management circuit. This last-mentioned block contains the key function for the developed harvester approach.

As most of the electronics require more than 1.8 V to operate adequately and often the input voltages are far smaller than that, a boost converter block is implemented. If connecting a TEG to the input, additionally variation in the temperature of the heat source can lead to an unstable output, which requires a regulation. The charge management block handles the different types of energy storage devices, which can either be an electrochemical cell (battery), or any kind of capacitor. Batteries offer a high energy storage density and less leakage current compared to capacitors, but therefore cannot provide high current bursts for a short period of time.

The load management circuit is used to automatically switch the load between the regulated voltage and the storage device, depending on the environmental conditions and the status of the regulator output. In case of using a battery, also a protection block to prevent overcharging or over discharging is implemented in the block diagram.

III. DEVELOPMENT OF THE HARVESTER CIRCUIT

If dealing with very little energy, as it is contained in thermal gradients, one of the most important points is an adequate impedance matching for maximal power transfer. Additionally, an energy storage system must be considered, to accumulate enough energy before powering-up the connected sensor node electronics based on an intelligent start-up sequence switching scheme.

A. *Impedance Matching for Maximal Power Transfer*

Thermal energy harvesting systems require specific optimizations, either on the thermal level and on the other hand on the electrical circuit level. In particular, the thermoelectric device must be sized appropriately for the available heat and the electrical load. The presented work bases on the already optimized thermal setup and therefore just focus on the electrical domain of building up a harvesting circuit to supply a sensor node electronic circuit. Through the thermoelectric coupling equations, the open circuit output voltage of the TEG, described as U_{TEG} is given by [13],

$$U_{TEG} = \alpha \cdot \Delta T_{TEG} \tag{1}$$

with the Seebeck coefficient α and the heat difference ΔT_{TEG} between the hot and the cold side of the TEG, including of course the contact and thermal interface resistances of the build-up mechanical system. The unloaded TEG output voltage U_{TEG} varies linearly with the temperature difference. Figure 3 shows the measurement result U_{TEG} (without load) over time of the TEG system during the heating up process, when the electronic circuit should work, and the converter circuit is designed for.

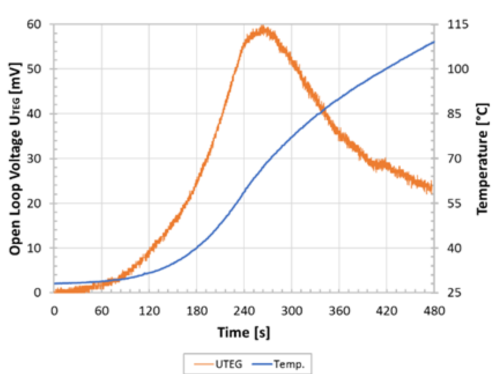

Figure 3. Open loop voltage U_{TEG} of the TEG versus the temperature raise in the oven over time. After about 260s the thermal mass of the sensor node is heated up, leading to a further decrease in voltage again.

The resulting current flow through a fictive resistive load R_L can be described as [14],

$$I_L = \frac{\alpha}{R_L} \cdot \frac{\Delta T_{TEG}}{1+\frac{1}{u}} \tag{2}$$

with,

$$u = \frac{R_L}{R_{TEG}} \tag{3}$$

where R_{TEG} is the electrical resistance of the TEG and u the ratio between the TEG impedance and the load impedance R_L. If applying formula (1) and (3), the resulting current I_L, expressed by (2), through the circuit becomes as,

$$I_L = \frac{U_{TEG}}{R_L + R_{TEG}} \tag{4}$$

As the current I_L flows through the internal impedance R_{TEG} and through R_L, the maximal voltage drop is achieved if both values are of the same value, or the ratio u = 1. In this case the maximum amount of energy can be transferred, and appropriate power matching is performed, which represents the aimed condition.

