Design of High-Efficient Converter for On-board Thermoelectric Generator

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Abstract—The efficiency of internal combustion engines in trucks and passenger cars are low (<40 %). Much work has been done to make the engines more efficient internally, by improving the mechanical and electrical components. However, there is still a large amount of fuel power, which gets converted into heat and escapes through exhaust gases as waste heat. Taking advantages of thermoelectricity, part of that heat power can be converted into electrical power. In this paper, the most suitable DC/DC converter for Thermoelectric Generator in Heavy Duty Vehicles is proposed and based on the simulation results, different aspects of designing high-efficient DC/DC converters are discussed.

I. INTRODUCTION

Owing to the high level of greenhouse gases and their environmental issues, the demand for efficient transportation has increased during the last decades [1], [2]. Much work has been done to manufacture more efficient combustion engines, but there is still a large amount of energy, which burns unused and heats up the globe. To decrease the fuel consumption and make the combustion engine more efficient, it is possible to recover part of the heat generated by the combustion process and friction inside the engine. The heat can be converted into electrical power using a thermoelectric generator (TEG), which is composed of thermoelectric modules (TEM) connected in strings. Thermoelectric energy conversion is based on Seebeck effect, and electrical energy is generated when a temperature gradient is applied to thermoelectric elements. It can be used in various applications and places where waste heat is available and affords a compact and non-moving part system with a stable output power. However, the levels of voltage and current generated by a TEG usually differ from the levels an electrical load can operate with. Therefore, the usage of power conditioner as shown in Fig. 1, in between the TEG and the electrical load, is necessary. The low conversion efficiency of TEG creates the demand of high-efficient power conditioner between the thermoelectric generator and the electrical load. The most common and well-studied converter in TEG-applications is the Boost converter. Since TEM can be modeled as an ideal voltage source with relatively low voltage and a series resistance, the most suitable DC/DC converter for thermoelectric generators is Boost converter, as explained in [3], [4]. 89 to 97 % efficiency of a Boost converter for TEG was reported in [5]. A Boost and a charge pump converter were also compared in

Fig. 1. Simplified overview of a TEG system.

[6] where the Boost converter with high inductance showed better performance. More studies have been published on other types of DC/DC converter with the ability to operate as a separate Buck or Boost converter. The benefit of such a converter is that power can be transferred to the load in the most operation conditions, independent of the TEG's output voltage [7]. Furthermore, to deliver the highest available power to the load, a Maximum Power Point Tracker (MPPT) should be employed. There are several MPPT algorithms and it was shown that the $\text{Frac. } V_{OC}/I_{SC}$ algorithm has the best performance in terms of stability in [8]. The mentioned algorithm, disconnects the TEG from the DC/DC converter during operation to measure the short-circuit current and open-circuit voltage of the TEG. Therefore, it is important to consider the transient behavior and the time response of TEG since the voltage of a zero-current generator and the current of zero-voltage generator can change over the measuring time, resulting in inaccurate tracking [9].

As a result of the low output power from a TEM, at least a few modules should be connected together. The connection choice is dependent on the application and available heat, and has an impact on the total output power. That is, a minimum output voltage can be obtained by a proper connection choice. If the minimum output voltage from the TEG is equal to or greater than the required load voltage, a Buck converter can be used as a power conditioner. The advantage of a Buck when compared to that mentioned converters in [4], [5], [7], [8] is its simplicity, ease of control, and low price, which are the most important criteria in the most areas, especially in the automotive industry. This paper presents the difference between series and parallel connections of

Fig. 2. Typical thermoelectric module.

Fig. 3. V-R model of TEM.

TEMs based on exhaust gas temperatures on-board Heavy Duty Vehicle (HDV). Furthermore, simulation results for the proposed converter, designed to operate with TEG, will be presented.

II. CONNECTION OF THERMOELECTRIC MODULES

Thermoelectric modules are made by a series of p- and n-type semiconductor-legs encapsulated in between ceramic plates, as seen in Fig. 2. A TEM acts as a voltage source with an internal resistor in its simplest form. The value of the voltage and resistance are, among others, functions of hot and cold side temperatures. If the dynamic behavior of TEM is of interest, a capacitor has also to be added into the model according to [10]. However, during normal condition, the temperature of combustion engine in a car or truck does not change rapidly; thus, the steady-state model, as in Fig. 3, can be used.

