A Comparison of Different Connection Techniques for Thermoelectric Generators in Vehicle Waste Heat Recovery

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Abstract

Increasing demand for lower fuel consumption increases the importance of a higher total energy efficiency in trucks. Since the efficiency of a diesel engine is low (less than 45 %), large amounts of waste heat is produced.

Recovering this energy can be done in several ways, one of them by using thermoelectric generators. However, the open circuit voltage and internal resistance of these generators are temperature dependant, which result in different optimal output currents for different working conditions according to the maximum power transfer theorem.

Connecting the thermoelectric generators to a DC/DC-converter using MPPT technology can aid in this matter, as can switching between different serial and parallel configurations.

In this thesis, the recovery potential for several different connection techniques of a low powered test rig are studied through simulations in *Simulink*.

It is shown that a switching network may allow more energy to be recovered than when using a DC/DC-converter. However, further investigations are needed to determine which solutions are more suitable for high power TEG-rigs.

Keywords: Waste heat recovery, thermoelectric generator, maximum power point tracking

Nomenclature

η	Recovery efficiency	$-$
η_{cycle}	Cycle recovery efficiency	$-$
D	Duty cycle	$-$
P_l	Load power	W
R_l	Load resistance	Ω
R_{int}	Internal resistance	Ω
u_{ol}	TEG open load voltage	V

Introduction

Internal combustion engines typically provide an efficiency peaking at roughly 40 %, where diesel engines reach a bit higher than otto engines. The majority of the lost energy is in the form of waste heat in the exhaust system. Recovering part of this energy would increase the total efficiency for the vehicle, hence lower the fuel consumption.

A thermoelectric generator (TEG) allows direct conversion between thermal and electric energy. This is due to the Seebeck effect described in [?].

The Thévenin equivalent circuit of a TEG with a resistive load can be described as in Figure 1.

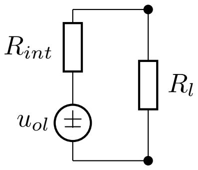

Figure 1: Thévenin equivalent circuit for TEG with load connected

Deriving the expression for the load power, it is found that

$$P_l = R_l I_{R_l}^2 = \frac{u_{ol}^2 R_l}{(R_{int} + R_l)^2} \quad (1)$$

which is maximised when $R_l = R_{int}$.

Plotting the load power as a function of the current in the circuit, the characteristics seen in Figure 2 are discovered.[1] As can be seen, to maximise the load power, the current needs to be optimised. However, as the TEGs open load voltage and internal resistance is temperature dependant, different currents will maximise the load power for different working conditions.

Herein lies the problem; How can the right current be achieved throughout a complete drive cycle with changing working conditions?

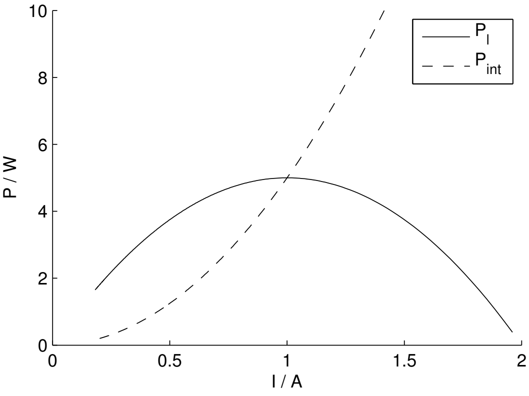

Figure 2: TEG characteristics

Two approaches to aid in this matter is studied; I.) Using a switching network that changes the amount of serial and parallel connected TEG modules between the TEGs and load in order to change the open load voltage and internal resistance of the equivalent circuit, and II.) using a DC/DC-converter between the TEGs and load. The main goal is to determine whether a switching network can compete with a DC/DC-converter using a maximum power point tracking (MPPT) algorithm from an energy recovery perspective.

Method

Models for the different parts of the systems is modelled in *Simulink* using *Simscape*- and *SimPowerSystems*-components.

The TEG model is created from data measured on a real TEG rig consisting of three TEGs connected in series. The input data to this model is the temperatures of the hot and cold side of the TEG. The load is consisting of a Lead-Acid 12 volt battery with a parallel resistive load.

Since long drive cycles are to be simulated, the steady state recovery efficiency, η, is sampled for all different connection solutions. These are thereafter stored in look-up tables. When simulating longer drive cycles, the theoretic maximal power output of the TEG can be multiplied with η in order to find out which power that could be delivered to the load.

Two drive cycles, named *Spain* and *Brussels*, are simulated, and the quotients, η_{cycle}, between the actually recovered energy and the theoretic maximal recovered energy for all different connections are stored. These drive cycles contains 9000 seconds of torque and RPM data that feed a look-up table where the EGR-gas temperature is mapped as a function of the torque and RPM of the engine. This value is then fed to the TEG model as the hot side temperature. The cold side temperature is assumed to be constant at 30 °C.

