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Optimization of the electric properties of thermoelectric generators

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Optimization of the electric properties of thermoelectric generators (Konstruktion och optimering av elektrotermiska generatorer)

Abstract

The efficiency in an internal combustion engine ranges from 25% to 45%. About 50% - 85% of the overall energy losses in a combustion engine is heat which is either cooled away by the vehicle’s radiator or blown out with the exhaust gases. The heat has to be cooled off by the vehicle’s cooler and this energy is never put into use again and is therefore called “waste heat”. Even if a small fraction of the waste heat could be turned into useful energy again it would be a step in the right direction of improving fuel economy. {1}
This master thesis aims to investigate how to harvest energy from the waste heat using thermoelectric generators, abbreviated “TEG”, and how to return this energy to a Scania truck. The waste heat energy is collected through a TEG. A thermoelectric generator consists of metals or semiconductors and by using the Seebeck effect it turns heat into electric energy. The aim of this report is to investigate how to return the electric energy delivered by the thermoelectric generator into the electric system of a truck with minimal energy conversion losses. Besides from investigating and explaining the electrical system dynamics of a Scania truck a numerical model was constructed in matlab/simulink and a demo DC/DC converter was built. The simulink model both verifies the calculated electrical system model and it also serves as a way of evaluating different thermoelectrical setups. The two main reasons why a demo DC/DC converter was built are because theory can be evaluated in practice and it will also be used to demonstrate a waste heat recovery system on a Scania truck.
There are two alternatives when connecting a TEG unit to a vehicle’s electric system; either with a DC/DC converter or without a DC/DC converter. The configuration to prefer is with a DC/DC converter since it will produce more power with a fewer TEG modules in series. It also enables the possibility to output multiple output voltages like 12V and 24V. Last but not least it is the only option for larger TEG systems.

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Preface

The aim of this thesis is to investigate how to extract energy from the waste heat and how to return it to a Scania truck in the most efficient way.

This master thesis was performed during the first semester of 2010 at Scania CV AB, Södertälje Sweden. The supervising department is the control department at the faculty of engineering, LTH. This faculty is a part of Lund University in Sweden.

This report is divided in the following manner; First off is a brief introduction of the report followed by general information and theory needed for the latter part which tries to explain the whole system and a model is presented from which the conclusions are made.

I would like to thank everyone at the department REP at Scania in Södertälje and especially Jan Dellrud who has been my supervisor and mentor throughout the report. It has been very educational to work along with experienced engineers and it has also been a lot of fun! I would also like to thank Jan Hellgren at the department of RECU who has thought me how to put theory in electronics into practice.

Table of Contents

PART I

1. Introduction

Energy in any form is a scarce resource that has to be carefully used. Not only is the lack of energy a problem but the impact made on the environment when energy is somehow extracted and used cannot be neglected. Therefore one of major objectives today's society is to decrease the overall energy being used in different processes. Today's vehicle manufacturer is no exception when it comes to trying to reduce the energy used both in the process of making a vehicle and the energy involved in the actual transportation done by the vehicle.

A Scania diesel engine designed for the R-series truck is currently reaching an efficiency of slightly above 40%. One should know that this is considered to be a high efficiency in the industry. Still it cannot be neglected that the majority of the energy is just wasted. Not ideal if energy is a scarce resource. A greater part of the waste energy is heat and this heat is usually cooled off and is referred to as "waste heat". The amount of waste heat produced by a R440 Scania truck is about 150kW at road load and if only a fraction of this energy can be harvested and put into use it still would be a great deal of energy. {1}

One way of harvesting the waste heat and turn it into useful energy is to use thermoelectric generators which convert a temperature difference directly into electricity. Prior to this master thesis there have been studies of how much energy can be collected through thermoelectric generators and where to place the thermoelectric generators. This master thesis will investigate how to put the useful energy, consisting of electricity, back in a Scania truck. The thermoelectric generator, abbreviated TEG, is a solid state generator consisting of semiconductors. One of the great advantages of the TEG is that when it generates power it does so without any moving parts. This means that the TEG requires low maintenance and it is quite robust. Unfortunately the efficiency is currently no more than 5% but since we are dealing with waste heat, every wasted watt recovered to useful energy again is a gain. The investigation will be done both with and without a DC/DC converter which is a device to keep a steady output voltage from a voltage source which has a varying voltage level. A model will also be constructed for simulating the behaviour of the electric system of the vehicle and thermoelectric generator system. This model will be an extension of an already existing model made in the study prior to this thesis. A demo converter is also constructed and it will be fitted on a Scania R truck for evaluation of the concept of using a DC/DC converter.

2. The thermoelectric generator

2.1. Introduction

In 1821 Tomas Johann Seebeck discovered that two different metals in junction with each other would deflect a compass if the two metals were subjected to a temperature difference. Seebeck thought that the only thing influencing the compass was a magnetic field and he failed to recognize that there was an electric current involved in this phenomenon.
Thirteen years later a French physicist named Jean-Charles Peltier discovered that when electricity was put through two different metals in junction with each other heat would evolve at one side of the junction and the other side would absorb the heat. This phenomenon which is the reversed Seebeck effect is called the Peltier effect. {2}

2.2. Electric current and potential

Before the theory of how the thermoelectric generator works electric current and potential are briefly explained. Electric current is the movement of electric charge. This charge consists of electrons which have an electric charge of -1.602×10^{-19}Coulomb. Thus, the charge in a cross section per second through a conductor is the current and 6.241×10^{18} electrons passing through in one second correspond to one Ampere. {3}

For the electric charge to be able to move a force must be present. If the charge moves from one point to another this force has performed a work. Voltage is the electrical potential difference between these two points, e.g. the voltage is the electric force needed to move an electric charge between these points. {3}

2.3. The Seebeck effect in Semiconductors

In a pure semiconductor the structure is stable and all outer electrons are fixed. This makes a pure semiconductor a poor electric conductor unlike for example a metal which has one valence electron. Valence electrons are the electrons in the outer shell orbiting an atom. However it is possible to add impurity to the semiconductor to alter its conducting behavior. This is called to dope the semiconductor. There are two types of doping, Negative-type (N-type) and Positive-type (P-type). N-type means that valence electrons have been added and a P-type means that valence electrons have been removed. If we have a N-type semiconductor the added valence electrons are loosely bound and when a voltage is applied they act as charge carriers. P-type means that we are missing out on a valence electron and this missing electron is referred to as a hole. The hole is thought of as a positive charge carrier.

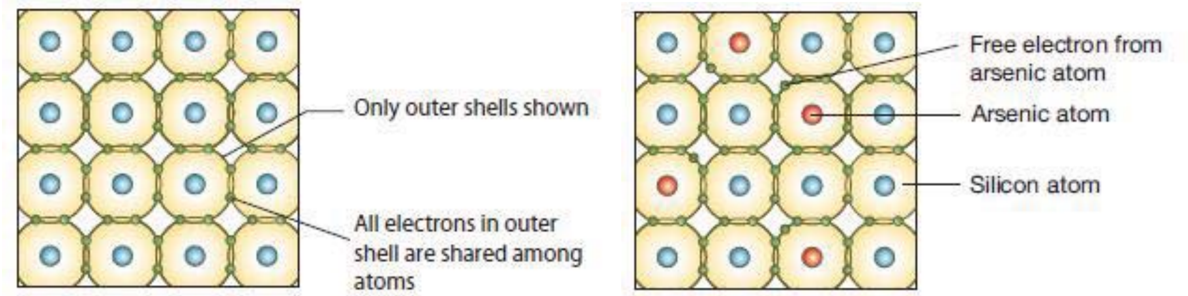


Figure 2.1 To the left a silicon crystal is shown were all the valence electrons are shared among the atoms making the crystal a poor conductor. To the right the silicon crystal has been doped with arsenic giving the structure one valence electron acting as a charge carrier. {4}

An electrical conductor with a cold side and a hot side will transfer thermal energy. Not only will there be a thermal movement but electrical charge carriers will move in the same direction as the thermal energy as seen in figure 2.2 to the left. If we want to use the electric energy we have to complete the circuit and this is not a trivial matter since completing the loop with an identical conductor would result in an equally large set of charge carriers in both conductors which would result in no net current flow at all as seen in figure 2.2 to the right. To address the problem two different conductors can be used and this would in fact result in a net current flow. Different in this case means different capacities to move charge carriers. This current corresponds to the difference between the two conductor current capacities.

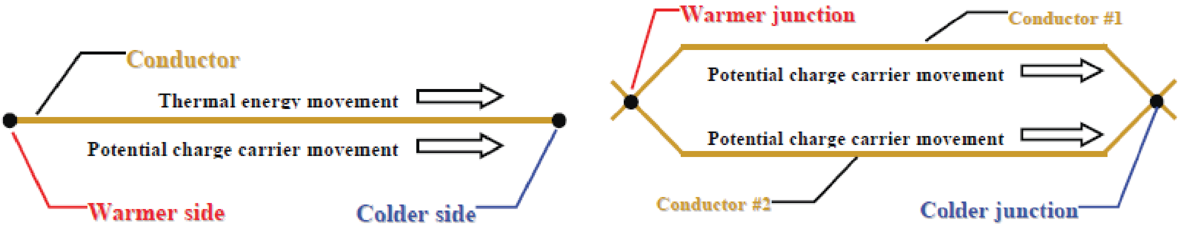


Figure 2.2 To the left the thermal and electric movement can be seen when a conductor is subjected to a temperature difference. To the right the difficulties of using this principle in practice can be seen. {4}

The temperature difference applied to the two conductors will create a voltage. This voltage can be measured by breaking the current loop and using a voltage meter measuring at each end were the loop was opened. The voltage is referred to as the Seebeck voltage and it’s no greater than a couple of millivolts for a temperature difference of 100°C. A couple of millivolts is not much and if the Seebeck effect should have any practical usage the voltage must be boosted.

A thermoelectric generator uses semiconductor materials, which are both of N-type and P-type connected in series to boost the voltage. Since the TEG consists of nothing but semiconducting material it is a solid state device with no moving parts. Both the N-type and the P-type are explained and how they are connected to form a TEG.

The N-type is a semiconductor doped in such way that additional valence electrons are present. As the thermal energy moves towards the cold side the charge carriers move along with it. The movement of the electrons is seen in figure 2.3. If the loop is opened up and the voltage is measured we will have the “open loop voltage” (i.e. Seebeck voltage).

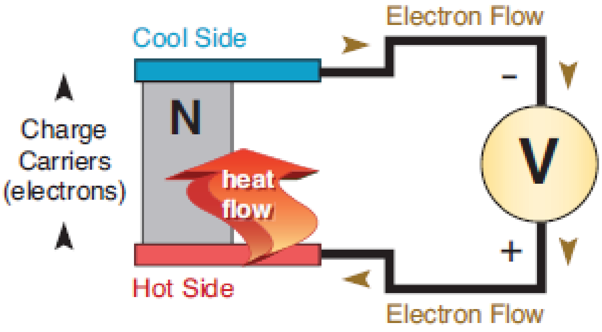


Figure 2.3 The movement of the electrons in a N-type semiconductor. {4}

In the P-type semiconductor the charge carriers move in the opposite direction of the thermal energy, this is shown in figure 2.4.

