Design of a Low Input Voltage Converter for Thermoelectric Generator

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Abstract - **Low-grade exhaust heat is used to provide a reliable and independent power source for instrumentation circuitry by means of a thermoelectric generator (TEG). A design of a self-starting dc-dc converter is developed and optimized for very low input voltages (below 300 mV) in order to allow operation at temperature differences of 20°C and less. A prototype is built, and the results are experimentally verified.**

I. Introduction

Electronic instrumentation is used to monitor and control a variety of processes. It plays an important role in a chemical enterprise as well as in many other places. Usually, the circuit is supplied with power from a standard outlet or by a battery. In many cases it is, however, not feasible to run a cable from the power source to the location of application because of the rough environment prevailing in such plants, especially for small, low-power applications like sensors. Therefore, an independent and reliable power source is needed. One solution is to use a thermoelectric generator (TEG) to convert low-grade heat energy into electricity which powers the application, or charges a battery back-up. Typically, exhaust heat from already available sources can be used, e.g. from engines or warm pipes. Yet, the temperature difference from this kind of sources may be very low, e.g. 20°C. For this temperature difference, a high-performance bismuth telluride thermoelectric module provides an open-circuit voltage in the order of 300mV at an internal resistance of about 130mΩ. In order to get a sufficient voltage output to power the application, a large array of high-performance TEGs would be needed. With a single high-performance module costing an everage of several hundreds of dollars, this option often becomes economically unviable. To reduce costs, especially for low-power applications, a single cell could be used where the output power is transformed to the 5-volt level.

The theory of dc-dc converters is well known [1], [2], and their design is still the subject of many journal publications. However, designs for very low voltages, as in this application, have not been reported yet [3], [4]. The design of the conversion circuit is a major task and the main contribution of this work. The TEG provides a very low voltage at a high current. This causes, even for a reasonably low internal resistance of the converter, a very large relative voltage drop and, therefore, a very low efficiency. Also the power consumed by the converter itself for regulating and switching is much more critical because of the little total power available. Besides, to provide reliable and maintenance-free operation, the circuit needs to be self-starting. This is a challenge when dealing with supply voltages below 300mV. Moreover, it is desirable to base the converter on standard available circuitry to minimize the effort of the manufacturing, especially when produced in low quantities. Hence, standard converter design cannot be used in this case.

The purpose of this work is to develop a circuit which can easily be built, is reliable and self-starting and converts the above-mentioned input power for $\Delta T = 20°C$ to a stabilized 5-volt level with as high an efficiency as possible. The problems arising hereby are discussed in detail in Section II, and from that the used devices are deducted, and the novel twin converter is introduced to achieve the required performance. In Section III the final circuit is presented. A prototype of the circuit has been built, and Section IV shows the obtained measurements and discusses the results.

II. Circuit Considerations

It is understood that all dc-dc converters are based on switching a current through an inductor. The main consideration in the design consists in deciding which kind of switching device to use.

Most converters employ high-power MOSFET's as switching devices. Their very low on-resistance and their zero gate current lead to very low losses. Unfortunately, a rather high gate voltage is needed for switching them, and, therefore, they cannot be used in a self-starting design.

BJT's need a voltage of about 0.7V for switching them on. In addition, they typically have a considerable collector-emitter voltage drop. This leads to a very poor efficiency. One could mount them upside-down to eliminate the voltage drop but this would yield a high base current which increases losses. Therefore, this kind of device is also excluded from an efficient design.

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The self-starting requirement of the circuit certainly demands a normally-on device. This is obvious as no output can be expected without a current flowing at the beginning, and no device can be switched on by a voltage of less than 300mV. On the other hand, normally-on devices have very high on-resistances, typically at least 3Ω. This limits the maximum achievable power output to less than 10mW at best. With the internal resistance of the used TEG of about 130mΩ, the theoretically available power is 173mW. In order to get close to this value at all, the resistance of the switching device has to be much lower than the TEG's internal resistance.

Considering all factors, it becomes apparent that the requirements cannot be achieved in one single circuit. This gave rise to the twin design consisting of two converters, the *main circuit* and the *starter circuit*. For the starter circuit a normally-on device with as low an on-resistance as possible was chosen, i.e. the N-channel FET JFET J105 with $R_{on} = 3\Omega$. In the main circuit, the on-resistance is the limiting factor for the overall efficiency of the conversion. The high-performance high-power MOSFET SMP 60N06-18, which has an on-resistance not exceeding 18mΩ (typically 14mΩ) and a fairly low gate charge, was chosen. During the initial phase, the MOSFET is switched off, and the main circuit is dysfunctional. All the energy is pumped into the starter circuit which provides enough energy to the switching circuit to initialize the main circuit. As soon as this circuit is operational, the much lower on-resistance of the MOSFET basically short-circuits the input of the starter circuit, and the energy almost exclusively flows into the main circuit.