From TEM's electrical model, the load power of one single module can be derived by:

$$P_{R_L} = \frac{V^2 R_L}{(R_{in} + R_L)^2}, \quad (1)$$

where V is the open-circuit voltage, R_{in} is the internal resistance of the TEM, and R_L is the load resistance. The maximum power is delivered to the load when:

$$\frac{dP_{R_L}}{dR_L} = \frac{d}{dR_L} \left(\frac{V^2 R_L}{(R_{in} + R_L)^2} \right) = 0, \quad (2)$$

Fig. 4. String of series or parallel connection TEMs.

which is obtained when $R_{in} = R_L$ and together with Eq. (1) the maximum load power can be defined as:

$$P_{R_L max} = \frac{V^2}{4R_{in}}. \quad (3)$$

In a TEG, however, a number of modules need to be connected in series or parallel to produce more power. The equivalent voltage and the internal resistance of a string of TEMs according to Fig. 4 can be calculated by Thévenin and Millman's theorems. The maximum load power for the string in Fig. 4 is then:

$$P_{R_L max-series} = \frac{1}{4} \frac{(\sum V_n)^2}{\sum R_n}, \quad (4)$$

and

$$P_{R_L max-parallel} = \frac{1}{4} \frac{(\sum \frac{V_n}{R_n})^2}{\sum (\frac{1}{R_n})}. \quad (5)$$

It is clear that if two or more TEMs with identical internal resistances are connected together, the maximum load power is also identical and independent of their connection. However, in reality, that is not the case and the resistances of two TEMs are different. The internal resistance of a TEM is temperature-dependent and in a TEG on HDV, one can only try to keep the temperature difference (ΔT) over a whole string as constant as possible by design of a heat exchanger. In that case, the internal resistance of TEMs will stay close to each other, which creates an insignificant difference of the output power between series and parallel connections. Figure 5 shows the load power from two different connections of two TEP1-1994-3.5 modules from Thermomax; one (TEM1) with $T_{Cold1}=50^\circ\text{C}$ and $T_{Hot1}=200^\circ\text{C}$ and the other (TEM2) with $T_{Cold2}=100^\circ\text{C}$ and $T_{Hot2}=250^\circ\text{C}$. According to the datasheet, the internal resistance of TEM1 is $5.65\ \Omega$ and that of TEM2 is $6.2\ \Omega$. The difference in load power in Fig. 5 at point $R_{in1}=5.65\ \Omega$ is $0.51\ \%$. Similar result with very low power difference ($<0.6\ \%$) is obtained even for other temperatures. However, as it can be seen in the same figure, the power difference increases as the resistance difference of two TEMs is increasing. Consequently, as long as ΔT over a string of TEMs is constant, the internal resistances will stay close enough so that the TEMs can be connected in series without any significant power loss when compared with parallel connection. This means creation of a high output

Fig. 5. Comparison of electrical load power between series and parallel connection of two TE1-1994-3.5 modules with constant $\Delta T=150^{\circ}C$.

voltage of the whole string, which can operate with a Buck converter.

III. CONVERTER DESIGN AND SIMULATION RESULTS

There are at least three main converter topologies: step down (Buck), step up (Boost), and step up/down (Buck-Boost). All the converter types have three main components, namely diode, switch and inductor, see Fig. 6. In case of efficiency optimization, one should minimize the power consumption of these components. The output voltage of all three converter types as a function of duty ratio (D) when a certain input voltage is applied can be seen in Fig. 7. Duty ratio is the time when the switch is On, divided by the time of a whole period. It is clear that Buck has a linear transfer function while the Boost and Buck-Boost are non-linear systems in continuous conduction mode. Especially, when the input voltage of a Boost or Buck-Boost is much lower than the required output voltage, a small change in duty ratio results in significant changes in output voltage causing instability issue when MPPT is employed.

Reference [7] proposes a cascade Buck-Boost that can operate either as Buck or Boost depending on the available input voltage and required output voltage. These types of converters need more semiconductors when compared with simple Buck or Boost, which means higher losses and cost. The control complexity of such a system can also be found in [11], [12]. Therefore, Buck converter is the most suitable and economical choice for automotive industry for TEG on-board.