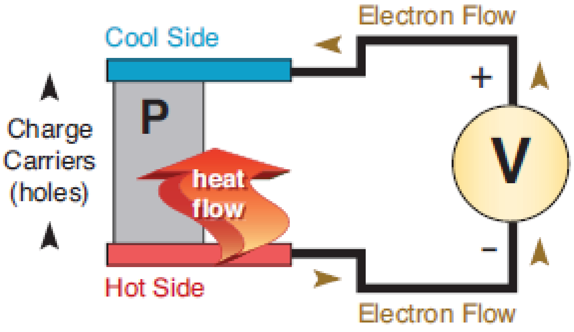


Figure 2.4 The movement of the electrons in a N-type semiconductor. {4}

In both the P-type and the N-type case the open voltage is about 20mV with a temperature difference of 100°C. So the semiconductor is slightly better than the metal when it comes to the Seebeck effect. This is still not enough for any practical application and another advantage with the semiconductor will be demonstrated. To boost the voltage the N-type and P-type can be connected in series very much like putting batteries in series. Figure 2.5 shows how the charge carriers move along from the N-type side to the P-type side. To reach voltage levels that are adequate it is not unusual to connect over 100 P-type and N-type semiconductors in series. {4, 5}

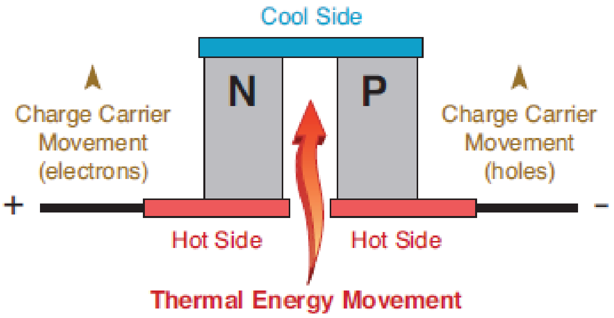


Figure 2.5 P-type and N-type connected electrically together in series to achieve higher voltage. {4}

2.4. Figure of merit ”ZT”

The thermal properties of a TEG is vital when measuring the efficiency, also the Carnot efficiency is very important since this is the maximum efficiency that can be achieved with any heat engine (a thermoelectric generator belongs to the heat engine family). Both within the academic world as well as in the industry the figure of merit is how different TEGs are compared to each other. The definition of the figure of merit is $ZT = \frac{\alpha^2 T}{\rho \mathrm{K}}$ where α is the Seebeck coefficient, T is the temperetaure, ρ is the electric resistivity and K is the thermal conductivity. This implies that a high Seebeck coefficient and a low thermal conductivity and low resistivity are desireable. Different semiconducting materials will have different ZT depending on the temperature which is shown in figure 2.6. The Carnot efficiency is given by $\frac{\Delta T}{T_h}$. When the efficiency of a TEG is measured the following formula is used

$\eta = \frac{\Delta T}{T_h} \times \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+1}$.

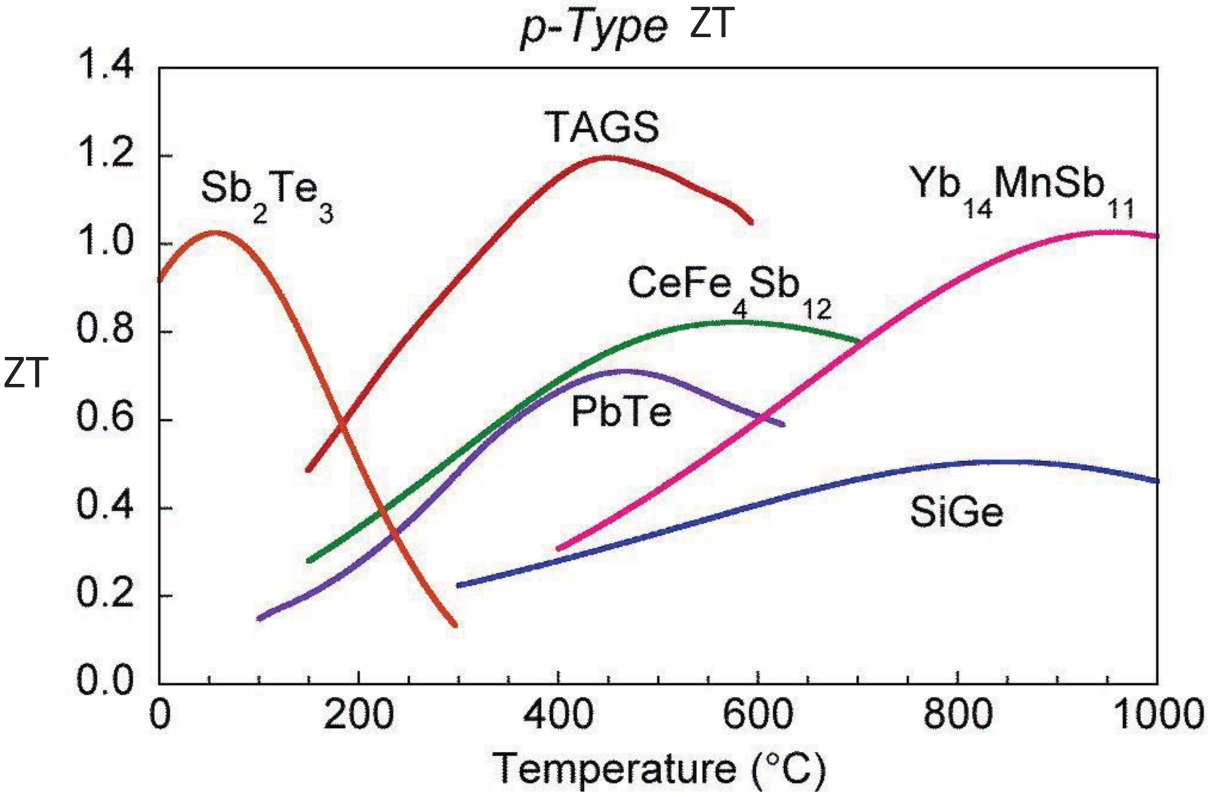


Figure 2.6 The figure of merit “ZT” for different materials and temperatures. {5}

As a result of how different TEG material behave with different temperatures a thermoelectric generator must be carefully choosen to suite its application. {5}

3. Maximum power theorem

To obtain maximum power out of an electric system the load impedance should be equal to the source impedance. The electric circuit in figure 3.1 together with the calculations will illustrate that statement. The

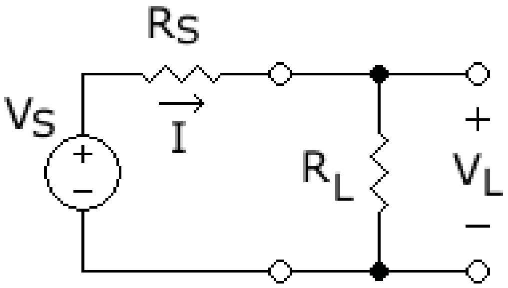


Figure 3.1 To achieve maximum power out of V_S with its source resistance R_S the resistance of the load R_L should be equal to R_S. {6}

The voltage over the load is $V_S \times \frac{R_L}{R_S+R_L}$ and the current through the system is $\frac{V_S}{R_S+R_L}$. The power of a system is $P = U \times I$ and in this particular case it is $P = V_S \times \frac{R_L}{R_S+R_L} \times \frac{V_S}{R_S+R_L} = \frac{V_S^2 \times R_L}{(R_S+R_L)^2}$. With the derivative with respect to R_L and the equation set to zero we will find max and min of the equation. $\frac{d}{dR_L} = \frac{-R_S{}^2}{R_L{}^2} + 1 = 0$. For the expression to be zero R_L must be equal to R_S .

Maximum power transfer is not the same as maximum efficiency. To achieve maximum efficiency the source resistance should be as small as possible or ideally zero. All power delivered from the source will then be delivered to the load. {7}

4. Control regulator

Regulators are commonly used in a vast range of different technical solutions such as power plants, airplanes and optical reading device (DVD or CD) just to mention a few. The purpose of the regulator is to maintain a certain desired value. This could be a specified temperature or speed. In this thesis a regulator has been designed to keep the voltage at the system voltage of the truck despite of what the voltage level is delivered by the TEG or how big the vehicle's electrical load is. It will also be used when the interaction between the vehicle's electrical system and the TEG system are explained.

The regulator in a control loop will try to minimize the deviation between the desired value and the actual value in a system. This is usually done by negative feedback which is shown in figure 4.1. The desired value denoted "r" is compared to the actual value denoted "y" and

the error is called “e”. The regulator will then try to control the process through the signal sent to the process denoted “u” to acquire the correct set point.
The PID controller or a variant of it such as the PI controller is probably the most commonly used controller and will serve as a model when simulations are done regarding the truck’s electrical system. A PID controller consists of three parts. The proportional part called “P”, the integral part called “I” and the derivative part “D”. The proportional part makes a change which is proportional to the error and therefore a bigger proportional part makes the system quicker to react to the disturbances but with the disadvantage of making the system less stable.

The integral part removes the steady state error. An integral part which is too large will cause the regulator to overshoot with large disturbances and make the system unstable. The derivate part will reduce the overshooting by predicting the magnitude of the overshooting. The derivate is sensitive to noise. These three terms are then weighted together to find a controller which works satisfyingly fast without making the system unstable.

Although one controller is built for the DC/DC converter the theory behind making an optimized controller is quite complicated and not in the scope of this thesis. The regulator built for the demo DC/DC converter is called a type-III controller. The principles of a type-III controller are as explained earlier; it will try to maintain the output voltage no matter what voltage level is delivered by the TEG or despite the fact that the vehicle’s electrical load varies over time. {8}

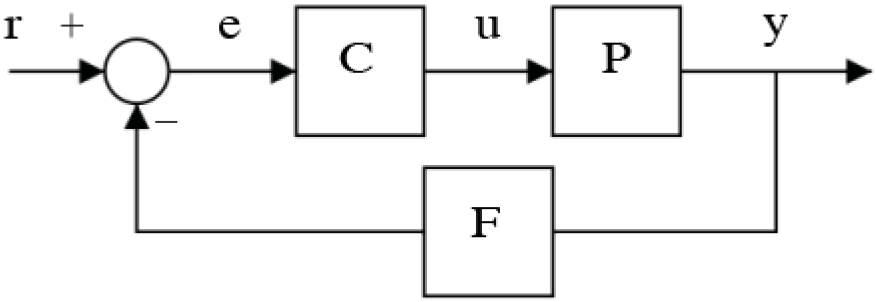


Figure 4.1 A control loop with negative feedback

5. Fundamentals of the switching converter

5.1. Before the switching converter

It is often desirable to be able to switch from one DC voltage to another and to do so with minimum power loss. Until early 1960's this was done with linear voltage regulators. The four major drawbacks with this type of converter is the poor efficiency at low output voltages, it can only produce lower output voltages from a higher one, it requires AC input, and the size of the converter. Due to the poor performance huge heat sinks had to be used and the current was limited. However there are some advantages with the linear regulator, to begin with it is quick when it comes to regulating the output voltage and another benefit is that it has very low radio frequency interference.