In this development, the situation is more complicated, because several aspects must be considered. First, Figure 3 just illustrates the voltage of the TEG generated during a heat up ramp without any load. Before applying this result to (4) also the real impedance of the TEG is measured with an LCR bridge, at a frequency of 100 kHz, which value is equal to the switching frequency of the connected DC-DC converter circuit. It turns out that the internal resistance of the TEG is about 5.4 Ω and additionally there is a small inductance, caused by the wires and the internal cabling of about 2 µH. Furthermore, also the input impedance of the DC-DC converter unit is analyzed with a source meter according to the input voltage level, shown in Figure 4. The discontinuity in the curve at about 25 mV represents the level of start-up of the circuit. From the harvesting point of view this means that for about 230 s the voltage just increases to that level, which represents the moment of reaching twice the value of the unloaded result in Figure 3 performed at the state of perfect power matching. After that, energy is transferred to a storage element, which is just possible for a certain time, in this particular case just as long as the system does not reach +85°C, which occurs after approximately 330 s. Higher temperatures are not allowed, due to the fact of proper reliable functionality of the circuit. Figure 5 illustrates the temperature raise of the oven versus the achieved temperature difference over the TEG, which represents a linear correlation of the generated voltage U_{TEG} in Figure 3. Due to the fact of still increasing temperatures in the oven, the whole sustainable sensor setup will heat up, resulting in a decreasing voltage difference over the implemented TEG. So, there is just a limited time-window to supply the electronics and perform the processing ability of the sensor node. In the timeframe from the start-up of the converter to the maximal allowable temperature, enough energy to perform all the processing for the controller unit must be collected. Also, all the losses and the conversion efficiency of the converter unit must be considered.

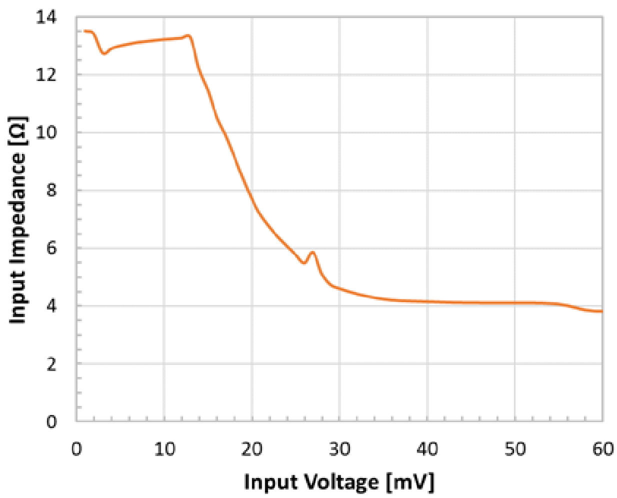

Figure 4. Measurement of the input impedance of the DC-DC converter circuit, dependent on the voltage level on its input. The discontinuity in the impedance chart around 25 mV represents the start-up condition of the electronic circuit.

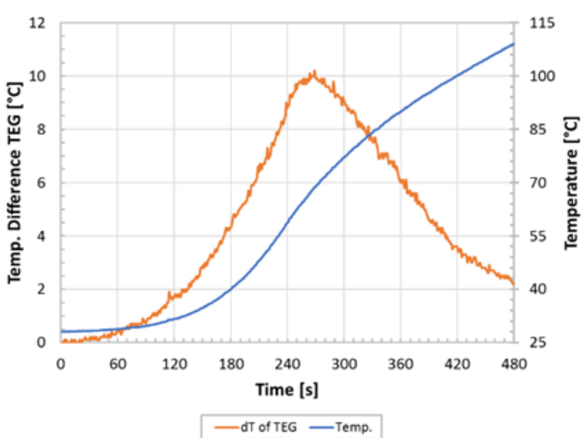

Figure 5. Temperature raise of the oven (blue curve) and temperature difference between the hot and the cold side of the TEG in the setup (orange curve).