The most conventional TEMs based on bismuth telluride are usually able to operate on temperature $T_{H,max}=220-250^{\circ}C$. The exhaust temperatures in an HDV can reach much higher than $250^{\circ}C$ depending on engine load [13]–[15]. That is, the problem is rather to protect the TEMs from overheating and control the high side temperature. Neglecting the losses in the heat exchanger and contacting losses, it is possible to

Fig. 6. Three main converter topologies.

Fig. 7. Output voltage as a function of Duty ratio for three types of converters.

reach $250^{\circ}C$ on the hot side of the TEM, which means that $20^{\circ}C < T_H < 250^{\circ}C$. Using the ordinary radiator on-board as the coolant gives a cold side temperature of $T_{C,max}=100^{\circ}C$ (worst case). Assume the TEG connection in Fig. 8 with 40 pieces thermoelectric modules of type TE1-1994-3.5 from Thermanamic and apply the above $T_C=100^{\circ}C$ and $125^{\circ}C < T_H < 250^{\circ}C$ on all TEMs. The equivalent voltage and internal resistance of the whole string is a function of hot side temperature, shown in Fig. 9.

The open-circuit voltage of such a TEG is varying between 30 V and 150 V and the delivered power to the load changes from almost 3 W to 100 W. To design a high-efficient converter for such a TEG, the main components have to be optimized for this range of the voltages and powers. The most important power consumer components in this converter are the diode, switch, and the inductor. The diode should withstand at least the TEG input voltage, in this case 150 V, and have low voltage drop and fast reverse recovery time. The low voltage drop minimizes the conducting losses and the reverse recovery

Fig. 8. The electrical model of TEMs forming a TEG, connected two by two in parallel and each pair in series.

Fig. 9. Equivalent open circuit voltage, internal resistance and power of the TEG based on data provided by supplier of TEP1-1994-3.5.

time affects the switching losses. The converter could also be designed as a synchronous one where the diode is replaced by an additional switch. Usually, the voltage drop over a switch is lower than a diode minimizing power loss in the system.

In case of simple Buck, a few diodes can be connected in parallel to lower the voltage drop. Although the synchronous Buck is more complicated, it usually has better performance and therefore the results presented in this paper are based on synchronous Buck converter.

The second component to consider in Buck converter is the inductor. The inductor has two types of losses; electric and magnetic losses. The magnetic losses can be decreased hardly by choosing a bigger core, which in turn will affect the electric losses. It is important that with a reasonable trade-off, one choose the biggest possible core while the resistance of the coil can be kept low at the same time that the inductor operates in continuous (non-zero current) mode. The minimum inductor value should be calculated from the general formula in Eq. (6) or the specific one for the Buck converter according to Eq. (7).

$$V_L = L \frac{di_L}{dt}, \quad (6)$$

$$L = V_{out} \frac{(1-D)T_s}{\Delta I_L}, \quad (7)$$

where V_{out} is the load voltage, T_s ($=1/\text{switching frequency}$) is time period, D is duty ratio, L is inductance, and ΔI_L is the inductor current ripple. The core and coil properties can be obtained by Ampere's law:

$$\oint_{l_c} \vec{H} d\vec{l} = NI_L, \quad (8)$$

which results in

$$\frac{B}{\mu_0 \mu_r} l_c = NI_L, \quad (9)$$

and definition of flux density and inductance gives:

$$B = \frac{\Phi}{A_c} = \frac{LI_L}{A_c N} \quad (10)$$

where H is the magnetic field, l_c is the magnetic path related to the size of the core, N is the number of turns of the coil, B is the magnetic flux density, A_c is the core cross-section area, and Φ is the total magnetic flux. Using Eqs. (7), (9), and (10), one can find the required inductance, number of turns and the core dimensions. According to the calculations on this particular converter, an ETD-54 core needs 20 turns of coils, giving an inductance of $250 \mu\text{H}$ and a flux density of 110 mT with negligible magnetic losses. Such a core was built with a coil resistance and capacitance of $15 \text{ m}\Omega$ and 2 nF , respectively.