5.2. The switching converter

The switching regulator is a pulse width modulated controlled converter which can produce a lower output voltage or even a higher output voltage compared to the input voltage. A switching voltage regulator has an efficiency ranging from 70% up to over 95%. The three most basic regulators are the Buck converter, Boost converter and the Buck/Boost converter. To understand how these circuits work some general component knowledge will be presented. The law of the inductance states that the voltage across the inductor equals the time derivate of the current times a constant L:

$$V = L \times \frac{dI}{dt}$$

This means that there will be a voltage over the inductor only if the current is varying over time. The law of the capacitance states that the current across the capacitor equals the time derivative of the voltage times a constant C:

$$I = C \times \frac{dV}{dt}$$

This means that there will be a current through the capacitor only if the voltage is varying over time. A transformer transforms an input AC voltage, V_A, or current, I_A, into a different output voltage, V_B, or current, I_B, which is dependent of the transformer windings N1 and N2

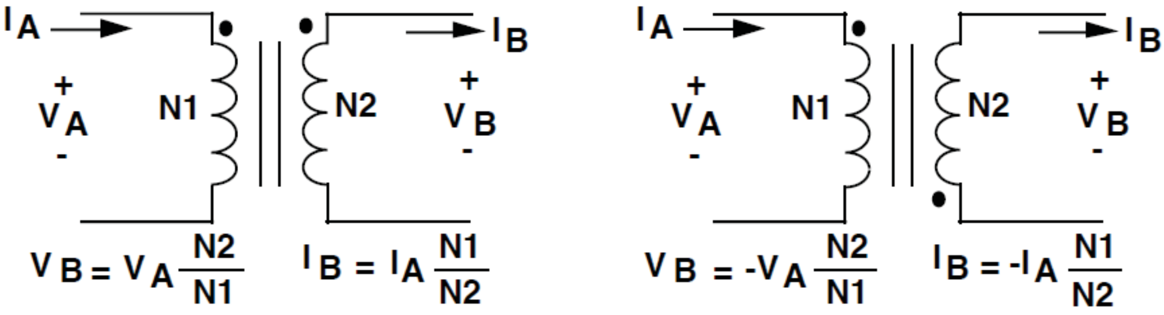


Figure 5.1 In the transformer to the left the windings of the transformer starts at the top on both sides. To the right the winding starts at opposite sides in the transformer giving an output with reversed sign. {11}

The dot in figure 5.2 indicates the polarity of the transformer and the lines in between represents a magnetic core.

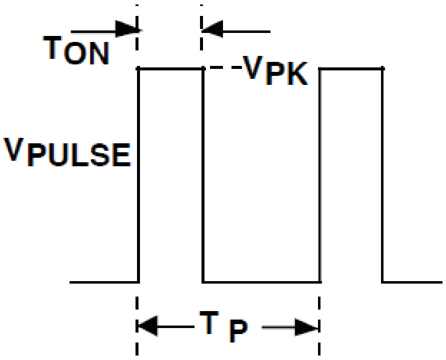


Figure 5.2 A typical PWM signal {11}

PWM which is short for pulse width modulation is used to control the converter. A feedback loop will affect the PWM and adjust the output voltage to ensure that a correct output is given. The PWM signal is a square wave pulse with a fixed frequency, only the width, T_{ON}, of the square in each period, T_P, is varied.

5.3. The buck converter

The buck converter seen in figure 5.3 is a regulator that converts from a higher voltage to a lower voltage. This is done by controlling the transistors on and off time with a PWM signal. When the switch is turned on the voltage difference over the inductor will cause the current to increase. The inductor current will then charge the capacitor and feed the load. When the switch is turned off the inductor will try to hold the current constant and the voltage over the inductor will drop. The diode will force the energy into the capacitor and the load. To conclude the current will ramp up when the switch is turned on and ramp down in the off state. The current over the load will be the average inductor current during these to states. Output ripple refers to the current amplitude difference and should be as small as possible.

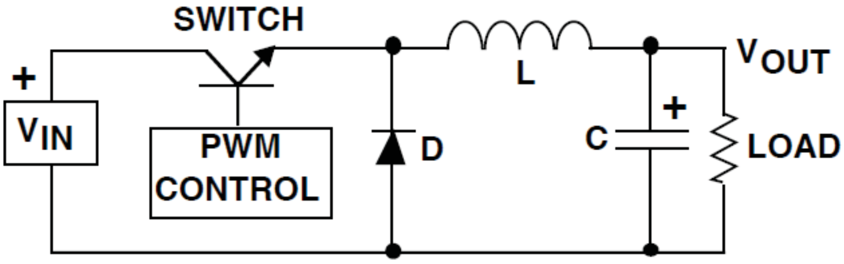


Figure 5.3 A buck converter where $V_{IN} > V_{OUT}$ {11}

5.4. The boost converter

The boost converter has a higher output voltage than the input voltage. When the switch is on the inductor current will ramp up and the capacitor is supplying the load with energy. When the switch is turned off the inductor side connected to the switch will turn positive and forward bias the diode and charge the capacitor to a higher voltage compared to the input voltage. The boost converter is, just as the buck converter, PWM controlled. Since the output voltage is higher than the input voltage the current running through the load is always smaller than the current on the input side.

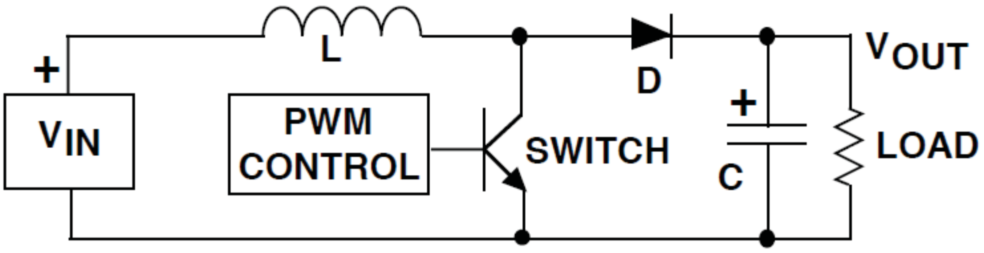


Figure 5.4 A boost converter where $V_{IN} < V_{OUT}$ *{11}*

5.5. The Buck/Boost converter

In figure 5.5 the buck/boost converter is shown. This type of converter can be used both to increase and decrease the output voltage over the load. One important aspect to keep in mind is the fact that the voltage over the load will be inverted.

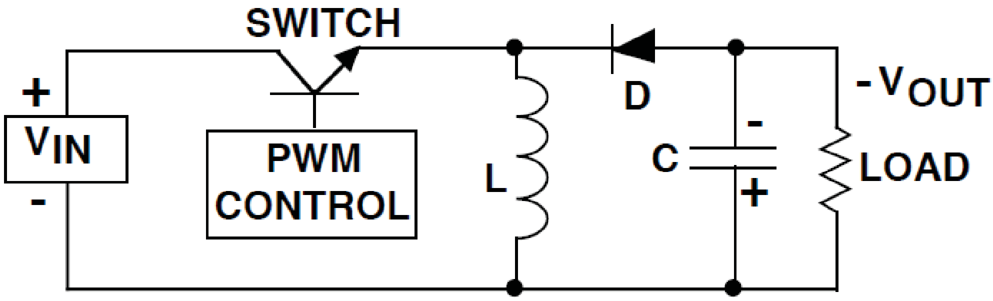


Figure 5.5 The Buck/Boost converter where $V_{IN} < V_{OUT}$ *or* $V_{IN} > V_{OUT}$ *{11}*

When the switch is on the inductor current will ramp up while the diode is making sure that no energy is reaching the output side. Thus the only thing supplying the load with power is the capacitor. When the switch is turned off the inductor current will flow into the positive side of the capacitor to charge it and at the same time supply the load.

5.6. The flyback converter

This type of converter, see figure 5.6, either increase or decrease the output voltage. Since a transformer is used there is an opportunity to have multiple output voltages by having different wirings at the secondary side of the transformer. When the switch is on the current will flow through the transformer primary side causing the current to ramp up. The dot indicates which side is negative on the transformer. During the on time there will not flow any current from the secondary side of the transformer because of the blockage of the diode. This means that the capacitor will be the power supply of the load. When the switch is turned off the voltage on the primary side will change direction and the secondary side will flow in the forward direction of the diode. This will charge the capacitor and supply the load with current.

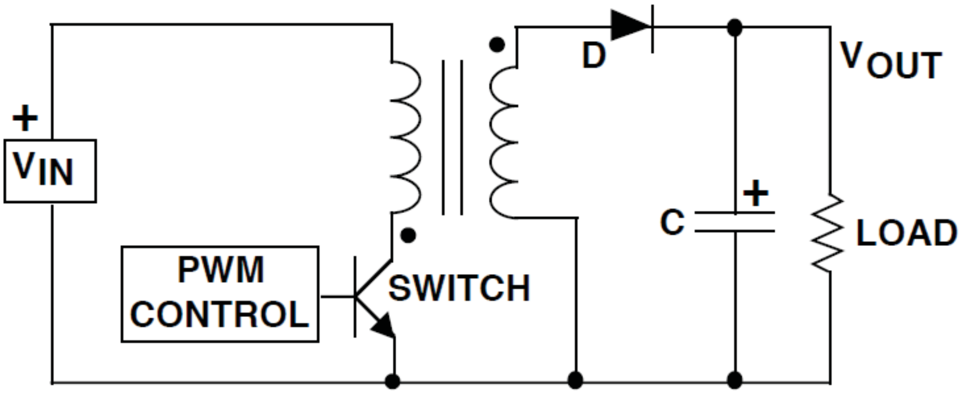


Figure 5.6 A flyback converter which uses a transformer to switch from one voltage level to another {11}

5.7. The push-pull converter

The push-pull converter is slightly more complex since it uses two transistors as switches. The efficiency is fairly good and it can be implemented to deliver multiple outputs. The drawback is that the MOSFETs must be able to handle twice the input voltage thus making this suitable for relative low voltage levels.

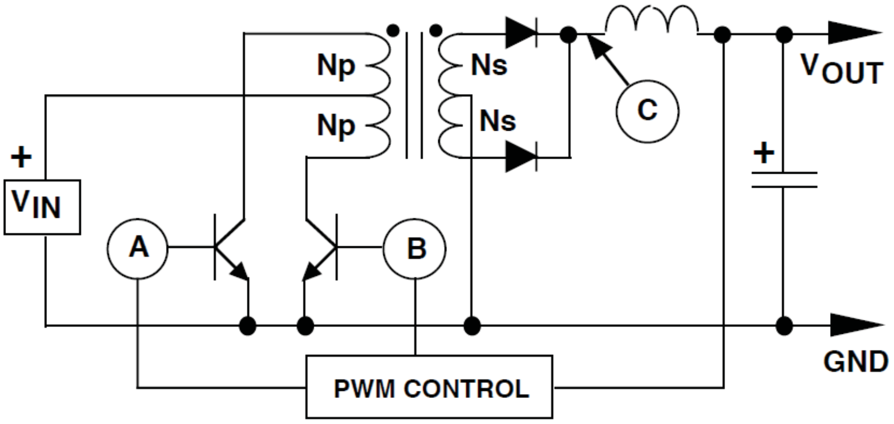


FIGURE 35. PUSH-PULL CONVERTER

Figure 5.7. A push-pull converter which uses a center-tapped transformer and two MOSFET transistors to alter the voltage level. {11}

When switch A is active switch B is inactive and vice versa. This means that the two different sides, divided by the center tap on the converter, work every other time. The two diodes are making sure that nothing is fed in the wrong direction.

5.8. The half-bridge converter

A converter that is similar to the push-pull is the half-bridge. There are two MOSFETs which never are turned on simultaneously and only the secondary side of the transformer is center tapped. Unlike the push-pull converter the MOSFETs are not subjected to twice the input voltage, the voltage at the MOSFETs will be equal to the input voltage. The voltage over the primary side is no more than half of the input voltage. When switch A is turned on the dotted primary side will be positive as well as the dotted secondary side. This will forward bias the upper diode which is supplying the output. When A shuts off and B is active the dotted primary side will be negative and the lower diode on the secondary side will be forward biased. If either switch A or B is turned on there will be current through the transformer which will power the output. If none of them is active the output capacitor is discharged via the load.