Putting all these dependencies together and additionally applying formula (4) the maximal available electrical power at the input of the DC-DC converter can be expressed by,

$$P_L(t, U_{TEG}(t)) = \left(\frac{U_{TEG}(t)}{R_L(U_{TEG}(t))+R_{TEG}}\right)^2 \cdot R_L(U_{TEG}(t)) \quad (5)$$

Figure 6 shows the result of equation (5) (blue signal) and additionally the respective integral of the signal (orange), which leads to the available energy value at the circuit input to supply the sensor node electronic circuit. Still it must be considered that this power is available at the input, and additional conversion losses of the circuit itself must be added and determined.

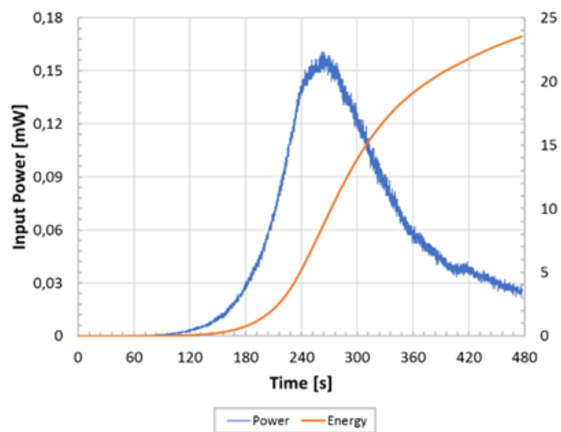

Figure 6. Blue signal represents the available input power and the orange signal represents the integral and therefore the energy over time at the circuit input.

There are just a few vendors of integrated ultra-low power converter and management IC on the market, where the LTC3108 [14] from Linear Technology Inc. seems to be the best fitting one for the present use case. This circuit is intended to provide a highly integrated DC-DC converter for harvesting and managing surplus energy from extremely low input voltage sources, such as the described TEG system. Referring to the datasheet [14], the implemented step-up technology operates from input voltages as low as 20 mV. This minimum input voltage depends on the transformer turns ratio, the load power required and the internal DC resistance (ESR) of the supplying source. A lower ESR allows the use of lower voltages and provides higher output power capability, but in the described use-case, the limitation is given by the TEG's resistance of 5.4 Ω resulting in a circuit start-up voltage level around 25 mV, shown in Figure 4.

B. *Wiring scheme of the DC-DC Converter according to the modified block diagram*

The recommended wiring scheme for a wireless remote application is given in the datasheet [15], shown in Figure 7. Since this is just working for continuous applied input voltage levels, some modifications must be applied, to realize the suggested wiring scheme according to the extended block diagram shown in Figure 2.

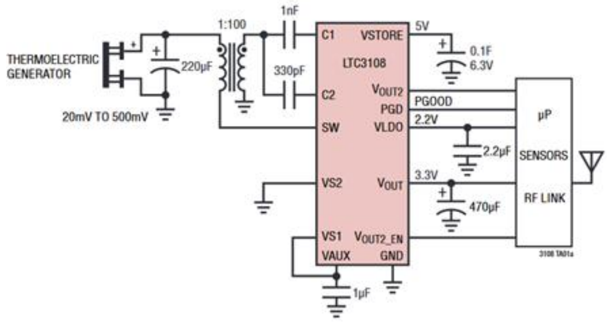

Figure 7. Wireless remote sensor application powered from a Peltier cell, according to the datasheet suggestion. This wiring scheme represents a solution according to the typical block diagram, shown in Figure 1.

Before thinking of how to change and modify the connection scheme of all the implemented blocks within the LTC3108 it is necessary to have a deeper look into the sequencing of the chip, refer to Figure 8, considering that this is always, just valid for stable and constant input conditions.

