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ANALOG MAXIMUM POWER POINT CIRCUIT APPLIED TO THERMOGENERATORS

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Abstract: The objective of maximum power point tracking (MPPT) circuits is to find automatically the MPP and therefore extract the maximum amount of power available in the energy supplier (e.g. TEGs, solar cells). Nowadays, the most common techniques of MPPT employ DSPs or microcontrollers. However, simpler solutions employing analog circuits already exist but the power consumption and complexity of these solutions is still not fully optimized.This paper presents a MPPT circuit implemented with four low-power operational amplifiers.

Key words: maximum power point tracking, thermogenerator, step-up converter

1. INTRODUCTION

Thermogenerators (TEGs) can be used as energy harvesting power supplies instead of batteries in low power consumption applications where a temperature gradient is present. As in solar cells, TEGs have a maximum power point (MPP) where the transferred power from the TEG to the connected load is maximum.The power generated by state of the art TEGs (size e.g. 3x3 cm) exposed to low temperature gradients (3-10 K) is in the order of units of milliwatts.

Many methods have been developed to employ MPPT in conjunction with solar cells for outdoor applications where the power generated is bigger than in the case of TEGs. Therefore, the power consumption of the MPPT circuit is not a constraint for its use with solar cells but it is for the case of TEGs.

Nowadays, the most common techniques of MPPT employ DSPs or microcontrollers [1]. However, simpler solutions employing analog circuits already exist but the power consumption and complexity of these solutions is still not fully optimized [2].

This paper presents a simple analog circuit where only four low-power consumption operation amplifiers are employed in conjunction with a step-up converter based on coupled inductors. Since state of the art TEGs generate approximately an open circuit voltage of 50mV/K, a step-up converter is necessary.

2. TEG ELECTRICAL MODEL

The design of the MPPT circuit for TEGs requires the knowledge of its equivalent electrical circuit, as well as the levels of its output voltage and power.

The electrical part of the TEG equivalent circuit is composed by a voltage source, V_{oc}, and an internal resistance, R_m [3]. The value of V_{oc} is proportional to the temperature gradient, ΔT, between the hot and the cold junctions and to the Seebeck coefficient, α_m, of the thermoelectrical module, see Eq. 1.

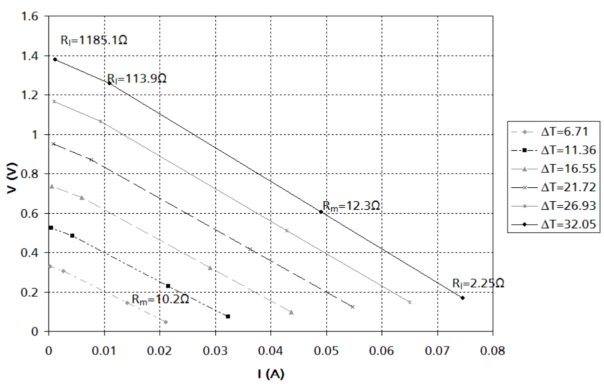

Fig. 1. Output voltage-output current characteristic of a state of the art TEG for different temperature gradients.

$$V_{teg-oc} = \alpha_m \Delta T \quad (1)$$

Fig. 1, Fig. 2 and Fig. 3 show the experimental data obtained from the measurements done with the Peltrom thermoelectric module 128A1030 which is a state of the art TEG. Fig. 1 shows the voltage as a function of current for different ΔT. The open circuit voltage increases with an increase on the temperature difference.

Fig. 2 shows the output power of the TEG vs. output current for the same temperature gradients. The maximum power from the TEG is obtained when its output voltage is $1/2V_{teg-oc}$. Thus, a match between the internal resistance of the TEG and the input resistance of the dc-dc converter assures that the maximum power has been harvested from the TEG.

Fig. 3 shows that the internal resistance of the TEG slightly increases from 10.2 Ω to 12.3 Ω for the temperature gradient considered.

The input resistance of a dc-dc converter is controlled with its duty cycle, D. A step-up converter has been selected as the dc-dc converter for its use with the MPPT circuit due to the low input voltages obtained from the TEGs with the temperature gradients under consideration.

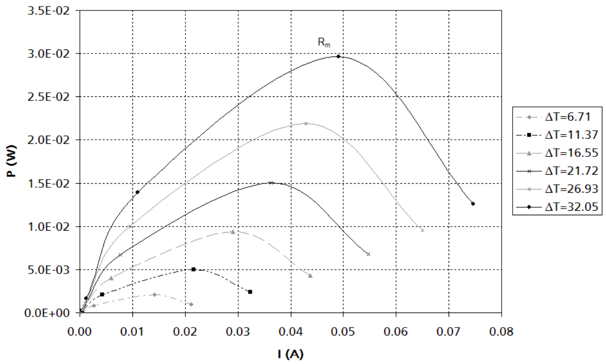

Figure 2. Ouput power-output current characteristic of a state of the art TEG for different temperature gradients.