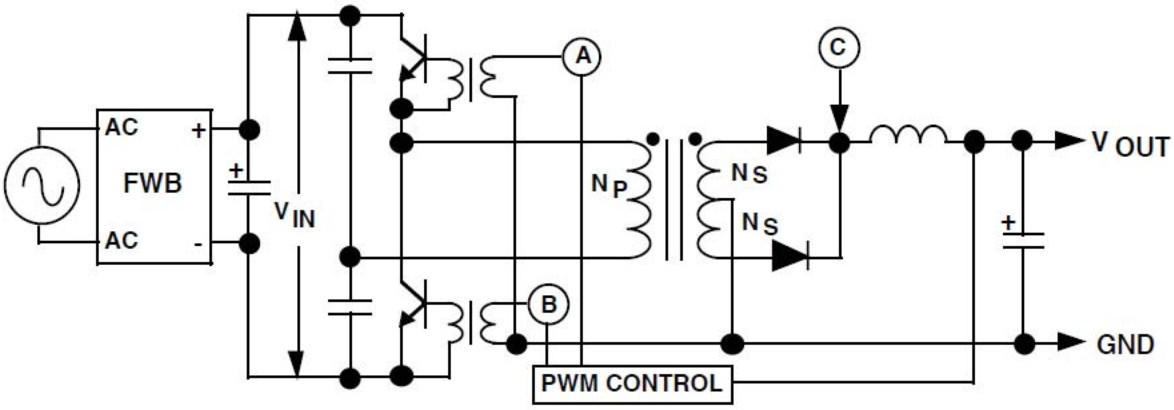


Figure 5.8 The advantage of the half-bridge is that the MOSFETs only have to be able to handle a voltage level equal to the input voltage. {11}

5.9. The full-bridge converter

This type of converter is suited for heavy power applications in the range from 1kW to 3kW. Apart from the two extra switches the full-bridge is quite similar to the half-bridge. By adding two extra MOSFETs the full-bridge can handle twice the output power but still the voltage stress is no more than the voltage stress on the half-bridge. This is because the voltage over the primary side will be equal to the input voltage.

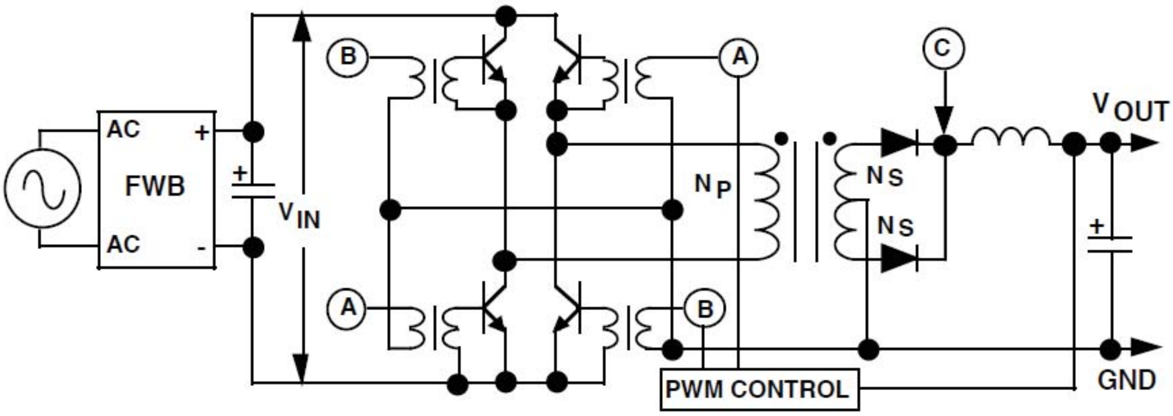


Figure 5.9 The full –bridge converter, a topology well suited for high power applications. {11}

5.10. Other topologies

There are other several types of converters which only will be mentioned here for some general knowledge. The Sepic converter is a buck/boost type that uses flyback technique to change the output voltage. Flyback means that the energy is stored as magnetic energy and then released into the load. The Ćuk converter has a continuous output current and is also capable of both bucking and boosting the output voltage. The Split-pi converter is also a buck/boost variant. It uses four switches to accomplish the voltage conversion. Both the Ćuk and Split-pi emit less RF noise making them more suitable for sensitive environments. *{11}*

6. Scania truck electrical system

Unlike passenger cars which use a 12Volt DC system in their vehicle's most of today's truck manufacturers use a 24Volt DC electric system. How much electric power the truck consumes varies quite a lot depending on its purpose and use but a regular long haulage vehicle consumes about 40A {12}. The truck's electrical system consists basically of three different parts; a battery, an alternator and actuators/consumers.

6.1. The alternator

The alternator is an electric generator and it keeps the voltage constant, through a voltage regulator, and this is done by altering the magnetic flux density. The generated electricity is of 3-phase AC type and it has to be converted into DC, which is done by a diode bridge. A Scania alternator is capable of delivering 100 – 150 Ampere and its efficiency is somewhere around 70%. The cooling fan needed to cool the alternator is not included in this figure which means that in reality the efficiency is below 70%. The efficiency is also rpm dependent and this means that the efficiency presented here is the best case scenario. The alternator delivers a voltage between 28.4V and 28.9V.

The power generated by an alternator can be explained with the Lorenz force law and the Lenz induction law. The Lorenz force law states that $F = I \times l \times B$ so the force equals the current times the length of the alternator windings times the magnetic flux density. The following formula is the Lenz law of induction $e = l \times v \times B$ where e is the induced voltage, l is the length of the alternator windings and B is the magnetic flux density. This means that if the vehicle needs more current the alternator load on the diesel engine will increase. It also means that there are two ways of changing the voltage, either by changing the rpm or by changing the magnetic flux density since changing the length of the winding is not an option. With the use of a TEG we can reduce the alternator load on the diesel engine and have a better fuel consumption. A TEG delivering 200W, which is half of the power needed under long haulage, will provide around 8 A. If a 1kW TEG is used the alternator could be disabled under long haulage driving and the fuel consumption would drop significantly. {13}

6.2. Battery

The battery acts either as an load by consuming power from the alternator when charging or as a power source when the alternator is not running or under extreme working conditions were the vehicle requires a lot of current. Most of the batteries used in the truck industry use lead batteries and Scania is no exception. Fully charged the battery delivers 26.3V and they range from 140Ah to 225Ah. To charge a battery the charging voltage must be set above the battery voltage. How many amperes the battery will require depends on the charging status of the battery as well as the temperature. A fully charged battery will only need a couple of amperes while an almost empty battery will need a lot more. For example a 170Ah battery which has 50% of its capacity left, charged with a voltage at 28.5V and in an ambient temperature of 0C° will require 45A in the initial charging phase. After two hours of charging it will require less than 10A to continue charging. If the temperature is -18C° the battery will initially require almost 100A! This implies that even if a 2kW TEG system was installed in a truck the generated power will not be enough to completely power the vehicle. {13}

6.3. Actuators and power consumers

There are a lot of devices that consume electric power in a truck for instance a fridge, headlights or power windows. How much power different devices consume differs quite a lot from a 0.5 A up to 30 A. The most important aspect of the actuators are that the lifespan of the electric devices decrease significantly with increasing voltage levels above the specified voltage level of the vehicle, e.g. 28 volts. Therefore the voltage delivered from the TEG system should preferably not exceed 29 volts. {13}

PART II

7. TEG module behavior

Before investigating how to feed the Scania truck with the harvested electric energy a study of how the voltage level would fluctuate under long haulage working conditions. This study was done both by running the simulink simulation originally created by H. Schauman {9} and modified during this thesis as well as verifying the results by hand calculations. First simulations and calculations are done with a separate cooler for the TEG system and then simulations and calculations are done with the truck engine cooler used for cooling the TEG system.

The hot side of the TEG unit is assumed to be constant at 190 C°. The cooling medium at the cold side will be 20-60C° (based on an ambient temperature of 0-40 C°) if a separate cooler is used or 80 C° if the vehicle's engine cooler is used. The cold side of the TEG will increase somewhere between 10-15 C° due to heat transfer through the TEG module itself.

7.1. Separate cooler

$\Delta T_{MAX} = 190 - 35 = 155$ and $\Delta T_{MIN} = 190 - 75 = 115$

The characteristic of the voltage is linear and the following calculations are made with the TEP1-12656-0.6 module in mind. The voltage, which depends on the temperature, is calculated as follows $y = k \times x$ where $k = 0.0506$ and $x = \Delta T$

Worst case voltage output: $V_{TEG\min} = 0.0506 \times 115 = 5.8\,\mathrm{V}$

Best case voltage output: $V_{TEG\max} = 0.0506 \times 155 = 7.8\,\mathrm{V}$

With an average voltage output: $V_{TEGavg} = 6.8\,\mathrm{V}$

Using the simulink model an output voltage is plotted over time using a specific driving cycle.

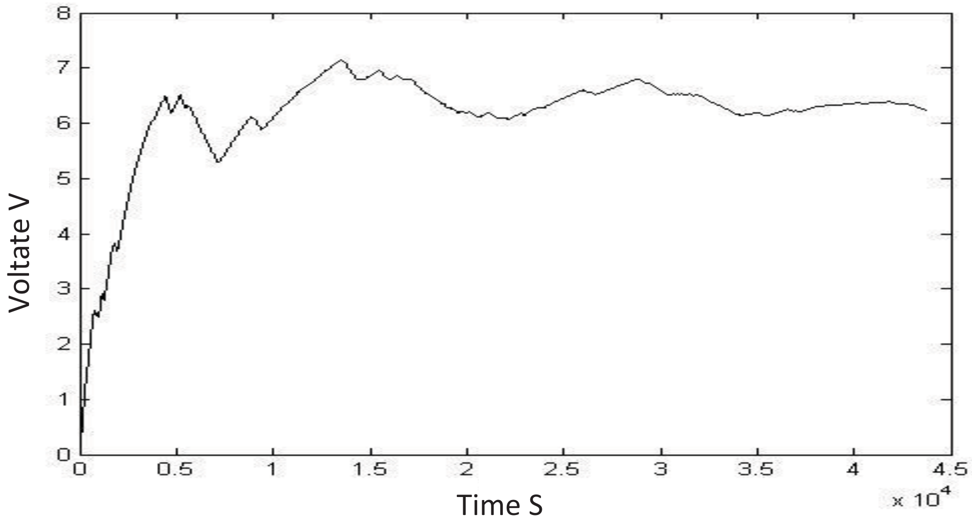


Figure 7.1 The output voltage from one TEP1-12656-0.6 under long haulage working conditions using a separate cooler for the TEG system

According to the simulation the output voltage from the TEG module is between 6V and 8V.

7.2. Engine cooler

In contrary to the separate cooler the temperature of the cooling medium here will not fluctuate as much, it will be rather constant at 80C°. Heat transfer through the TEG will be assumed to add another 10 C°.

