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POWER MANAGEMENT ELECTRONICS FOR THERMOELECTRIC ENERGY HARVESTING SYSTEMS

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Abstract: The presented paper gives an overview of basic principles and recent trends in power management electronics for thermoelectric energy harvesting. Energy harvesting systems are a modern way how to feed the autonomous devices on-site using ambient energy. The ambient energy in the case of thermoelectric generators is represented by temperature gradients. Different temperatures are applied to the hot and cold sides of thermoelectric module which generates the thermoelectric voltage on its terminals. This effect is called the Seebeck Effect. Thermoelectric generators have recently been found as a promising way for powering the autonomous sensors. This application is particularly promising utilizing a higher integration by the MEMS or NEMS technology. Power management electronics is an essential part of any energy harvesting system. It utilizes a connection between the energy harvester and powered application. The main tasks for power management electronics also include the maximum power point tracking (MPPT), power conditioning, interconnection with accumulator and self-diagnostics. The presented paper shows the general requirements, principles and system-level considerations in the design and development of power management electronics for the thermoelectric generator. The presented principles are subsequently applied on the real case study.
Keywords: thermoelectric generator, TEG, energy harvesting, power management, power electronics

1. INTRODUCTION

Thermoelectric generator (TEG) is a reliable energy harvesting device used for supplying electrical devices from heat gradients. Moreover, the thermoelectric generator is a highly complex mechatronic system containing more mutually interacting sub-systems. This closer look on TEG include subsets of the thermoelectric module (TEM) itself, thermo-mechanical integration components (heat sink, heat exchanger), energy storage element (rechargeable battery, supercapacitor) and a part with the very important interface role – the power management electronics.

The promising area for application of TEG in the CAAEEC project is focused to the power backup of sensor units in an aerospace industry. These units are normally fed from the onboard power distribution of an aircraft. TEG should provide the electric power in the failure state of power delivery from an onboard source. The Nextreme / Laird Technologies eTEG HV56 and Micropelt TGP-751 thermoelectric modules were previously selected as an appropriate solution for our application [1]. These modules are based on the MEMS technology enabling a high degree of integration.

The main tasks set in design of the power management electronics include the impedance matching known as Maximum Power Point Tracking (MPPT), power conditioning, interconnection with energy storage element and self-diagnostics. Proposed TEG should provide tens of milliwatts of the electric power on the voltage level of 3.3 V. Various serial/parallel/serial-parallel combinations of 1-4 TEMs will be tested consequently with a boost or buck-boost converter.

2. ANALYSES

The physical phenomenon of the thermoelectric energy conversion is called the Seebeck effect [2]. The governing equation of this effect is:

$$U_{oc} = S_{\Sigma} . \Delta T \qquad (1)$$

where U_{oc} is the open circuit voltage on the output terminals of the thermoelectric module, S_{Σ} is the net Seebeck coefficient of TEM and ΔT is temperature difference along the module ($T_h - T_c$). The net Seebeck coefficient is a characteristic parameter of each TEM.

Much more interesting part of analyses comes up with the connection of TEM into a closed circuit. Situation is depicted in Figure 1. On the right is depicted the equivalent circuit of TEM in the terms of Thévenin's theorem. Circuit is comprised of an ideal voltage source according to (1), TEM internal resistance R_{TEM} and load R_{load}. Thus the maximum power P_{max} which can be delivered to the load is:

$$P_{max} = \frac{(S_{\Sigma}.\Delta T)^2}{4R_{TEM}} \tag{2}$$

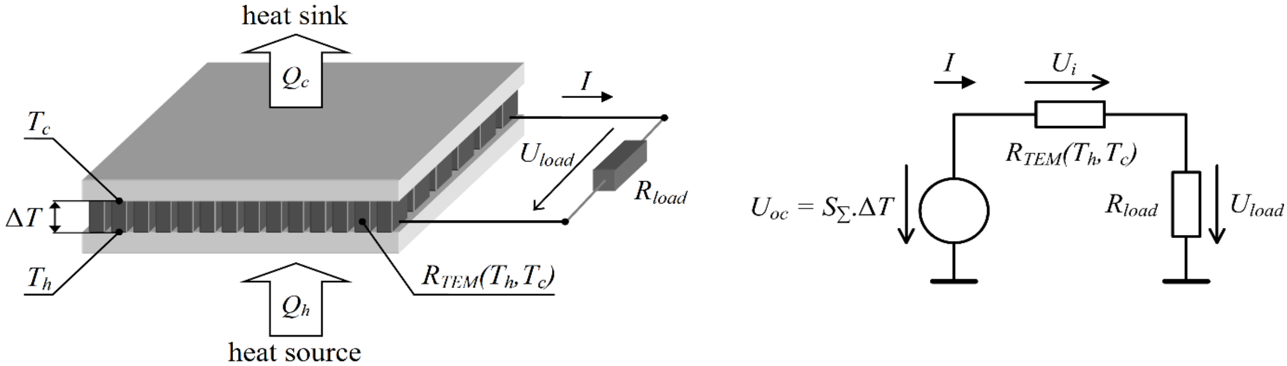

Figure 1: Thermoelectric generator and its equivalent circuit [1]

Operating state of the maximum power point P_{max} can be achieved only if $R_{TEM} = R_{load}$. This state is called the impedance match. Unfortunately, there are practically just a very few supplied applications having their internal resistance matched with energy harvester. Moreover, the internal resistance R_{TEM} is a function of module temperature (T_h,T_c). Differences between R_{TEM} and R_{load} are usually significant. Dynamic impedance matching is of high interest during the design of power management electronics for an energy harvesting device [3]. The dynamic impedance matching is usually implemented using a switching converter controlled by the Maximum Power Point Tracking (MPPT) driver. Further analyses of the impedance matching for TEG will be shown on the case of a boost DC/DC converter. The impedance matching conditions for other types of converters (buck, buck-boost) can be derived analogically. Proposed MPPT boost converter is depicted in Figure 2.

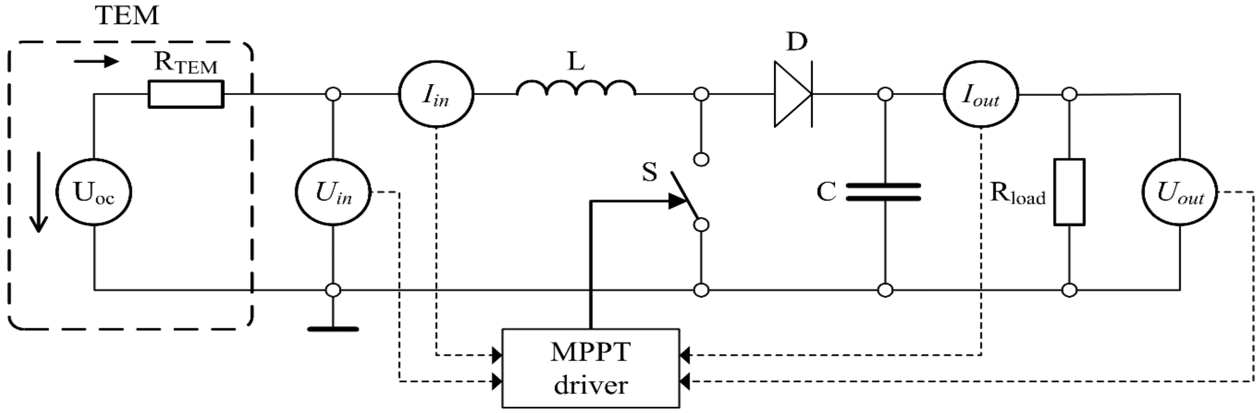

Figure 2: Boost converter with MPPT (fundamental circuit diagram)

Equations describing the operation of a boost converter controlled by the Pulse-Width Modulation (PWM) in a continuous conduction mode can be expressed as:

$$U_{out} = \frac{U_{in}}{1-D} \tag{3}$$

$$I_{out} = (1-D).I_{in} \tag{4}$$

$$R_{in} = (1-D)^2.R_{load} \tag{5}$$

$$R_{load} = \frac{U_{out}}{I_{out}} \tag{6}$$

where U_{in} and U_{out} are input and output voltages, I_{in} and I_{out} are input and output currents, R_{in} is the equivalent of electrical load R_{load} felt by TEM and D is the duty cycle defined as:

$$D = \frac{t_{ON}}{T} = \frac{t_{ON}}{t_{ON} + t_{OFF}} \tag{7}$$

where t_{ON} is the length of ON state, t_{OFF} is the length of OFF state and T is the PWM switching period (1/f) of switch S [4]. Then the duty cycle for the maximum power point condition can be expressed combining (5)-(6) as:

$$D_{MPP} = 1 - \sqrt{\frac{R_{TEG}(T_h, T_c).I_{out}}{U_{out}}} \tag{8}$$

The key problem of MPPT is the lack of direct measurement of internal resistance R_{TEG} during its operation. For the maintenance of D_{MPP} belonging to maximum power point can be employed various maximum power point tracking methods. Most common methods are Perturb and Observe (P&O) and Fractional Open-Circuit Voltage (FOCV) [5]. P&O method is perturbing the duty cycle and adjusting its new value based on the measurement of voltage and current on the input terminals of a switching converter. Factually, it's a search for a power maximum in the terms of D. FOCV method is periodically disconnecting the TEM from converter. Consequently, an open-circuit voltage on the terminals of TEM is measured and FOCV sets the duty cycle according to:

$$D_{MPP}(U_{oc}) = 1 - \frac{k_U.U_{oc}}{U_{out}} \tag{9}$$

where k_U is the empirically acquired constant describing the relationship between the open circuit voltage U_{oc} and voltage on maximum power point. The commonly used value for k in the case of TEG is $k = 0.5$. The Fractional Short-Circuit Current (FSCC) is an analogically implemented MPPT method. FSCC sets D_{MPP} using measurement of short-circuit current:

$$D_{MPP}(I_{sc}) = 1 - \frac{I_{out}}{k_I.I_{sc}} \tag{10}$$

where k_I is the empirically acquired constant describing the relationship between the short circuit current I_{sc} and current on a maximum power point.

3. HARDWARE IMPLEMENTATION

Hardware implementation of power management electronics for the energy harvesting is of rising interest amongst integrated circuits manufacturers. Various specialized ICs are commercially achievable. The main customer requirements for energy harvesting power management electronics include the Ultra-Low-Power (ULP) operation, minimum of external components and efficient MPPT algorithm. New trends in ULP electronics replace PWM by the Pulse Frequency Modulation (PFM) for a more efficient operation on low load currents. Key parameters entering the design process are the input/output voltages and currents delivered by TEM and consumed by supplied application.

Table 1 sums up the most prospective ICs for our thermoelectric generator. Different ICs are compared in the terms of implemented converter type, MPPT algorithm, input voltage range (U_{in}), output voltage range (U_{out}) and maximum output current ($I_{out,MAX}$). Selected ICs are tailored for the use without an external electromagnetic transformer. An innovative PFM is implemented in Texas Instruments bq25504 [6]. SPV1040T from ST Microelectronics combines P&O algorithm adopted from photovoltaics and requires minimum of external components [7]. SPV1050 is a brand new ULP IC in the stage of prototype [8]. LTC3105 is a long-proven energy harvesting solution from Linear Technology [9].

Table 1: Prospective ICs for a thermoelectric energy harvesting – extracted from [6-9]

	Conv. type	MPPT	U_{in} [V]	U_{out} [V]	$I_{out,MAX}$ [mA]
TI bq25504	boost	FOCV	0.13-3.0	2.5-5.25	300
ST SPV1040T	boost	P&O	0.3-5.5	2.0-5.2	1800
ST SPV1050	buck-boost	FOCV	0.18-5.3	2.1-5.3	70
LT LTC3105	boost	FOCV	0.25-5.0	1.4-5.0	500

4. CONCLUSION

As was clearly shown in this paper, the thermoelectric generator is a complex mechatronic system. Thermal and electrical parts of TEG are interacting together. Thus the interdisciplinary approach during the development of this system is a must. The analyses of equivalent circuit shown a connection between the temperatures applied on thermoelectric module and electrical behavior of TEG. Based on analyses, the basics of Maximum Power Point Tracking for the impedance matching of power management electronics were shown. Integrated circuits ST SPV1040T and TI bq25504 were selected for the design and build of a functional sample. The selected ICs are implementing a different MPPT algorithm which allows a proper evaluation and final selection of the TEG electronic hardware.

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