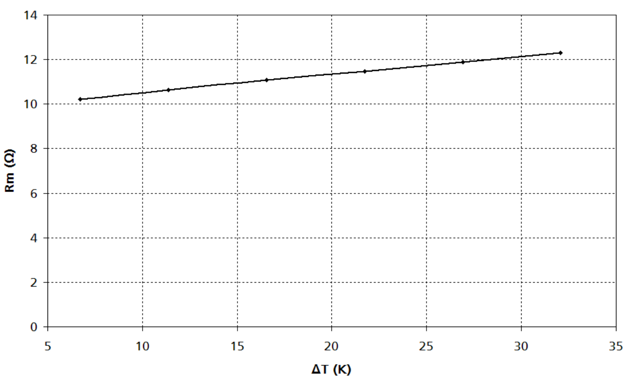

Figure 3. Internal resistance of the TEG as a function of the temperature gradient.

3. MPP ALGORITHM

A common implemented algorithm in microcontrollers for tracking the MPP is the P&0 where the duty cycle is perturbed in the same direction when the output power of the dc-dc converter is increasing and in the opposite direction when it is decreasing [1]. Analog circuits can also be employed for tracking the MPP obtaining high efficiencies [4].

When the output of a step-up converter is connected to a battery, it can be considered that its output voltage is constant and that the output power is proportional to the output current, I_o. Therefore, for the MPPT only output current measurements are necessary to modify the value of the duty cycle, D. A simplified version of the step-up converter based on coupled inductors, presented in [5], has been employed for testing purposes of the MPPT loop. This DC-DC converter works in the boundary between continuous and discontinuous modes due to the employment of a transformer that causes self oscillation.

Fig. 4 shows the duty cycle versus output current for a step-up converter in the boundary between continuous and discontinuous conduction modes. Thus, the approach employed is to use the derivative dI_o/dD to change the value of the duty cycle to force the derivative to zero. When I_o increases, the duty cycle must decrease its value and when I_o decreases, the duty cycle must increase in order to reach the optimum duty cycle, D_{maxp}.

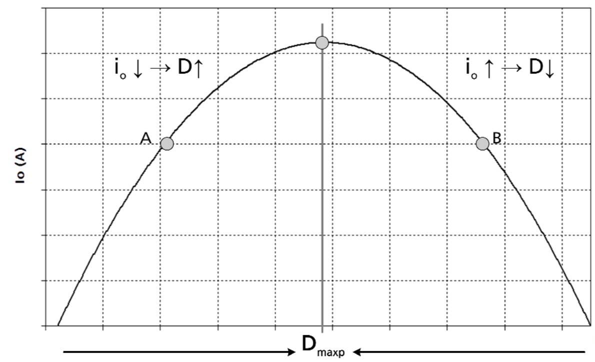

Fig. 4 Output current-duty cycle output for a step-up converter.

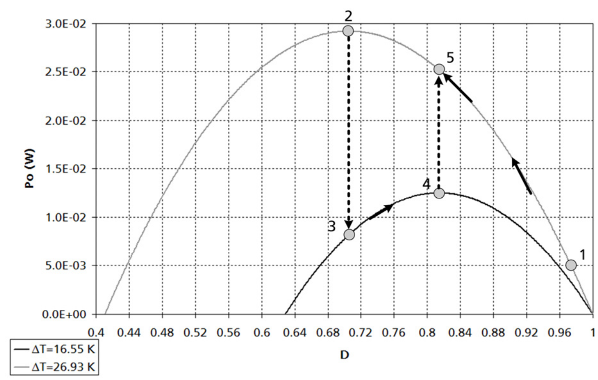

Fig. 5. Power-duty cycle output of the boost converter. Operation of the MPPT when there is a change in the temperature gradient.

Fig. 5 shows the output power versus the duty cycle for the Peltron TEG 128A1030. The MPPT has to be able to change properly the duty cycle of the DC-DC converter when the temperature gradient of the TEG, and consequently its open circuit voltage, changes. In Fig. 5, it is assumed that ΔT=26.93 K and that the duty cycle is at point *1*. In order to increase the output power, the duty cycle must decrease and the maximum power for this temperature gradient will be reached at point 2. If the temperature gradient decreases to ΔT=16.55 K, the output power characteristic will change and the working point will be *3*. From *2* to *3*, the output power has decreased and therefore, the MPP has to increase the value of the duty cycle until it achieves its MPP at *4*. When the temperature gradient rises, the working point moves from *4* to *5* and also the output power is increased. Therefore, the duty cycle decreases until it reaches its MPP again at *2*. If the variation in the output current is big due to a fast variation in the temperature gradient of the TEG, the MPPT can surpass the MPP resulting in a temporary loss of power.