$\Delta T = 190 - 90 = 100$

The characteristic of the voltage is linear and the following calculations are made with the TEP1-12656-0.6 module in mind. The voltage, depending on the temperature, is calculated as follows $y = k \times x$ where $k = 0.0506$ and $x = \Delta T$

Voltage output: $V_{TEG} = 0.0506 \times 100 =$ 5.1V

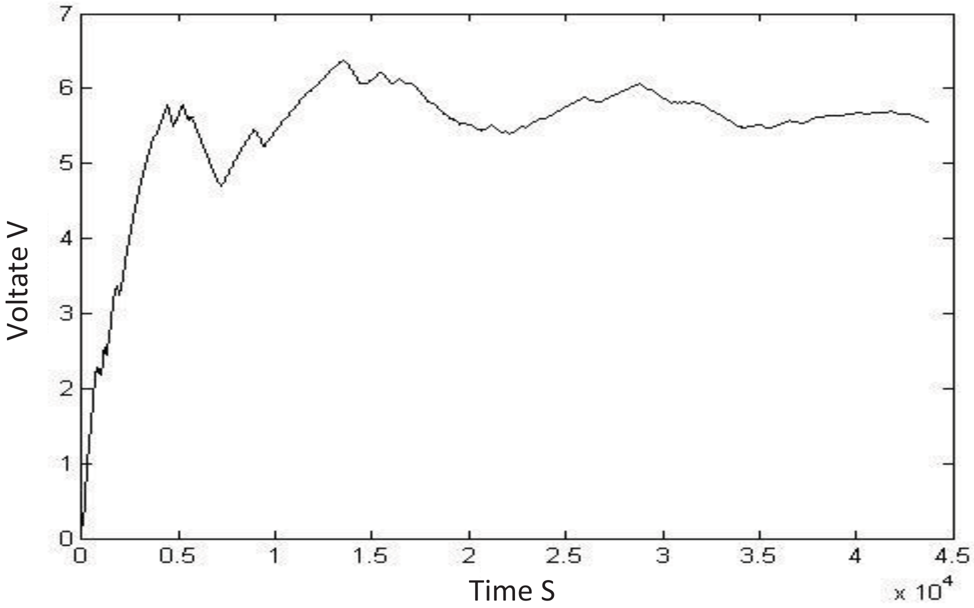


Figure 7.2 The output voltage from one TEP1-12656-0.6 under long haulage working conditions using the engine cooler for the TEG system

This plot shows that the output is about one voltage above the calculated values. This is due to the fact that the model allows the hot side of the TEG to reach over 220 C°.

8. Physical configuration of the TEG modules

If two TEG modules are put in parallel to each other and one of them has a higher output voltage, then the module with lower voltage will be fed with energy. This will be energy lost as the TEG module will function as a Peltier element. There are ways, to some extent, avoid that the TEG modules feed each other with energy. The modules should be configured as shown in figure 8.1. The reason why this setup is to prefer is because the energy flow over the modules in parallel will decrease equally. This will result in the same voltage between the modules in parallel. Another way to ensure that the TEG modules will not feed each other is by using diods. Unfortunately there is always a voltage drop over diods and therefore this method is should be avoided.

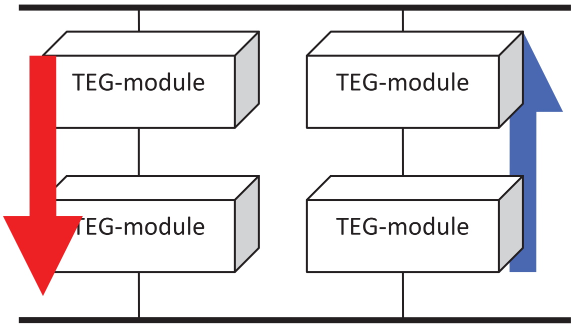


Figure 8.1 This figure shows how the TEG modules connected in parallel both will have the heat coming from the top from the front side of the modules and the colder medium working its way from the bottom up on the back side of the modules.

9. DC/DC converters

9.1. Source resistance and converter impedance

First off is an investigation of how different physical TEG module configurations will affect the converter efficiency. In this case physical configuration means how the modules are connected to each other, e.g. in series or in parallel. Due to the nature of the TEG modules with very high source resistance, impedance matching must be made to ensure that the power delivered to the converter is moved forward to the intended load. There are some obstacles when transferring the power produced by the TEG to the truck’s actuators. The lowest input voltage that the converter can operate at is set by the voltage drop over certain components as well as voltage requirements of other components. The efficiency of the converter also limits the power that reaches the load. Another maybe not so obvious factor is the input-impedance of the converter which is dependent of the source resistance which in turn is dependent of the output impedance. It is this input-impedance that has to be taken into consideration when the specifications of the TEG configuration as well as the specifications of the converter are set.

The input-impedance of the converter is the input voltage to the converter divided by the input current. Since we have a source resistance there will be a voltage drop and the converter will experience a lower voltage than the voltage delivered by the TEG modules. A good design rule is to ensure that the source resistance is ten times smaller than the input-impedance. This is not doable because of the TEG module's high source resistance which ranges somewhere between 1Ω to 7Ω. The modules used for this project are the TEP1-12656-0.6 with a source resistance of 3Ω. A more "on the edge" approach is necessary. {10}

To be able to extract maximum power we want to keep the source resistance as low as possible and the voltage fairly high. How the source resistance and voltage are entwined is now shown. To minimize the source resistance of the TEG system viewed from the converter as many modules should be put in parallel as possible. The constraint of how many modules are in parallel is set by the voltage needed by the converter for a specific power configuration and the maximum current which the converter can handle. In the demo case 72 modules are used with each a maximum output voltage of 8V. If the converter requires minimum 15V to function correctly and a broad working range is desirable 3 modules in series should be used (according the long haulage simulation in section 6). With 3 modules in series we have 72/3=24 in parallel.

With 24 modules in parallel and 3 such units in series the source resistance is

$$R_{source} = \left((TEG_{series} \times R_{TEGmoduleresistance})^{-1} TEG_{parallel}\right)^{-1} = 0.375\ \Omega$$

and the input voltage will range from 0 to 24V.

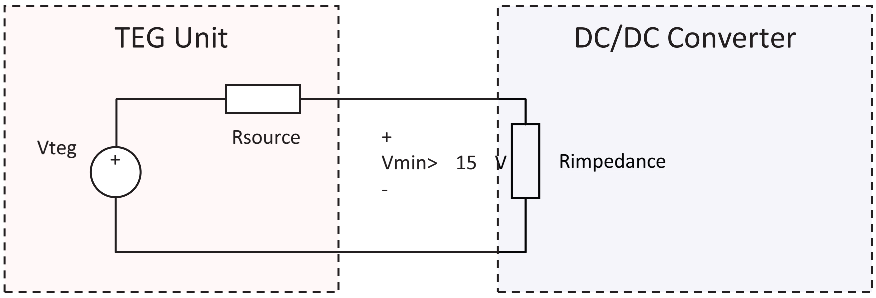


Figure 9.1 An view of the TEG modules with their source resistance and the input-impedance of the converter.

The equation for how the input-impedance will look like $R_{impedance} = \frac{-R_{source} \times V_{min}}{V_{min} - V_{teg}}$

This is what actually limits the output power to the load of the system (that and the maximum current or voltage which the components can handle). This is illustrated in figure 9.1.

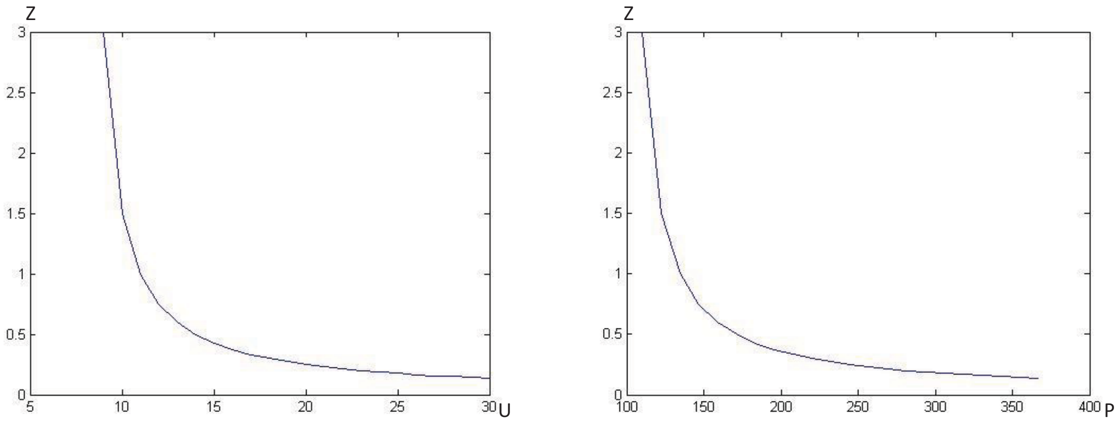


Figure 9.2 To the left the input-impedance Z is plotted versus the converter input voltage U. To the right is the achievable output power P at different in-impedances Z.

To the left in figure 9.2 it can be seen how the voltage from the TEG sets the input impedance of the converter. To the right in the same figure the maximum achievable input power for given input impedance. This shows that at 200W the input impedance should not be more than Z=0.35Ω which means that the input voltage must reach 16.5V. At this point the TEG and the converter are matched according to the maximum power theorem.

9.2. Input impedance of the converter

The following subjects are investigated:

- Bi-stability due to high input resistance and when it occurs
- Input resistance and input voltage relations.

The system will be investigated in a black box model where the converter represents the black box. Principals of the system to be investigated can be seen in figure 9.3. The aim of this part is to investigate if and in that case how the different TEG module configurations will affect the DC/DC converter.

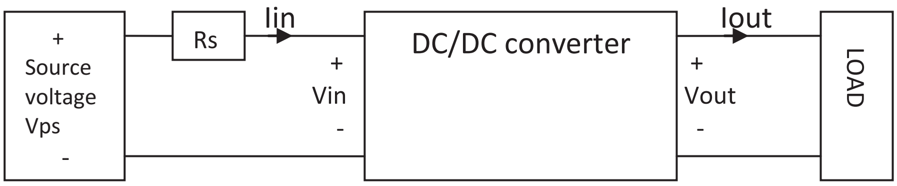


Figure 9.3 Schematics of the TEG unit connected to the converter which in turn is connected to the vehicle load.

9.3. Source efficiency

The efficiency of the source will be

$$Eff_{SOURCE} = \frac{V_{IN} \times I_{IN}}{V_{PS} \times I_{IN}} = \frac{V_{IN}}{V_{PS}}$$

and the efficiency of the converter is

$$Eff_{DCDC} = \frac{V_{OUT} \times I_{OUT}}{V_{IN} \times I_{IN}}.$$

Eff_{DCDC} is usually somewhere between 75% to 95% and the properties of the converter decides what the configuration of the TEG unit will look like. These calculations are later applied on the demo converter.

The source efficiency can now be calculated by combining the two following equations.

$$I_{IN} = \frac{V_{PS} - V_{IN}}{R_S} \text{ and } I_{IN} \times V_{IN} \times Eff_{DCDC} = V_{OUT} \times I_{OUT} \Leftrightarrow I_{IN} = \frac{V_{OUT} \times I_{OUT}}{V_{IN} \times Eff_{DCDC}}$$

This gives

$$V_{IN} = \frac{V_{PS}}{2} \pm \sqrt{\frac{V_{PS}^2}{4} - \frac{V_{OUT} \times I_{OUT} \times R_S}{Eff_{DCDC}}}$$

Now the efficiency of the source is as earlier stated $Eff_{SOURCE} = \frac{V_{IN}}{V_{PS}}$ which leads to

$$Eff_{SOURCE} = \frac{1}{2} \pm \sqrt{\frac{1}{4} - \frac{V_{OUT} \times I_{OUT} \times R_S}{Eff_{DCDC} \times V_{PS}^2}}$$

{14}

9.4. Bistability

Bistability is when the converter has very low efficiency due to two working points. This occurs when the source resistance is not small enough. According to the article "Source Resistance: The Efficiency Killer in DC-DC Converter Circuits" {14},

$$R_{BISTABLE} = \frac{Eff_{DCDC} \times V_{MIN} \times (V_{PS} - V_{MIN})}{P_{OUT}}$$

where $P_{OUT} = P_{IN} \times Eff_{DCDC}$. This means that for one TEG-module (TEP1-12656-0.6 with a source resistance of 1.25Ω) we must choose $V_{MIN} = 4V$ to ensure stability.

With $V_{MIN} = 4V$ $R_{BISTABLE} = \frac{4 \times (8.6 - 4)}{14.7} = 1.25\Omega$.