III. Circuit Design

Fig. 1 shows the block diagram of the complete circuit which consists of the *main circuit*, the *starter circuit*, the *switching circuit* and the *supply circuit*.

- The starter circuit provides voltage at the beginning to initialize the conversion.
- The main circuit contains the main converter which provides the output voltage with high efficiency.
- The switching circuit switches the main circuit and, in this way, regulates the output.
- The supply circuit generates the 8.5V for the switching circuit from the 5V output.

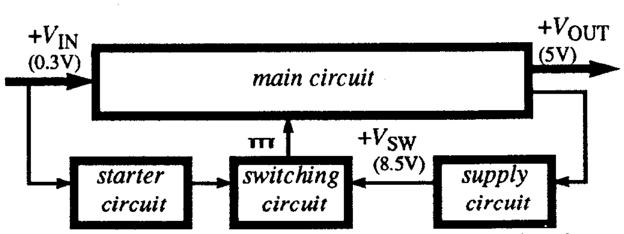


Fig. 1. Block diagram of the complete circuit. In parentheses the voltages during regular operation are given.

In the following, the operation of the circuits will be outlined in detail. The complete circuit diagram is shown in Fig. 4.

A. The Starter Circuit

The starter circuit is similar to those used in heart-pacemakers, e.g. [5]. At the beginning, the capacitor C3 (cf. Fig. 4) is discharged. The current through the normally-on JFET T1 and the transformer leads to a negative feedback and, hence, to an oscillation. Fig. 2 shows the measurement with an oscilloscope. The pn-transition of the transistor also acts as a diode. The capacitor C3, hence, is charged to a negative voltage. The resistor R1 ensures that C3 is discharged at the beginning. Since the switching circuit requires a positive supply voltage, the voltage across the capacitor could not be used as the output. Instead a third winding was added. The turn ratio is critical for the proper functioning of the circuit. It is found that the input voltage, at which the circuit starts oscillating, is a linear function of the turn ratio between the first and the second winding of the transformer, as long as the resistance of the secondary winding does not become too large.

The starter circuit only supplies the switching circuit with power until the main circuit starts working. Hence the output need not be regulated.

B. The Main Circuit

The main circuit in Fig. 4 is a modified boost-converter (see [1]). In order to achieve a high efficiency, a very low input resistance is essential. The electric path through the primary winding and the MOSFET T2 was made as short as possible. The paths on the stripboard were reinforced by wire. The primary winding consists of three turns on a toroi-

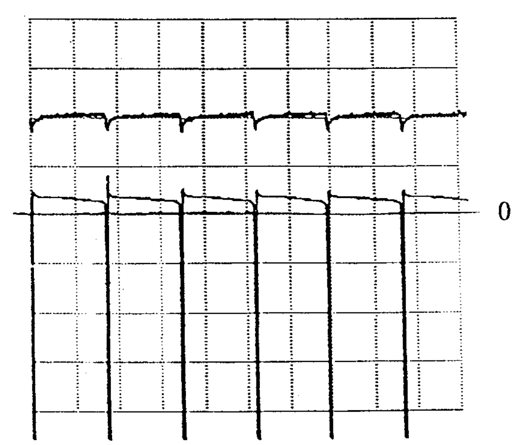


Fig. 2. Gate voltage (lower line, 1V/div) and drain current (upper line, 50mA/div) of transistor T1 in the starter circuit. The timebase is set to 0.5ms/div.

dal body. Six wires with a diameter of 0.9mm were connected in parallel. This way the input inductance became 70μH, and the dc input resistance, with T2 switched on, less than 15mΩ. Also, the 0.3V of the TEG with its 130mΩ internal resistance led to a saturation current of the coil of more than 2A. Fig. 3 shows the gate voltage and the drain current of the main circuit.

The first design did not incorporate the second transistor T3. This resulted in a voltage of approximately 0.7V across the diode D2. At an output voltage of 5V, thus, a considerable portion of the power was absorbed in the diode. Hence the second MOSFET T3 and the secondary winding were introduced. Whenever T2 is switched off, the transformer turns on T3. This practically eliminates the voltage across the diode, thus significantly increasing the maximum achievable output power.

