Sizing Optimization with Thermal and Electrical Matching of a Thermogenerator placed on the Human Body

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**General context:** Energy harvesting in the human environment
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Conversion of heat from human body into electricity
Introduction (1/2)

- **Conversion of heat** from human body into **electricity**
- **Strong effect of thermal coupling** of the generator with its environment

**Low output voltage** of the generator
**Conversion of heat** from human body into **electricity**

- **Strong effect of thermal coupling** of the generator with its environment

- **Low output voltage** of the generator

- **Necessity** of a **boost converter** between the generator and the storage element
Aim of this study: Sizing optimization taking into account:
Aim of this study: Sizing optimization taking into account: Thermal coupling with the environnement
Aim of this study: Sizing optimization taking into account:

- **Thermal coupling** with the environment
- **Electrical coupling** with the DC-DC converter
Outline

1. Study of thermoelectric generator (TEG)
   - Thermal and electrical models of TEG
   - Thermal impedance matching

2. Study of the whole system with DC-DC converter
   - Electrical model of the converter
   - Electrical impedance matching corrected

3. System sizing optimization
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**Thermal model**: simplified for low temperature difference $\Delta T_0$

$$\Delta T_G = \frac{R_{thG}}{R_{thB} + R_{thA} + R_{thG}} \Delta T_0$$

with

$$\Delta T_0 = T_b - T_a$$
Thermal and electrical models of TEG

**Thermal model:** simplified for low temperature difference $\Delta T_0$

$$\Delta T_G = \frac{R_{thG}}{R_{thB} + R_{thA} + R_{thG}} \Delta T_0 \quad \text{with} \quad \Delta T_0 = T_b - T_a$$

![Diagram of thermal model](image)

- Conduction of the skin, thermal contact
- Radiation and natural convection (or heat sink)
- Thermal resistance of the generator

With the thermoelectric module TM-450-0.8-3.0 produced by Ferrotec:

$$R_{thG} \ll R_{thB} + R_{thA}$$

⇒ **poor thermal coupling** (without heat sink) of the TEG with its environment
Thermal and electrical models of TEG

**Thermal model:** simplified for low temperature difference $\Delta T_0$

**Electrical model:**

Electrical impedance matching:

$$U = \frac{E_G}{2} \Rightarrow P_{eM} = \frac{E_G^2}{4R_G} = \frac{(\alpha \Delta T_G)^2}{4R_G}$$
Thermal model of the heat sink

**Adding a heat sink:**

- Better thermal coupling between the cold side of TEG and ambient air.
Thermal model of the heat sink

**Adding a heat sink:**

Better thermal coupling between the cold side of TEG and ambient air

**Thermal model:**

Thermal resistance $R_{thH}$ depends on:

- The captation surface area $S_{th}$
- The height $h_d$
Thermal model of the heat sink

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Study of Aavid heat sink (empiric law)

$$R_{thH} = \left( \frac{k_{H1}}{h_d} + k_{H2} \right) \frac{1}{\sqrt{S_{th}}}$$
Expression of the maximum electrical power $P_{eM}$, according to the leg length $l_{th}$:

$$P_{eM} = \frac{k_f \alpha_0^2 \Delta T_0^2}{16 \rho} \frac{S_{th} l_{th}}{(l_{th} + k_{env})^2}$$

With $k_{env}$, a coefficient depending on the presence or not of a heat sink.
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With $l_{th \_opt}$ without a heat sink

With $l_{th \_opt}$ with a heat sink
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$$P_{eM} = \frac{k_f \alpha_0^2 \Delta T_0^2 S_{th} l_{th}}{16 \rho (l_{th} + k_{env})^2}$$

With $k_{env}$, a coefficient depending on the presence or not of a heat sink

Thermal impedance matching $\Rightarrow l_{th} = l_{th\_opt} = k_{env}$

$R_{thG} = R_{thE} = R_{thB} + R_{thA}$ (or $R_{thB} + R_{thH}$ if presence of a heat sink)

$\Delta T_G = \frac{\Delta T_0}{2}$
Thermal impedance matching

**Expression** of the maximum electrical power $P_{eM}$, according to the leg length $l_{th}$:

$$P_{eM} = \frac{k_f \alpha_0^2 \Delta T_0^2 \cdot S_{th} l_{th}}{16 \rho \left(l_{th} + k_{env}\right)^2}$$

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Generally **not** technologically **feasible** $\Rightarrow$ **solution** = **stacking** identical thermoelectric modules and connecting them electrically in series
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Electrical model of the converter (1/2)

Boost converter with two **dual-gate** MOS transistors: LTC3537 (Linear Technology)

Gate charge $Q_G \propto A_{MOS}$ and channel resistance $r_{ds(on)} \propto A_{MOS}^{-1}$

In **low power**, the controlled **area** is **smaller**: $A_{MOS}=A_{MOS}/10 \Rightarrow Q_G \downarrow$ and $r_{ds(on)} \uparrow$
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The **MOS transistors losses** taken into account are: (with $k_M = 1$ for high power $= 10$ for low power)

**Conduction losses:**

$$P_{cond} = k_M r_{dson} I_{IN}^2$$
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- **Conduction losses:**
  
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- **Control gate losses:**
  
  $$P_G = 2f(Q_G/k_M)V_{OUT}$$
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- **Control gate losses:**

  \[ P_G = 2f(Q_G/k_M)V_{OUT} \]

- **Switching losses:**

  \[ P_{SW} = fV_{OUT} I_{IN} t_{SW} \]
Simulated and measured efficiency curves for $V_{\text{OUT}}=3.3\text{V}$:

**discontinuity** = effect of switching gate area
Simulated and measured efficiency curves for $V_{\text{OUT}}=3.3\text{V}$:

- **Discontinuity** = effect of switching gate area

- The efficiency of the converter is better when the ratio $V_{\text{OUT}}/V_{\text{IN}}$ is lower

- **Dual-gate MOS transistors:**
  $\Rightarrow$ extends the range of the maximum converter efficiency
Electrical impedance matching corrected

- $E_G = 1.8V$
- $R_G$
- $V_{IN}$
- $V_{OUT} = 4V$
- LTC3537
Electrical impedance matching corrected

\[ P_{IN} \]

\[ V_{IN} = \frac{E_G}{2} \]

Maximum power of the TEG

\[ V_{OUT} = 4V \]
Electrical impedance matching corrected

\[ \text{Maximum power of the TEG} \]

\[ V_{\text{IN}} = \frac{E_G}{2} \]

\[ P_{\text{IN}} \]

\[ P_{\text{LOSS}} \]

\[ \text{LTC3537} \]

\[ \text{STORAGE} \]

\[ V_{\text{OUT}} = 4V \]
Electrical impedance matching corrected

\[ V_{IN} = \frac{E_G}{2} \]

Maximum power of the TEG

\[ P_{OUT} = P_{IN} - P_{LOSS} \]

⇒ Displacement of the maximum power

⇒ Electrical impedance mismatch, in relation with converter efficiency
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Optimization methodology

Optimization algorithm based on particle swarm optimization

- **Two competing criteria:**
  - maximizing the electrical power harvested
  - minimizing the volume of the TEG
Optimization methodology

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**Optimization parameters:** \( S_{th}, l_{th}, \) and \( h_d \)

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- **Optimization constraint:** $V_{IN} > V_{IN_{\text{min}}} = 0.7V$ for the LTC3537

- **Constant Parameters:**
  - The density of thermocouples ($N_{th} \propto S_{th}$)
  - Thermoelectric materials
  - Temperatures $T_b$ and $T_a$
  - The technology of the heat sink
Solutions of the optimizations (1/2)

Pareto fronts

- Parameters variations

- Solutions of the optimizations
Solutions of the optimizations (1/2)

Pareto fronts

Parameters variations

- TEG+DC-DC
  - Surface area $S_m$ (cm$^2$)
  - Height of the TEG $h_T$

- TEG+DC-DC
  - Height $h_n$, with heat sink
  - Height $h_n$, no heat sink
From a given volume, adding a heat sink makes it possible to harvest more power.
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Minimum volume due to harvested power has to compensate the converter losses.
What about the thermal and electrical impedance matching?

When $P_e$ is maximal, $R_{thG} \neq R_{thE} = R_{thB} + R_{thA}$

$\Rightarrow$ No Thermal impedance matching
Solutions of the optimizations (2/2)

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$V_{IN} > E_G / 2$

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Modification of the impedance matching

\[ P_{\text{IN}} \rightarrow \text{REAL CONVERTER} \rightarrow P_{\text{OUT}} \]

\[ E_g \rightarrow R_g \]

\[ V_{\text{IN}} \rightarrow \text{TEG} \]

\[ V_{\text{OUT}} = 4V \]

![Diagram of impedance matching system]

**Graph:**

- **Red dashed line:** \( P_{\text{OUT}}, \text{if } P_{\text{IN}} \text{ maximized} \)
- **Blue dashed line:** \( P_{\text{IN}}, \text{if } P_{\text{IN}} \text{ maximized} \)

**Axes:**
- **Y-axis:** Electrical power (mW)
- **X-axis:** Leg length \( l_{th} \) (cm)
Modification of the impedance matching

Electrical impedance mismatch

P\text{OUT} (if P\text{OUT} maximized) > P\text{OUT} (if P\text{IN} maximized)
Modification of the impedance matching

- Electrical impedance mismatch
  \[ P_{\text{OUT}} \text{ (if } P_{\text{OUT}} \text{ maximized)} > P_{\text{OUT}} \text{ (if } P_{\text{IN}} \text{ maximized)} \]

- Thermal impedance mismatch
  \[ l_{\text{th opt}} = 8 \text{ cm (and not 5 cm like in case of thermal impedance matching)} \]
We presented the study of a whole thermoelectric conversion chain incorporating a TEG with its DC-DC converter and a possible heat sink.
Conclusion

We presented the study of a whole thermoelectric conversion chain incorporating a TEG with its DC-DC converter and a possible heat sink.

The thermal and electrical models of the TEG associated with the converter model allow us to optimize the volume of the TEG in order to maximize its harvested power.
Conclusion

- We **presented** the **study** of a whole thermoelectric **conversion chain** incorporating a **TEG** with its **DC-DC converter** and a possible **heat sink**.

- The **thermal and electrical models of the TEG** associated with the **converter model** allow us to **optimize the volume of the TEG** in order to **maximize its harvested power**.

- We show that, from a given volume, **adding a heat sink** makes it possible to **harvest more power**.
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- We show that, from a given volume, adding a heat sink makes it possible to harvest more power.

- The study of TEG with a real converter (including losses) shows that it might be interesting to mismatch thermally the TEG impedance and also not to work at the theoretically optimum electrical operating point by increasing the output voltage of the TEG.
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- We show that, from a given volume, **adding a heat sink** makes it possible to **harvest more power**.

- The study of **TEG with a real converter (including losses)** shows that it might be interesting to **mismatch thermally the TEG impedance** and also **not to work at the theoretically optimum electrical operating point** by increasing the output voltage of the TEG.

- However, the DC-DC converter studied is not necessarily well suited, we should optimize it.