To summarize the boundary set by the bistability equation is the lowest possible value of V_{MIN}, e.g. working range of TEG-system. Now, as the TEG materials will become better and better this problem will surely slowly fade away but as for now $R_{BISTABLE}$ has to be calculated in each and every specific case. To avoid this problem with a minimum voltage needed modules will be connected in parallel. A satisfying low voltage level which one would be certain of avoiding the stability problem would be with $V_{MIN} = 1V$

$$R_{BISTABLE} = \frac{1 \times (8.6 - 1)}{14.7} = 0.52\Omega$$

And with a converter efficiency of 85% the bistability problem would appear if the source resistance would be greater than 0.41*Ω*. This means that 4 TEG modules would do the trick since the source resistance would be 0.31Ω

The impact on the efficiency due to the configuration

Because we want to extract as much of power from the TEG-unit as possible we investigate in what way Eff_{SOURCE} is affected by different type of configurations (TEG-units connected in series or in parallel manners). Since V_{PS} =open load voltage times the number of TEG-units in series and $R_S = ((Source\ resistance\ \times modules\ in\ series)^{-1} \times parallel\ modules)^{-1}$ the Eff_{SOURCE} is not changing depending on how the TEG-units are configured but rather of the TEG-module properties. To get a larger Eff_{SOURCE} a smaller source resistance is preferable but a higher voltage would also work. To visualize the statement just made the configuration is put into the equation.

$$Eff_{SOURCE} = \frac{1}{2} \pm \sqrt{\frac{1}{4} - \frac{P_{IN} \times series \times parallel \times \left(\left(R_S \times series \right)^{-1} \times parallel \right)^{-1}}{\left(V_{PS} \times series \right)^2}} = \frac{1}{2} \pm \sqrt{\frac{1}{4} - \frac{P_{IN} \times R_S}{{V_{PS}}^2}}$$

As seen the configuration is cancelled out and the converter efficiency is not dependent on the configuration but there are some limitations of how one can connect. As mentioned earlier the input-impedance is what sets the configuration and this is what will determine the minimum number of modules in series. Hence that we want to use as few modules in series because if one module fails when connected in series the whole chain of modules in series will fail. {14}

9.5. Behavior of the converter and alternator

Questions as whether the converter will cooperate with the alternator in harmony or not and whether the converter will behave well over different loads are inventible. To be able to accurately answer these questions empirical data is collected through tests in an alternator-rig and calculations are performed to support the conclusion made from the test.

The alternator in a new Scania truck is fitted with a 100-150 A PWM controlled alternator with a voltage regulator. An Electronic control unit controls the output voltage with the PWM signal based on a numerous factors such as battery status, temperature and etc. Electronic control units, abbreviated ECU, are the computers used in vehicles. The voltage regulator makes sure that no matter what the load of the vehicle’s electrical system is the voltage is stable at the preset value. Intuitively one would think that as long as the output voltage of the converter is higher than the output voltage of the alternator, the converter will be the dominant power feeder to the vehicle’s electrical system. But what happens if the output voltage from the converter and the alternator are equal to one another? Under these working conditions the TEG system and the alternator will share the load since the alternator can’t distinguish the voltage from the TEG system and its own voltage. This is a state that is less preferable since not all power from the TEG will be delivered to the vehicle’s electric system. When the converter moves up from the output voltage of the alternator with a voltage of at least 0.5V it will be dominant. This is because the alternator has, as mentioned before, a voltage regulator which constantly checks the vehicle’s electrical voltage. If the voltage of the converter is 28.8V and the alternator is set to give 28.3V it will try to decrease the current until the voltage will drop down to 28.3V. This will of course not happen as long as the converter delivers enough current to keep up the voltage. When the power consumed exceeds the power delivered by the TEG system the voltage will drop down until the alternator steps in to deliver the remaining current to keep the voltage above 28.3V. This is an important observation since this means that all the TEG power will be put into the system and the alternator will only provide with the power necessary to maintain the correct voltage. Table 1 found in the appendix shows the measured values from the test in the alternator-rig which supports the statement just made.

To further support the observations made in the rig the behavior can be explained with the following calculations. In the case where the alternator and the TEG system output voltage are close, e.g. within 0.5V, they will behave as in fig 10.1 since the alternator regulator will be put out of the equation.

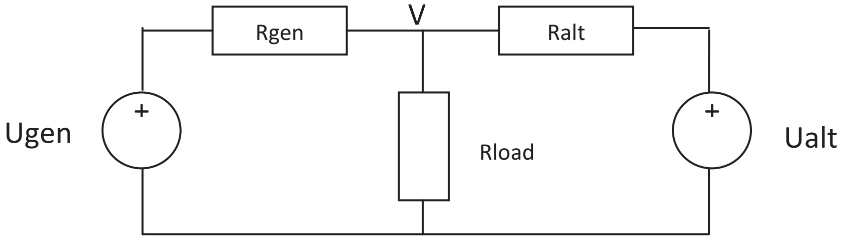


Figure 10.1 Rgen and Ralt are << Rload

$$V = \left(\frac{V_{gen}}{R_{gen}} + \frac{V_{alt}}{R_{alt}}\right) \times \left(\frac{1}{R_{gen}} + \frac{1}{R_{alt}} + \frac{1}{R_{load}}\right)^{-1}$$

The setup in the alternator rig supports the two parallel voltage sources theory since a decrease in the voltage can be seen in the narrow voltage span when the alternator and TEG system are sharing the load.

10. TEG system without DC/DC converter

There is a way to avoid a DC/DC converter and its power dissipation. This is done by making sure that the output voltage from the TEG unit always is above the voltage set by the vehicle's alternator. The power will be drained from the TEG unit so that it balances out to the same voltage level as the alternator voltage level. But there are challenges to address in such a system. To begin with we need to configure the TEG modules in such a manner that they can produce such a high voltage under normal driving conditions. This means that many TEG modules must be connected in series and again we have a reliability problem. Furthermore many modules in series will cause a large internal resistance which will lead to a poorer power performance. Another performance killer in this kind of system is due to the fact that the TEG unit must be disconnected when the voltage level is too low, otherwise they will be fed with power from the alternator. Finally the power from the TEG must never exceed the power needed by the vehicle since this will lead to a voltage level above nominal values which might end up destroying some of the vehicle components or actuators.

A workaround is to have a switched network that will switch between a set of different configurations. To begin with most of the modules will be connected in series to ensure that high enough voltage is delivered even when the energy coming from the waste heat is quite small. When the truck starts there will not be enough waste heat and the TEG unit will be disconnected. As driving continues the waste heat energy will be enough for the TEG unit to be connected to the truck's electric system and finally when there is a lot of waste heat the network will switch to fewer modules in series and more in parallel. When a switched network is used there is an opportunity to increase the overall performance since the source resistance of the TEG unit will be smaller in nominal operation. It will also increase the ability to function when very little waste heat is available. This will require careful study of the truck's different driving conditions before choosing the TEG modules and how to configure them. Even if a switched network is used it will be virtually impossible to switch between different configurations to ensure the correct voltage if the TEG will be used to a greater extent to power the electric system in a vehicle. To conclude, this system is only an option if the TEG will deliver significantly less power than the alternator.

11. Simulation

This section aims to investigate if a TEG system with converter is to prefer over a TEG system without a DC/DC converter. The output power from the different systems are then compared.

11.1. Simulation setup

The simulation built in Matlab Simulink consists of five parts, all shown in figure 11.1. Prior to this master thesis Henrik Schauman did a master thesis at Scania where a simulation of how much power could be extracted from the waste heat in a R-series Scania truck.{11} This model is extended into simulating the power delivered from a TEG module which in turn is connected with several other modules. These modules are configured to form the TEG unit. The TEG unit with its own efficiency is connected either to a DC/DC converter or directly to the model of the vehicle electric system. The vehicle electric system consists of the alternator but no actuators are present since it is the power generated from the TEG system is the only thing of interest here. The alternator and the DC/DC interaction are simulated with PID regulators. Here it is not vital what kind of regulator or how fast they act but rather understanding the behavior between these two components. When the DC/DC converter is not present the TEG unit will interact directly with the alternator. Both the TEG system and the alternator have a saturation point when they cannot deliver any more current. The vehicle's electric load is constant at about 1500W. The power plots are made with a TEP-1264-1.5 module.

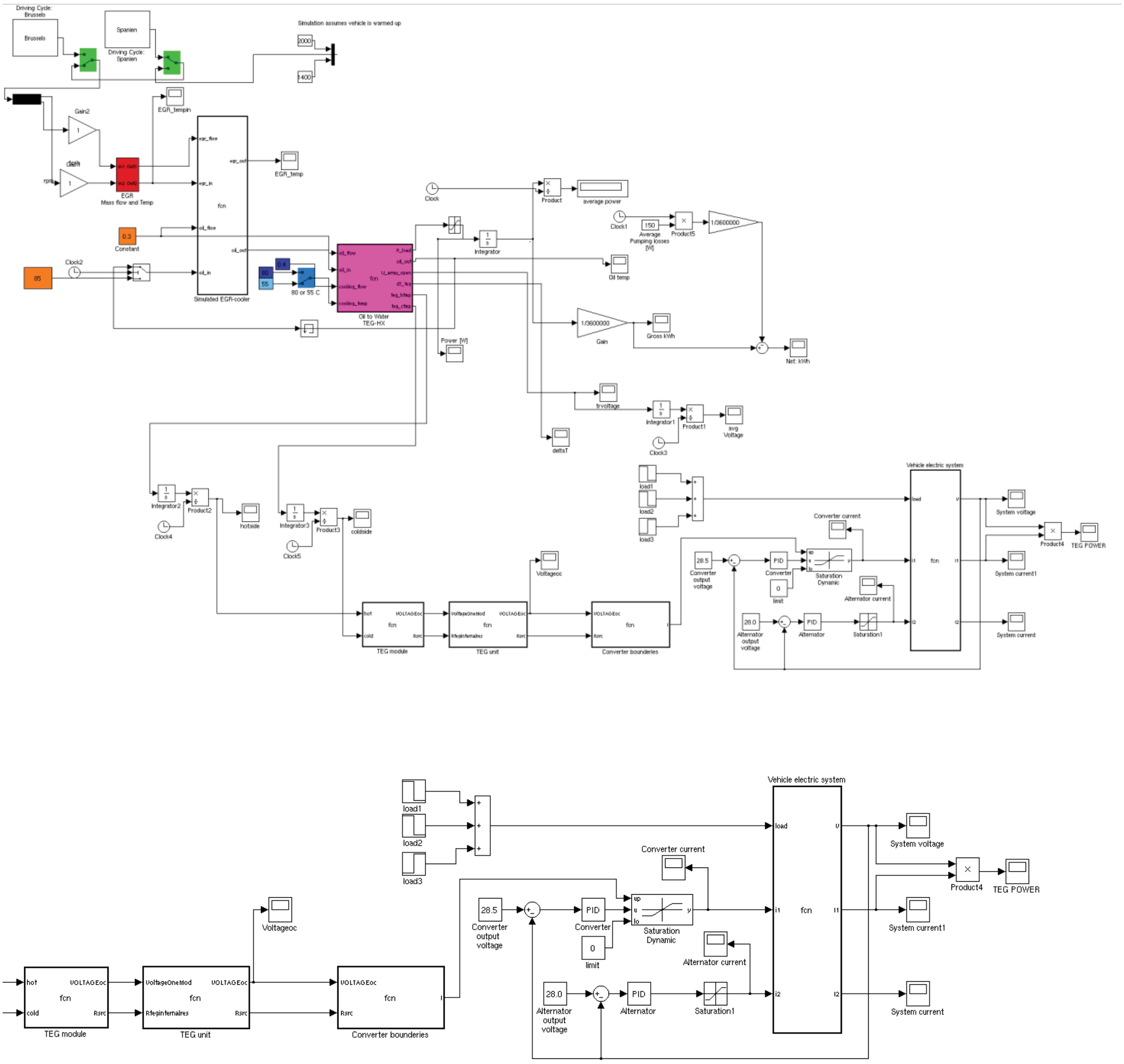
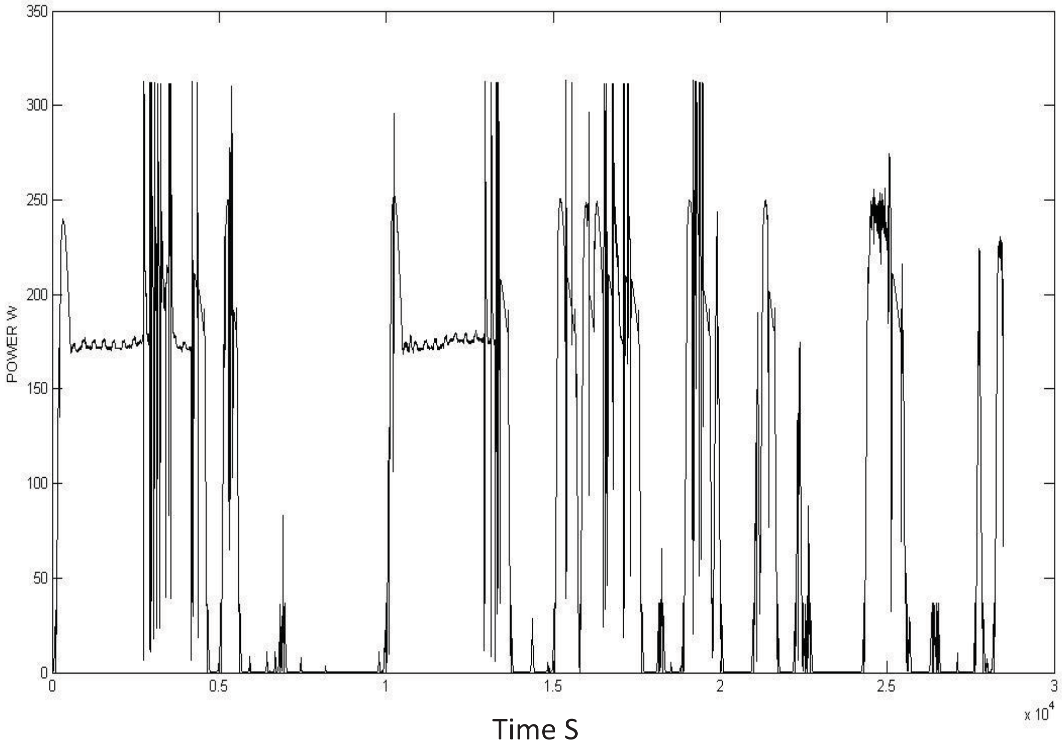