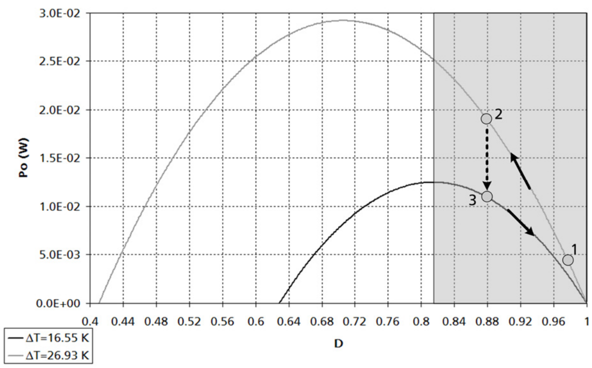

Fig. 6. Output power-duty cycle output of the TEG for two different temperature gradients. Possible failure in the operation of the MPPT.

Fig. 6 shows a situation where the loop can go to a point of malfunction. As in the previous explanation, it is assumed that ΔT=26.93 K and that the duty cycle is at point *1*. Then, the duty cycle decreases its value and the working point moves to *2*. When the temperature gradient of the TEG decreases and the working point moves to 3, the output current decreases and therefore the duty cycle increases its value and follows the wrong direction. However, if the values of the components of the analog circuit are adjusted correctly, the loop must be able to go afterwards in the correct direction when it detects that the derivative of the current continuous decreasing.

4. MPPT ANALOG CIRCUIT

Fig. 7 shows the coupled inductor boost converter that steps up the low voltage of the TEG. The control loop, see Fig. 8, employs the voltage V_i that is proportional to the current flowing into the battery, I_{bat}, as input. After the current amplifier, the control circuit is composed by a differentiator, a comparator and an integrator. These three operational amplifiers are referenced to $V_{batt}/2$ in order to employ only a positive power supply and be able to respond to increments and the decrements of I_{batt}.

The differentiator is employed to determine when the current flowing into the battery is increasing or decreasing. In the next stage, the comparator gives an output voltage of $+V_{batt}$ or ground depending if the current is increasing or decreasing. The integrator gives a voltage which is incremented or decremented proportionally over time depending of the voltage obtained by the comparator. The output of the integrator is employed as the regulation signal of the boost converter based on coupled inductors and controls the gate voltage on the transistor T_1, see Fig. 7.

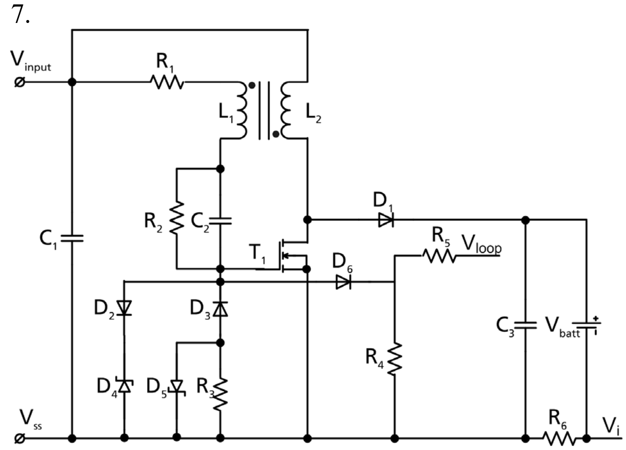

Fig. 7. Step-up converter based on coupled inductors.

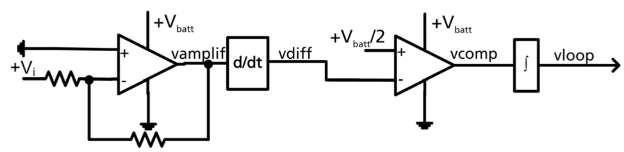

Fig. 8. Analog circuit for the MPPT implementation in the boost converter of Figure x.

5. SIMULATIONS AND MEASUREMENTS

Fig. 9 and Fig. 10 show two different simulations where it is displayed the open circuit voltage of the TEG $V_{teg\text{-}oc}$, the voltage obtained at the output of the TEG V_{teg}, the voltage proportional to the output current v_{amplif}, the voltage at the output of the differentiator v_{diff}, the output voltage of the inverting amplifier v_{comp}, and the control loop voltage at the output of the integrator v_{loop}.