It is commonly known (see e.g. [1]) that the output voltage of a boost-converter can be estimated by

$$V_{OUT} = \frac{V_{IN}}{1 - dc} \qquad (1)$$

where the duty cycle *dc* is the ratio of the on-time of the MOSFET to the period length. Equation (1) has its limits of validity, especially for *dc* close to 1. Theoretically, a *dc* of 1 yields an infinite output voltage according to (1). Physically, however, it leads to a short circuit at the input, i.e. zero output. It is the task of the switching circuit to control *dc* so that the output voltage V_{OUT} is regulated to 5V.

C. The Switching (Regulating) Circuit

The switching/regulating circuit as shown in Fig. 4 uses only one low-power dual CMOS comparator. Comparator A generates the modified saw-tooth voltage as shown in Fig. 5. The resistors R2 and R3 provide an almost fixed voltage V^+ at the positive input. Let us assume that the capacitor C6 is initially discharged. This means that the output of the comparator is open. Now, C6 is charged up through the pull-up

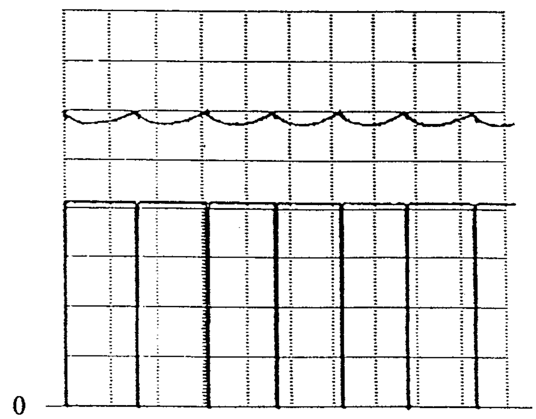
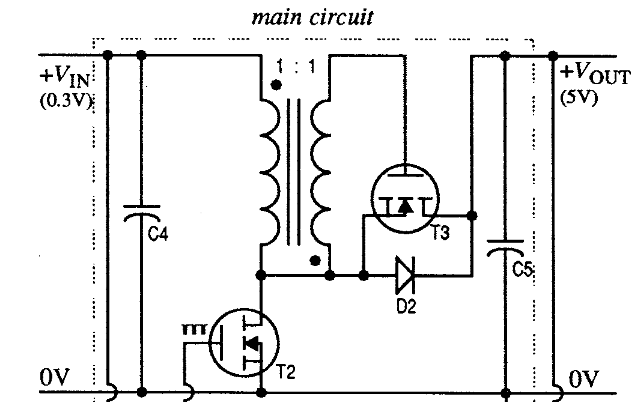


Fig. 3. Gate voltage (lower line, 2V/div) and drain current (upper line, 1A/div) of transistor T2 in the main circuit. The timebase is 50μs/div.