Figure 11.1 On the top the complete simulated system can be seen and on the bottom is the implementation of the TEG system

11.2. Simulation results

The simulation is done with a separate cooler for the TEG system and the data is based on a long haulage drive recorded in Spain. The heat is taken from the EGR cooler with oil as the heat transferring medium. Figure 11.2 shows the output power during the drive and with 72 TEG modules the truck will be fed with up to 300W



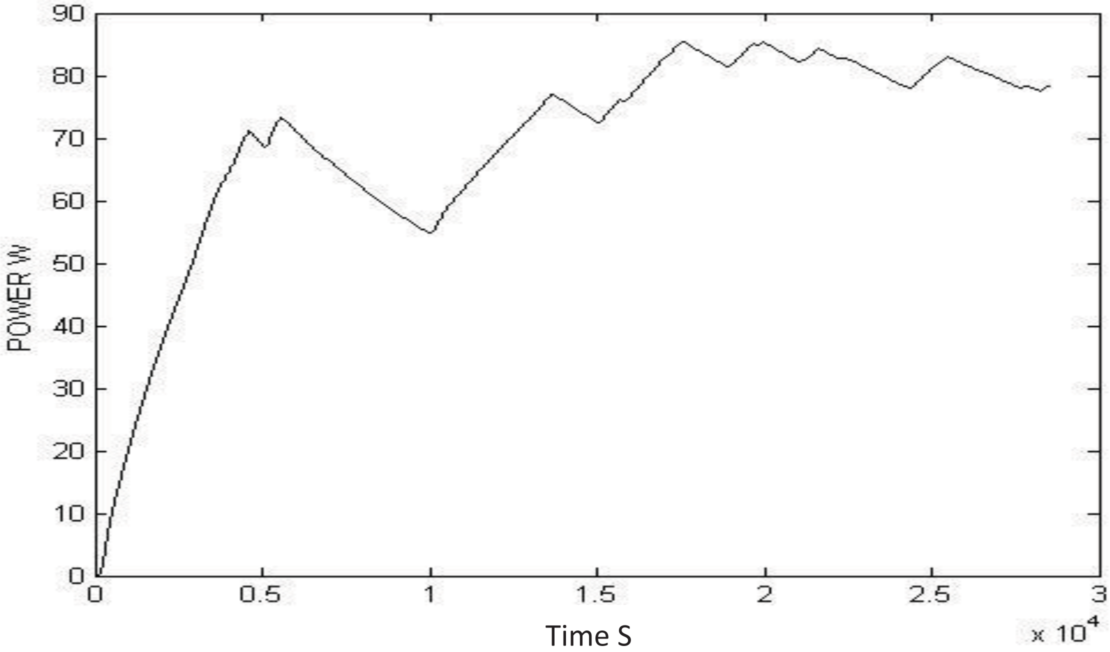


Figure 11.2 The output power from the TEG system with a DC/DC converter can be seen in the upper figure. The configuration is 6 modules in series and 12 modules in parallel. The lower figure shows the average power produced during the driving cycle.

Figure 11.3 shows the power delivered from the TEG system without using a DC/DC converter. To achieve the same amount of power as with the converter 12 TEG modules have been put in series and 6 modules are in parallel, to ensure a voltage level high enough to feed the system at all times. This method is much better suited for cars which use a 12 V system.

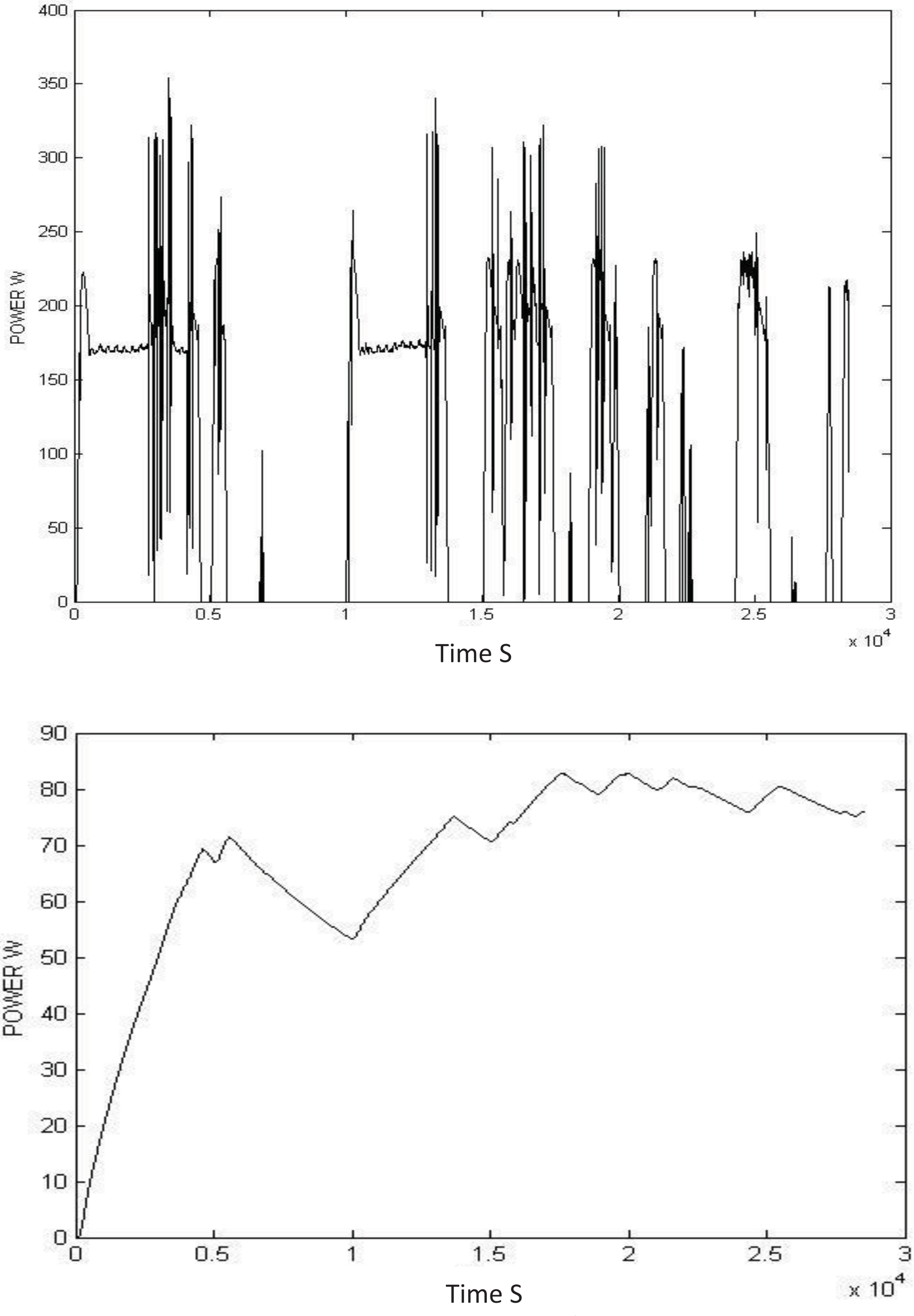


Figure 11.3 The output power from the TEG system without a DC/DC converter is seen in the upper figure. The configuration is 12 modules in series and 6 modules in parallel. The lower figure shows the average power produced over time.

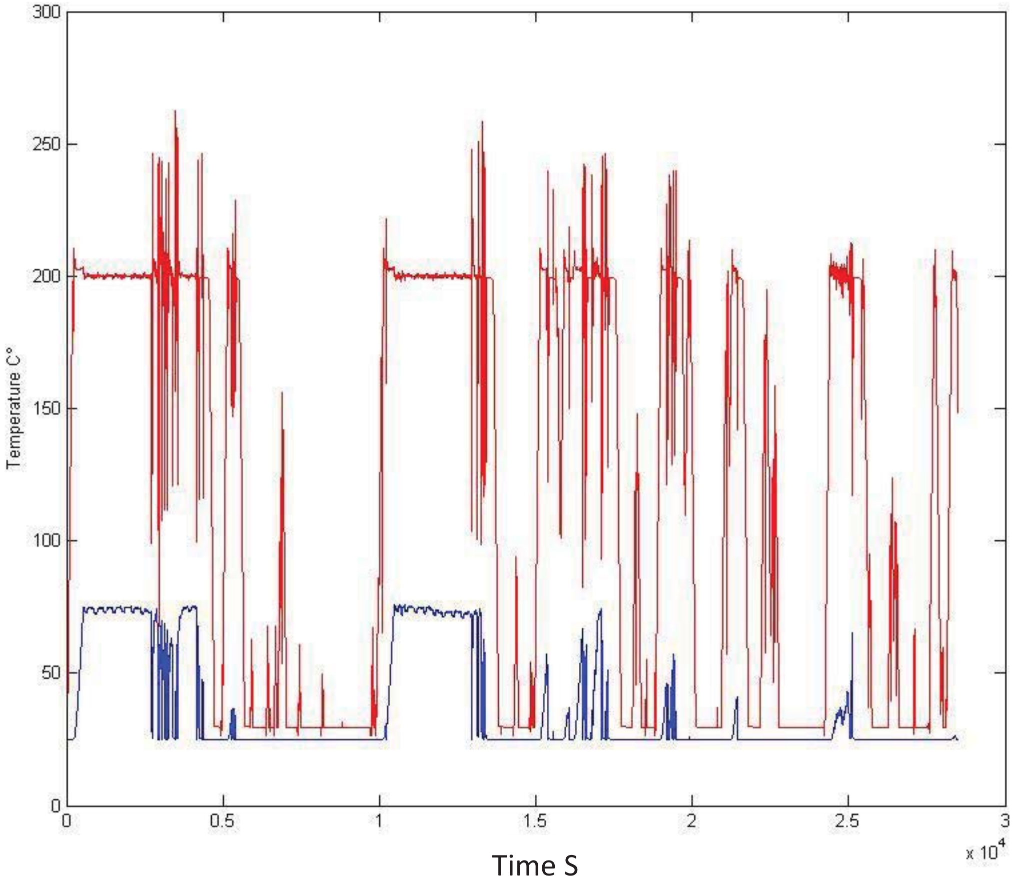


Figure 11.4 Here the cold side (colored blue) and the hot side (colored red) are shown. A bigger temperature difference will produce a larger output power from the TEG system.