To filter the TEG's input and output voltages, two capacitors are needed. The minimum value of the capacitance for a Buck converter can be calculated using Eq. (11), (12), and (13), where C is the capacitance, I_{TEG} is TEG's output current, ΔV_{in} and ΔV_{out} are the input and output voltage ripple, respectively.

$$I_C = C \frac{dv_c}{dt}, \quad (11)$$

TABLE I
PROPOSED COMPONENTS AND PARAMETERS

Component/Parameter	Value/Model
Frequency, F_s	100kHz
Inductance, L	200 μ H
Switch	IRL2910
C_{in}	220 μ F /227TTA250M
C_{out}	330 μ F /337TTA050M
Gate Driver	IXDD614

$$C_{in} = I_{TEG} \frac{(1-D)T_s}{\Delta V_{in}}, \quad (12)$$

$$C_{out} = \frac{T_s \Delta I_L}{8 \Delta V_{out}}. \quad (13)$$

The third component to be considered in this converter is the switch. Usually, for this range of voltage and power, MOSFETs can be used. Regardless of the type of switch, there are two types of losses; the conducting- and switching-losses, which should be kept low. The switch should have a low ON-state resistance, which decreases the conducting losses and fast switching properties to lower the switching losses. The losses in the switch can be estimated according to:

$$E_{ON} = \int_{ton} v(t)i(t) dt, \quad (14)$$

$$E_{OFF} = \int_{toff} v(t)i(t) dt, \quad (15)$$

$$P_{sw} = F_s(E_{ON} + E_{OFF}), \quad (16)$$

where E_{ON} is the energy needed to turn on the switch, E_{OFF} is the energy needed to turn off the switch, F_s is the switching frequency, and P_{sw} is the switching losses. Conducting losses, as it can be seen in Eq. (17), is related to the ratio of interval the switch is On versus the switching period, i.e. duty ratio D , current I , and ON-state resistance, R_{ON} :

$$P_{cond} = R_{ON} I^2 D. \quad (17)$$

The total losses in the switch can therefore be written as:

$$P_{tot_{sw}} = P_{sw} + P_{cond} = F_s(E_{ON} + E_{OFF}) + R_{ON} I^2 D. \quad (18)$$

The converter components were chosen based on the equations above and are listed in table I. As shown in Fig. 10, a component-based simulation using ORCAD/Pspice was performed to verify the functionality and efficiency of the converter. The input voltage and input resistance from TEG according to Fig. (9) and specifications from table I were applied to the software. Furthermore, the measured results from a real inductor and also an estimated inductance and resistance of cables were included into the simulation. Due to high input resistance and big capacitance at the input and output when the simulation is started, it takes 50 ms until the steady-state is reached. After that time, the input power to

Fig. 10. Schematic of simulated Buck converter, designed for the TEG.

Fig. 11. ORCAD/Pspice simulation result showing input and output power of converter based on TEG of 40 modules. $V_{oc} = 137$ V, $R_{in} = 61$ Ω , Duty ratio = 0.35.

the converter and the load power can be read, see Fig. (11). The efficiency of the converter for six different points was calculated and plotted as shown in Fig. (12).

IV. CONCLUSION

According to the simulation results, converter efficiency of 99.4 % $> \eta > 97.6$ % was obtained for all operating points for $T_C = 100$ $^{\circ}$ C and 125 $^{\circ}$ C $< T_H < 250$ $^{\circ}$ C applied on 40 TEP1-1994-3.5 modules. The efficiency seems to be high, but one should note that the simulation was done with the manufacturers' specifications and all ideal existing components such as the inductor and the capacitors were also adapted according to the datasheets based on table I. This

Fig. 12. Converter efficiency VS. power.

means that the simulation result is not only realistic but also very close to reality.

The efficiency is slightly decreasing when the power increases. The reason of this behavior is that the switching losses take over the conducting losses. In this particular case, to reach the highest load power, the duty ratio $D = 1$ is necessary for the lowest TEG power. Therefore, the conducting loss is the most essential but when the power is increasing, the switches conduct during shorter time. At that time, the voltage over the switches are higher allowing larger current through the switch, which increases the switching losses and make it as the dominant loss. It should be noted that in reality, the duty ratio has to be controlled employing MPPT. That is, the effect of MPPT behavior was not included in this study. In most TEG applications, many TEMs have to be connected together. It was found that if the temperature difference over a string of TEMs can be kept constant, the power difference between series and parallel connection is not significant so that a parallel connection would be preferred over a series connection. Series connection creates a high voltage, which helps the choice of DC/DC converter. A Buck converter together with the high input voltage from the TEG, can easily operate to drive an electrical load. It was also shown that a Buck converter can reach high efficiency if components are selected based on proper calculations. The relative simple operation, control and troubleshooting and also the low price of a Buck converter when compared with the other converters makes it an interesting power conditioner for renewable energy sources such as thermoelectric generators.

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