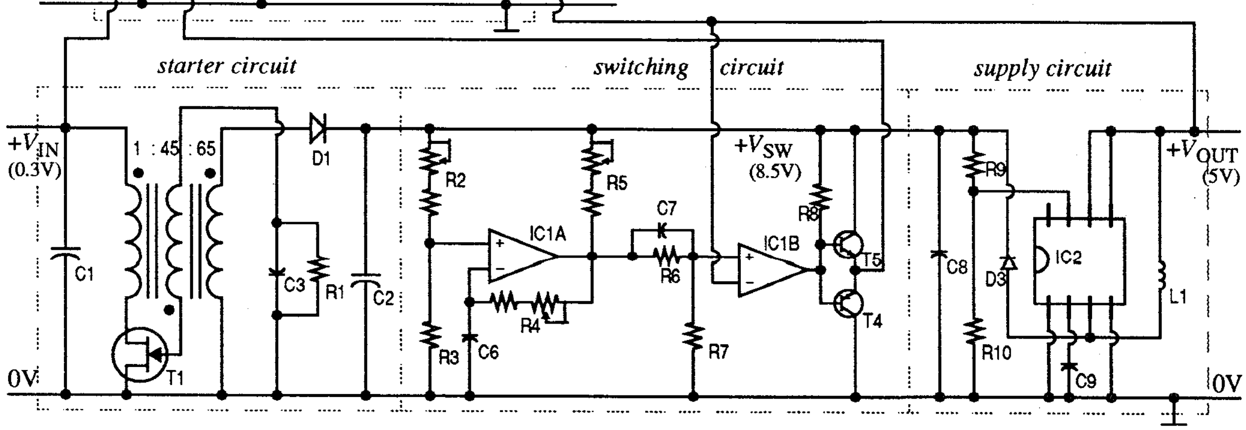


Fig.4. Circuit diagram of the complete circuit. In parentheses the voltages during regular operation are given. The values of the devices are given as follows: Starter circuit: R1=1MΩ, C1=1mF, C2=470μF, C3=1nF, D1=1N4148, T1=J105; main circuit: C4=2.2mF, C5=1mF, D2=1N4001, T2=T3=SMP 60N06-18; switching circuit: R2=350kΩ, R3=1MΩ, R4=1.8kΩ, R5=32kΩ, R6=270kΩ, R7=1MΩ, R8=2.2kΩ, C6=10nF, C7=1nF, T4=BC313, T5=BC182, IC1=TLC372CP; supply circuit: R9=1MΩ, R10=182kΩ, C8=100μF, C9=47pF, L1=1.7mH, D3=1N4148, IC2=MAX630.

resistor R5 and the feed-back resistor R4. Note that the pull-up resistor R5 is chosen much larger than the feed-back resistor R4. So when the voltage V^- across the capacitor C6 reaches V^+, the output of the comparator switches to ground, and C6 discharges very quickly through the small resistor R4. Hence the comparator switches to ground only for a very short period of time during which the output voltage becomes zero. Then, the output becomes open again, and the voltage at the output is determined by the voltage V^- of the capacitor C6 and the voltage divider R4 and R5, i.e., approximately V^-. The resistors R6 and R7 also represent a voltage divider which causes the voltage at the positive input of comparator B to be slightly lower than the output voltage of comparator A. Due to the capacitor C7, this is true even when the output of comparator A is zero volts, resulting in a slightly negative voltage of about -150mV at the positive input of comparator B for a very short time interval. This leads to the asymmetric shape of the saw-tooth voltage as seen in Fig. 5. However, it has to be ensured that the input voltage at the converter does not drop below -300mV, since it otherwise could be damaged.

Comparator B now compares this voltage with the output voltage V_{OUT} of the main circuit. Whenever the saw-tooth voltage is lower than the output voltage V_{OUT}, the voltage at the gate of the MOSFET T2 is connected to ground, otherwise to $+V_{SW}$. This way the duty cycle *dc* of the main converter is changed. A high output voltage yields a smaller *dc*, which, as we can see from (1), leads to a lower output. The opposite happens for a low output voltage. In particular zero output voltage leads to a *dc* which is given by the shortest possible off-time. Now we see why it is important that the saw-tooth voltage goes below zero for a very short time interval. In this way, it is always ensured that T2 is at least switched off for a minimum time, thus avoiding a short circuit at the converter input. In this design, the minimum off-time is 2µs. With the oscillating frequency of the saw-tooth generation of 12.8kHz, this is equivalent to a maximum *dc* of 97.5%. Depending on the load, the input voltage will vary between approximately 0.3V and 0.15V, thus requiring a duty cycle between 94% and 97%. We can see from Fig. 5 that this leads to a very small difference in the output voltage.

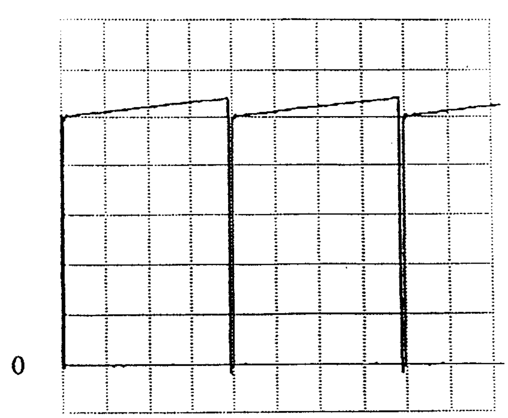


Fig. 5. Diagram of the modified saw-tooth voltage generated by the switching circuit. The y-axis shows the output of comparator A (1V/div), and the timebase is 20µs/div.

The transistors T4 and T5 finally are used to speed up the switching of the output of the converter, without lowering the value of the pull-down resistor R8. This would lead to higher losses.

Altogether, the circuit draws a current of less than 1mA, or, in terms of power, consumes about 8mW when operated at a voltage V_{SW} of 8.5V.