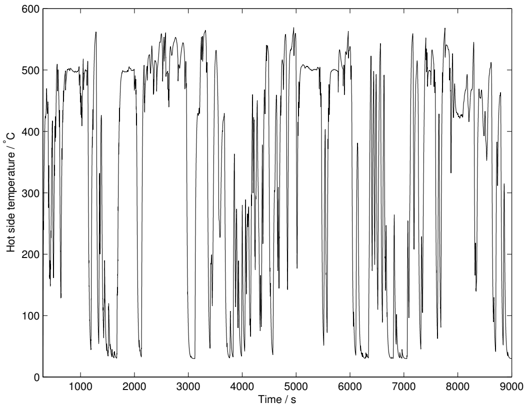

Figure 3: Hot side temperature for the *Spain*-cycle

Firstly, simulations are done using 3 TEGs comparing the DC/DC-converters. Thereafter simu-

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[1] An open load voltage of 10 V and an internal resistance of 5 Ω is used for the calculations.

lations are done with 8 TEGs, comparing different switching networks with a reference DC/DC-converter.

The switching networks can realised using both transistors and electromechanical relays, however, in the simulations, the switched network is assumed to be able to deliver the same power as the optimal available directly connected configuration of TEGs. Figure 4 shows an example of how a switching network with four thermoelectric generators can be realised.

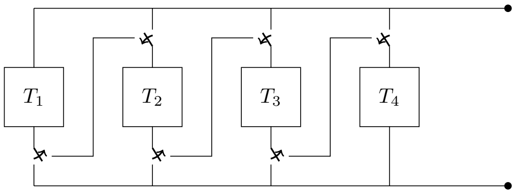

Figure 4: Ser/Par switching network for four blocks

The size and layout of a TEG-rig is described in the format $m * n$ where m indicates the amount of TEGs in parallel and n in series. Figure 5 shows an $m * n$-sized rig.

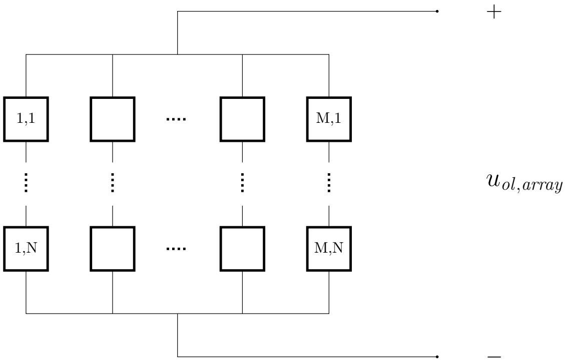

Figure 5: $M * N$ size TEG array

Directly connected and switched rigs are connected to the electrical system through a diode to prevent an undesired power direction.

All DC/DC-converters are modelled using the corresponding *Simscape*-component, except for the switching transistor that is modelled as a switch.

Results

The results of the simulations are shown in Table 1 and 2.[2]

Table 1: η_{cycle} for the drive cycles with 3 TEGs

Connection	Spain η_{cycle}	Brussels η_{cycle}
Boost $1 * 3$	0.6301	0.8165
Boost $3 * 1$	0.8334	0.8105
SEPIC $1 * 3$	0.8536	0.8806
SEPIC $3 * 1$	0.7692	0.7764
Ćuk $1 * 3$	0.8543	0.8808
Ćuk $3 * 1$	0.7690	0.7766
Buck/Boost $3 * 1$	0.4661	0.5317
Direct $1 * 3$	0.6392	0.8291
Direct $3 * 1$	0.7969	0.2057
Ser/Par $1 * 3$ / $3 * 1$	0.8720	0.8362

Connection	Spain η_{cycle}	Brussels η_{cycle}
$1 * 8$	0.2952	0.4318
$2 * 4$	0.5201	0.7149
$4 * 2$	0.7976	0.8745
$8 * 1$	0.7809	0.2009
$2 * 4$ / $4 * 2$	0.8109	0.9142
$4 * 2$ / $8 * 1$	0.8706	0.8751
$1 * 8$ / $2 * 4$ / $4 * 2$	0.8155	0.9183
$2 * 4$ / $4 * 2$ / $8 * 1$	0.8839	0.9149
SEPIC	0.7809	0.8332

Table 2: η_{cycle} for the drive cycles with 8 TEGs

Conclutions

The investigations made indicate that even a simple switching network can work well, and may even work better than a DC/DC-converter using MPPT.

It can also be seen that switching between two states almost reaches the same recovery efficiencies as when using three states. This may be a good route to investigate further, as fewer switches are needed compared to when using more states, and no inductances or capacitors are needed as with the DC/DC-converters. This implies that high recovery efficiency can be reached with relatively low investment costs for the power conditioning system.

For the DC/DC-converters; it can be seen that the Buck/Boost-topology studied only manages to recover small amounts of the available energy. This is because of the switch on the input, which sets the

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[2] $m * n$ indicates m TEGs in parallel and n in series.

TEG current and power to zero when the switch is not conducting.

Further, the SEPIC and Ćuk-converter provide very similar results, which is to be expected since the use exactly the same components.

To conclude, in terms of energy recovery potential, serial/parallel switching networks is an interesting alternative to DC/DC-converters and should be investigated further.