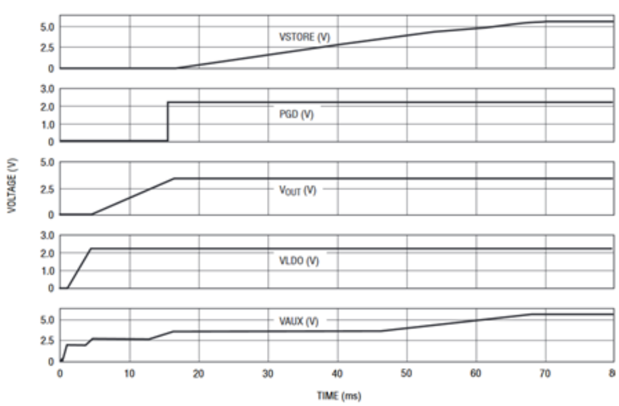

Figure 8. Start-up sequencing diagram of the management unit of the LTC3108 from Linear Technology Inc..

If a voltage is applied to the input of the circuit the level at VAUX starts to increase. The precision internal micropower voltage reference to accurately control the output voltage level V_{out} becomes active, after exceeding a level of 2 V. At this point, the synchronous rectifiers, which are switched in parallel to each diode, take over leading to an improvement in the conversion efficiency. After reaching a VAUX level of 2 V the VLDO supply starts-up, which provides 2.2 V output for powering low power processors or other low power ICs, if dealing with constant input conditions. Afterwards the level at Vout starts to increase till the output level is reached, which is programmed via the configuration pins VS1 and VS2 and set to 2.35 V in this dedicated case. If the level is valid the power good PGD indicator pin is activated and the internal charge control unit switches to another output to store the energy into an external capacitor connected to the pin VSTORE. The level will still increase up to 5.5 V and will remain at this level during the time where the V_{in} level is present. The whole routine will be processed within a few milliseconds at stable input conditions.

If using the implemented blocks of the semiconductor device to exploit temperature gradients, the switching scheme of the charge control circuit must be influenced from outside, to affect the hardware implemented start-up sequence. One major problem if working with thermal, time and slope varying gradients is the very limited contained energy. In the case of constant heat transfer of the TEG, load matching is targeted and enough to guarantee maximal power transfer. If dealing with that small temperature gradients this configuration is not enough, due to the fact that already a low-power load like a Microcontroller Unit (MCU) core connected to the Low-Dropout Regulator (LDO) output of the chip, the current flow leads to a decrease in voltage at the input. Tests showed that even for very low power MCUs, a valid start-up of the controller core is impossible. Therefore, another strategy must be implemented; meaning, first to harvest all available energy within the thermal gradient and just activate the controller circuit at the state of enough available power.

Figure 9 shows the adopted schematic scheme to deal with positive variable temperature gradients that result in a positive voltage level at the TEG system, which is suitable if using the sensor in an oven within the start-up procedure.

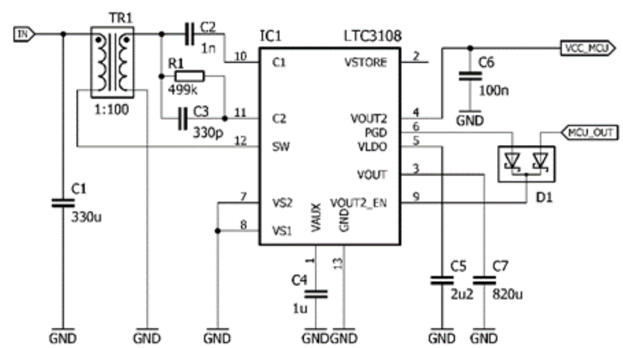

Figure 9. Developed circuit of the thermal harvester unit with improved power-up sequence influenced by external components.

If an input level of around 20 mV is reached, the DC-DC converter of the LTC3108 starts-up, leading to a raising voltage level at the pin VOUT. To avoid a constant current flow and perform adequate matching, just a capacitor as load is connected to this pin. This leads to a slowly charging of the energy storage device and capturing all available power from the input. The capacitance value must be matched to the slope of the thermal gradient, because a continuously heating up system, will result in a decrease of level over the TEG after a certain time.