D. *The Supply Circuit*

It has been mentioned before that the on-resistance of the MOSFET T2 is crucial for high efficiency. This resistance becomes smaller for a higher gate-source voltage, i.e., a higher operating voltage of the switching circuit. On the other hand this also leads to a higher power consumption of the switching circuit which, in terms of the output power, can be considered as losses. For this particular design, it has proven most efficient to use a switching voltage of 8.5V by employing a third converter. Since the power consumption of the switching circuit is small, the efficiency of this conversion is not so critical. In addition, the switching circuit requires a constant output voltage in order for the regulation to work. Hence, the MAX630 integrated circuit was used to generate a regulated voltage of 8.5V out of the output of the main circuit. This integrated circuit contains an oscillator, a comparator, a reference voltage and a MOSFET. Fig. 4 shows the circuit diagram of the supply circuit. The output voltage is divided by the resistors R9 and R10 and compared to the 1.31V internal reference voltage. Whenever the voltage is too low, the oscillator switches the MOSFET periodically on and off until the desired voltage of, in this case, 8.5V is reached. The capacitor C9 sets the oscillator frequency to 37.5kHz. Due to the high on-resistance of the on-board MOSFET of about 3Ω, a higher efficiency can be reached when using a large inductance L1. Also, the maximum peak current must not be exceeded. On the other hand, the inductance must be small enough to be able to generate the 8.5V from as low an input voltage as possible. Good results are achieved for L1=1.7mH.

This circuit could be powered from the 5V output of the main circuit or from its own 8.5V output. The lower operating voltage lowers the efficiency of the conversion but also the power consumption of the converter. Since the circuit provides only about 8mW for the switching circuit, it has proven more efficient in this case to power the supply circuit directly from the 5V output. In this way the supply circuit consumed a total power of 3mW.

IV. Results

Fig. 6 shows the results obtained from the circuit when connected to the TEG as a power supply for $\Delta T = 20°C$. The overall efficiency reaches up to 76%. We can see that the output voltage stays very constant until the load becomes too high. For a load of 175 Ω an output power of 131 mW is achieved, and practically all of the maximum available power from the TEG of about 170mW enters the circuit. 11 mW are consumed by the switching/regulation circuit and the supply circuit, while 13 mW are dissipated in the resistance of the main circuit. The remaining 16mW are attributed to switching losses in the main circuit and power creeping into the starter circuit whose influence could not be completely removed.

It should be mentioned again that the input power is considered exhaust energy, and, therefore, the power output was maximized instead of the efficiency. This explains the low efficiency for low loads. In particular the MOSFET T3, in parallel with the diode D2, in the main circuit, lowered the efficiency for low loads. This transistor short-circuits the diode which results in a reactive current even if the capacitor C5 still is sufficiently charged. This current leads to losses in the internal resistances of the TEG and the circuit. On the other hand, the transistor T3 considerably increases the maximum efficiency from the previous 60% to 76% and the maximum available power from 96mW to 131mW.

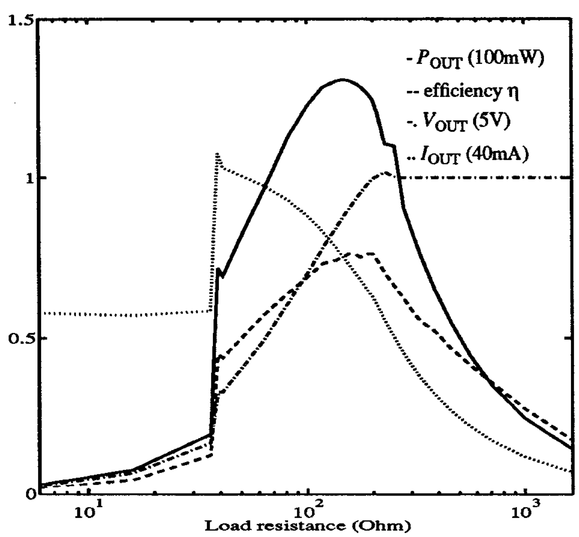


Fig. 6. Output power P_{OUT} (100mW), efficiency η, output voltage V_{OUT} (5V), and output current I_{OUT} (40mA) of the converter as a function of the load resistance R (Ω)

V. Conclusion

A new dc-dc converter circuit has been introduced. It offers a excellent performance in the low-voltage, low-power region. Results are shown when the converter is connected to a bismuth telluride thermoelectric module operating at a temperature difference of 20°C. This combination provides a reasonably stable output voltage of 5 V for up to 131 mW output load. This is 76% of the maximum available power and an excellent result for these low power levels. Another striking feature of the circuit is the self-starting capability which makes the circuit practically maintenance-free. Furthermore, the exclusive use of standard available devices makes the manufacturing very easy and economical even in small numbers. Overall the combination with the TEG shows a new kind of stable, economical and reliable off-line power source for low-power instrumentation and certainly will find many applications.

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