Fig. 9 shows a simulation where the open circuit voltage of the TEG is decreased in steps of 100 mV from 800 mV to 600 mV to show a limitation of the control loop. The adjustment of the components of the control loop causes that the response to the changes in the open-circuit voltage of the TEG surpasses the optimum duty cycle. However, the control loop is able to return to the MPP and maintain its value. Table 1 shows the theoretical and the simulated power extracted from the TEG in order to evaluate the accuracy of the MPP control loop proposed.

Fig. 10 shows the simulation results obtained when the open-circuit voltage of the TEG is modified and the circuit is previously adjusted to response to these changes. The open circuit voltage of the TEG decreases first from 1.18 V to 960 mV and afterwards to 743 mV. These values correspond to ΔT=26.93 K ΔT=21.72 K and ΔT=16.55 K, respectively. Next, the open-circuit voltage is increased to its first value and finally, it is decreased to the minimum voltage in only one step.

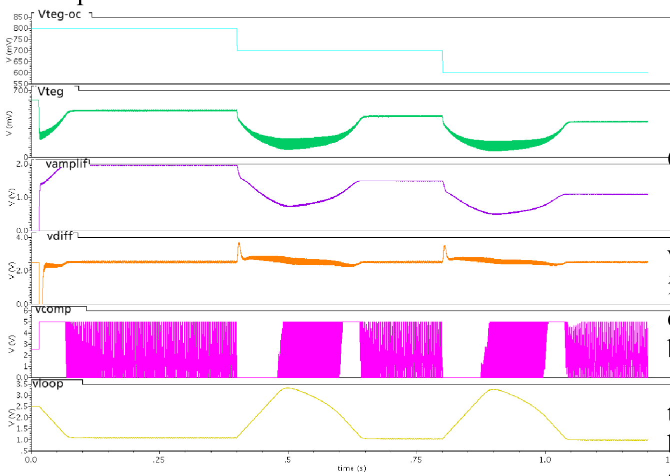

Fig. 9. Simulation results of the MPPT circuit when the MPPT circuit surpasses the optimum duty cycle.

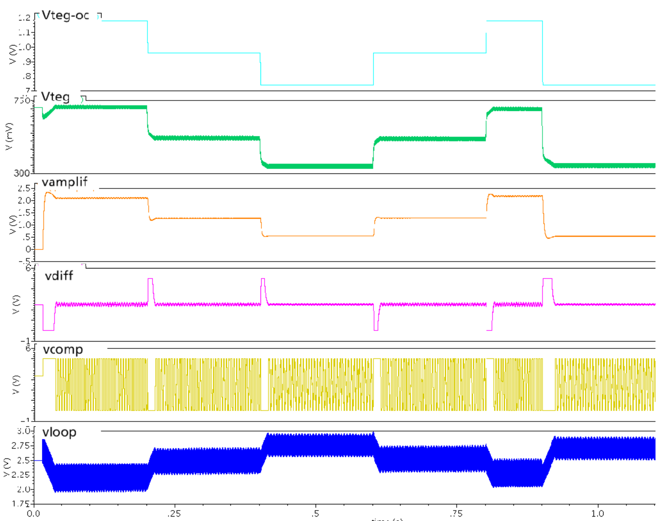

Fig. 10. Simulation results of the MPPT circuit when the open-circuit voltage of the TEG is modified.

Table 1: Theoretical $P_{TEG\text{-}theory}$ and simulated $P_{TEG\text{-}sim}$ power extracted for different open circuit voltages of the TEG.

$V_{TEG\text{-}OC}$	$P_{TEG\text{-}theory}$	$P_{TEG\text{-}sim}$	Error
0.8 V	32 mW	30.59 mW	4.4 %
0.7 V	24.5 mW	23.38 mW	4.6 %
0.6 V	18 mW	17.1 mW	5 %

The functionality of the MPPT circuit has been tested with a prototype. Table 2 shows the results obtained.

Table 2: Theoretical $P_{TEG\text{-}theory}$ and simulated $P_{TEG\text{-}sim}$ power extracted for different open circuit voltages of the TEG.

$V_{TEG\text{-}OC}$	$P_{TEG\text{-}theory}$	$P_{TEG\text{-}sim}$	Error
1.4 V	49 mW	48 mW	2 %
1.2 V	36 mW	35.9 mW	0.3 %
1 V	25 mW	24.45 mW	2.2 %

6. CONCLUSION

The paper proposes a simple MPPT analog circuit with only four low power operational amplifiers to use in combination with solar cells or TEGs. The MPPT circuit controls the duty cycle of a step-up converter based on coupled inductors.

The concept and the circuit presented has been tested and the simulation and practical results have been shown. The MPPT circuit is able to find the optimum duty cycle to achieve the MPP when there is an increase or a decrease of the open-circuit voltage of the TEG.

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