If remaining heating-up of the whole self-sustaining sensor node, the DC-DC converter will be deactivated again, if turning back below the approximately 20 mV. In the case of a too large capacitance value, the expected output voltage level at VOUT will not be reached and therefore PGD is not set. The stored energy in this capacitor can be used to supply the sensor electronics afterwards. The IC internally generates a PGD signal, if the programmed output level at VOUT reaches 2.35 V. In the presented application, the load formed by an MCU is connected to the pin VOUT2. The reason is that this pin is switchable by an internal low leakage transistor. For enabling this VOUT2 pin, the PGD signal is now used and connected to the respective input pin with a low voltage Schottky diode D1.

This diode D1 represents another key aspect of the presented circuit, because it forms together with the second one an OR-gate, controlled by an output pin of the external MCU. This method is necessary due to the load case at output VOUT2. The start-up current of the MCU, refer to Figure 10 a.) (state A), leads to a voltage drop at VOUT (state B), where the energy flows from the capacitor C7 over the internal transistor of IC1 to the MCU. The PGD condition of the LTC3108 is tied to an internal not access- and adjustable hysteresis setting, which leads to switch off again, if the voltage level decreases by 7.5% of the nominal set value (state B). This happens quite rapidly, because the start-up current even of a low power MCU is quite high in the range of a few mA, or approximately 1.7 mA in the presented application. If the supplying voltage VOUT2 is switched off by the PGD signal again, the electronics would never reach the properly run mode of the circuit electronics. After switching off again (state B), the load current is almost zero again, causing an increase in voltage at VOUT again and switching on the voltage regulator once more (state C). So, this effect of switching on and off the load leads to a ringing phenomenon, refer to Figure 10 a.), which must be prohibited.

Therefore, the energy stored in the capacitor C7 must be high enough to hold the voltage level during the start-up of the MCU, configuration and controlling the diode D1 above the rated voltage (set voltage level reduced by 7.5% representing the internally fixed hysteresis value). After that, a further decrease in voltage level is not critical anymore, due to the locking function of the high level of the MCU pin that deactivates the hysteresis because of the OR gate mechanism, resulting to the diagram shown in Figure 10 b.).

In the presented application, the output level V_{out} is set to 2.35 V, so the start-up procedure including the activation of the output pin is not allowed to decrease beyond 2.174 V. As an MCU with a supply rating of 1.8 V is used, still a margin for a further approximately 0.4 V voltage drop is guaranteed for valid operation. Depending on the stored energy, the permitted maximal voltage drop and the current demand, which is of course mainly influenced by the software control algorithms and its necessary internal hardware blocks of the controller, the active operation time of the system, can be evaluated.

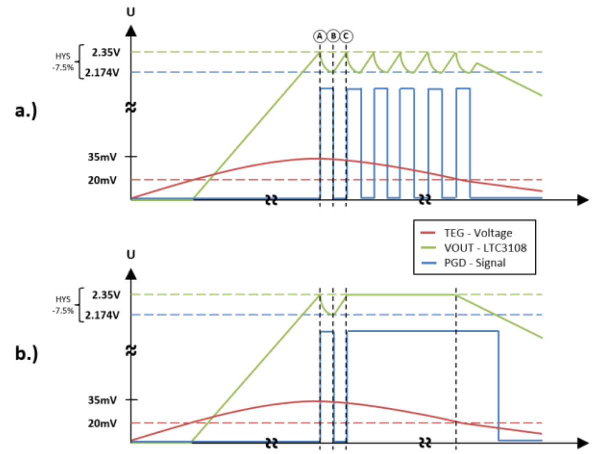

Figure 10. a.) Ringing phenomena due to different load conditions at VOUT, b.) Avoidance of the effect through self-locking circuitry via the MCU controlled OR gate configuration.

IV. Measurements and Validation

In this section, the developed circuit is evaluated. Compared to the measurement result of the open-loop voltage of the TEG, shown in Figure 3, it turns out that almost perfect maximal power matching is achieved, due to the fact of reaching nearly half of the voltage level. The measurement is shown in Figure 11 and it turns out that the harvesting part of the circuit starts-up at 21 mV, leading to an increase in the voltage level at VOUT. After the set output voltage level of 2.35 V is reached, the circuit tries to hold the level. Because the input voltage starts decreasing again the bursts in the signal at VIN becomes higher and the frequency decreases. At approximately 320 s the DC-DC converter stops working. Since there is still energy stored in the capacitor connected to VOUT, the level remains stable for a time. Referring to the measurement in Figure 3, at this time also a temperature of about +85°C is reached, meaning that the circuit will not work much longer. Because of the thermal mass of the sensor node, the inner temperature is slightly lower, leading the circuit to extend the working time.

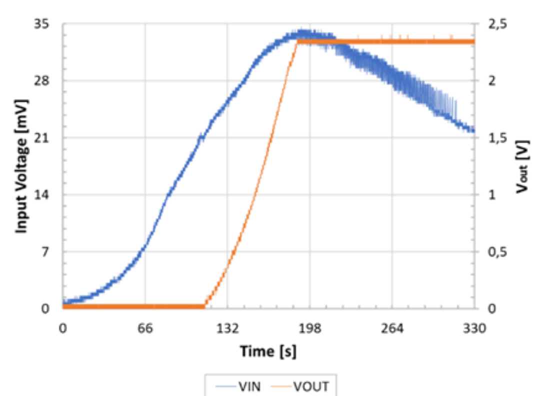

Figure 11. Blue signal: Input voltage level at the DC-DC converter input under load matching condition; Orange signal: Output voltage slope at pin VOUT achieved during heat-up process based on input level of the circuit.

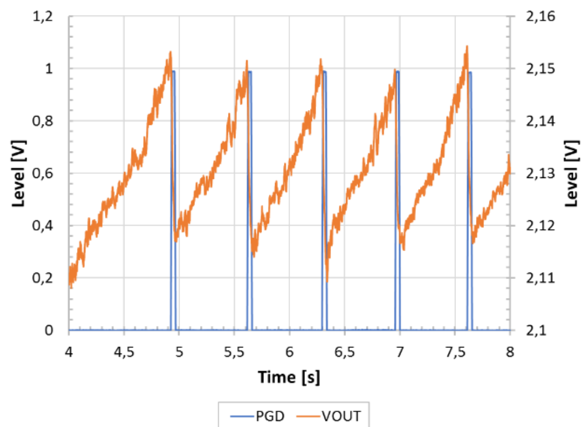

Figure 12. Circuit behavior without self-locking mechanism. If PGD (blue signal) is switched on, the circuit is supplied, leading to a voltage drop at VOUT (orange signal) caused by the current flow of the MCU and PGD is switched off again, if the value is lower than the internal hysteresis value. Due to the no-load condition after switching off, the capacitor charges up again and the voltage level increases.

Because the start-up current of the electronics is quite high, the voltage drops rapidly under the internal hysteresis value leading the LTC3805 to switch off again the PGD pin. Therefore, the circuitry does not have enough time to start-up properly. The active ON time is limited to the burst length, which is just 34 ms in this dedicated case. After switching off PGD, the current supply of the connected electronics stops, leading capacitor C7 at pin VOUT to charge up again. The desired and programmed output voltage is reached again after approximately 660 ms, refer to Figure 12. Now PGD is switched on again leading to repeat this sequence. Since the input voltage decreases, also the charge-up time of the capacitor is influenced, leading to longer charging times after a while. This kind of ringing phenomena makes it necessary to evaluate the function of the developed self-locking circuitry.

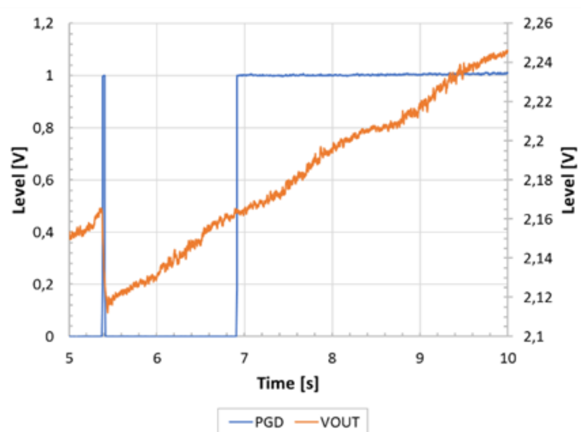

Figure 13. Working principle of the self-locking mechanism. Because the MCU switches on a pin to activate the OR gate leading to keep supplying the circuit, the PGD switches on after reaching the valid VOUT level again.

Comparing the time between the first and the second activation of PGD, shown in Figure 13, the time duration is longer than the one measured without the self-locking mechanism in Figure 12, which is approximately 660 ms long. The capacitor C7 needs approximately 1.5 s to charge up at the given input conditions and to reach the valid output level. This is the reason for implementing the self-locking mechanism, because the MCU already activates the pin to switch the OR gate configuration right after initialization, which is manageable to be done within a few milli seconds. The pulse time of the PGD signal is about 34 ms long, as pointed out in Figure 12. Within this time the MCU must take over the function of holding the level at the enable pin that switches on the supply of the electronics at VOUT2. Nevertheless, there is a trade off in dimensioning the capacitor C7 connected to VOUT. On one hand, it must provide enough energy to start-up the MCU and, on the other hand, it must not be too large, because then a charging up to the desired level, of 2.35 V in this case, is not possible anymore. So, the value of capacitance must be optimized according to the power consumption of the MCU or sensor node electronics and the input voltage VIN provided by the TEG matched to the input impedance of the DC-DC converter circuit. Additionally, the internal series resistance of the capacitor C7 should be as low as possible to provide high current pulses when switching on the MCU.

To sum up, if designing a harvesting unit for an electronic circuit that must deal with variable input conditions as it is given in the RF domain or even if dealing with thermal gradients, it is necessary, first to analyze the electrical energy needed, to measure the current afford necessary to start up the circuit and to investigate into the available energy source. Next, it must be tried to dimension the detector element, the TEG in this presented use case, according to the desired power budget and to perform best possible input matching. In a next step, the introduced modified block diagram must be applied to develop the circuit and finally the energy storage element must be matched, in respect to capacitance and technology, as described before. If all these stated items are considered it is possible to develop a harvesting circuit that is even possible to supply an electronic circuit for a certain time span under varying environmental conditions and in situations when very little energy is available, even under harsh environments.

V. CONCLUSION

This paper briefly introduces an overview of possible power sources, specially focusing on thermal sources that can be used to generate energy for a self-sustaining autonomous sensor node. Specially in harsh environments and closed compartments, like ovens, battery-based systems cannot be used. Therefore, thermal harvesting units that exploit the energy from the heating-up process in the oven are necessary. Since the contained energy potential is very limited, as it turns out of the theoretical analytics, as well as compared to the carried-out measurements, the presented novel approach deals with an optimized circuitry based on a commercially available harvesting IC. Externally applied components influence the implemented switching sequence and therefore realize a circuit based on the presented modified harvesting block diagram. Beside adequate power matching of the energy converter, or thermal electric generator in the presented use case, and the input impedance of the connected step-up converter, also an intelligent load management is necessary that guarantees in a first step to accumulate all the available energy and just after a certain time, to activate the processing unit or sensor node electronics. Without such switching mechanism, already a low power MCU that is instantaneously supplied, would cause a current flow that would not allow the electronics to start-up adequately, or even reach a proper and stable voltage level. Therefore, this paper presents a solution to solve these challenges, of harvesting little power from a thermal gradient, but also enabling a proper operation of a sensor node electronics over a certain time. Finally, measurement results prove the proper functionality of such a low power thermal energy harvesting unit electronics.

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