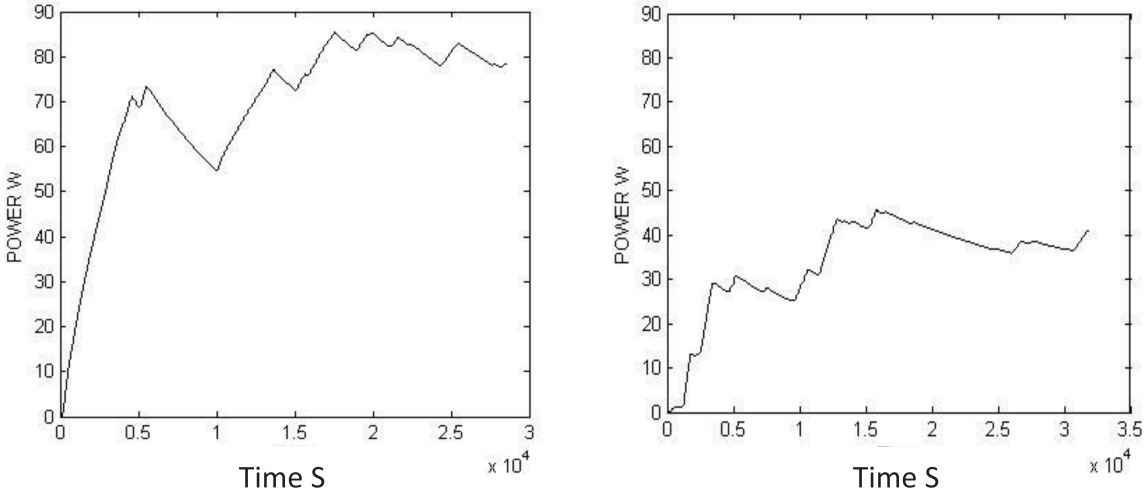


Figure 11.5 Here the output power of the TEG system of two driving cycles is shown. The left figure is based on a driving cycle recorded in Spain and the right figure is based on a driving cycle recorded in Brussels. Both are based on 6 TEG modules in series and 12 in parallel and the TEG system uses a DC/DC converter.

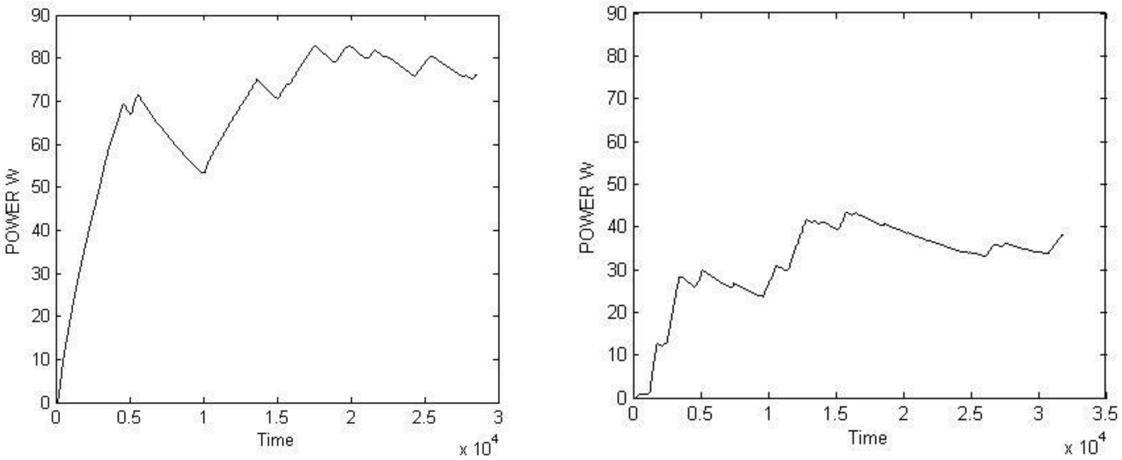


Figure 11.6 Here the output power of the TEG system of two driving cycles is shown. The left figure is based on a driving cycle recorded in Spain and the right figure is based on a driving cycle recorded in Brussels. Both are based on 12 TEG modules in series and 6 in parallel and the TEG system is not using a DC/DC converter.

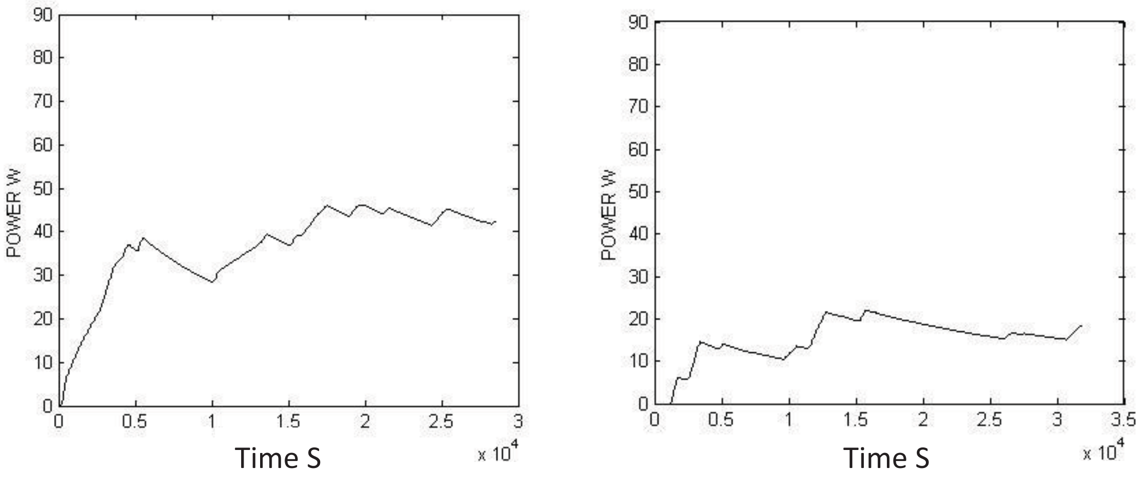


Figure 11.7 Here the output power of the TEG system of two driving cycles is shown. The left figure is based on a driving cycle recorded in Spain and the right figure is based on a driving cycle recorded in Brussels. Both are based on 6 TEG modules in series and 12 in parallel and the TEG system is not using a DC/DC converter. Note that this is the same configuration as with the converter.

11.3 Simulation errors

There are a lot of thermal transients in the model which can affect the simulation result. These transients are developed in the EGR heat exchange model whereas the real system is expected to behave well damped. How big influence this makes on the results is hard to evaluate. One should bear in mind that results are also based on specific TEG modules and on the specifications of the demo converter. If a more well suited converter would be used the difference between the converter and non converter case would increase. If better TEG modules were to be used even more power would be extracted but the TEG system would cost more.

12. Building the demo converter.

For demo purpose a 220 W switching DC/DC converter was constructed. Building a converter serves two purposes; to see what kind of obstacles there are when a TEG system actually is implement in a Scania truck and to get a good feeling of how the technology actually works together. The converter was constructed with the following specifications: The input range is between 15 V and 40 V with a switching frequency of 50 kHz. The output voltage is controlled from a pulse width modulation signal and the output range is 26 V to 30 V. The transformer is made to meet the desired specifications. A block diagram shows the different parts that the converter consists of. Complete calculations can be found in appendix. The DC/DC converter output voltage can be controlled by the truck's built in computer commonly known as an ECU. The ECU sends either a 12 volt or 24 volt PWM signal to the converter which translates this into an output voltage.

Figure 12.1 To the left the demo DC/DC converter is shown and to the right the DC/DC converter together with the alternator rig is shown.

13. Full bridge converter for 1kW or more

When it comes to high power DC/DC converters the full bridge is a suitable topology. In contrary to the push-pull converter which was built for the demo vehicle the full bridge is capable to handle power well above 2kW. With careful design it can reach an efficiency of more than 90%. To get best reliability the TEG modules should be configured in a parallel manner as earlier discussed. While the parallel configuration solves the reliability problem two other challenges appear. First of all high current will lead to greater loss within the converter and it will be more difficult to find suitable and cheap components. Secondly the full bridge converter will have a voltage drop over the transistors and diods. The minimum voltage at which the full bridge converter can operate is estimated to be 5V with some precautionary margins. This is calculated by adding the voltage drop over the two active MOSFET transistors and the diods using standard and commercially available components.

To summarize, three factors must be weighed against each other: reliability, efficiency and voltage drop. The voltage drop over the input stage of the converter is a limit we cannot change and therefore a good place to start. The TEG modules output power will fluctuate over time and the working point is highly dependent on the driving cycle of the vehicle. The working point under long haulage driving should not be set below 10V to ensure an active converter throughout the driving cycle. Due to the characteristics of the TEG the current should not reach over 2000/10=200 A since this will result in a peak current within the converter of 3.13x200=626 A. There are transistors that can handle such currents but there will be very large power dissipation even if R_{DSon} is very small.

13.1. Power dissipation and R_{DSon}

To avoid a large current running through one transistor multiple transistors could be placed in parallel. This way the converter will be configured in such manner that R_{DSon}in total is less than the single value of each transistor. This reduces the dissipation in the transistors and also the current through each component. The result is a greater freedom when it comes to choosing components as well as much less heat dissipation. Together with a snubber network connected to the transistor a very high efficiency is achieved. A snubber network reduces the power dissipation which emerges when the MOSFET is turned on or turned off. There is a limit of how many transistors can be put in parallel and eventually the gate capacitance will become too large for the MOSFET driver to handle.

14. Conclusion

14.1. TEG system including the DC/DC converter

The DC/DC converter can be connected directly to the vehicle's electric system without any modifications of the vehicle. It is important to keep the output voltage of the converter slightly above the output voltage of the alternator. When designing whether to place the TEG modules in series or in parallel one should strive to place as many as possible in parallel. This is to make sure that the source resistance of the TEG unit does not cause bistability in the converter. A parallel system is also less likely to break down. The downside of parallel modules is the high current levels which all components must be able to handle. The minimum input voltage required by the converter is what decides how many modules must be placed in series. The type of DC/DC converter preferably used is the full-bridge topology in some form. It should be designed to handle as low input voltage as possible and to increase efficiency parallel MOSFETs together with snubber networks can be used. This method is to prefer since it will significantly reduce the amount of TEG modules needed in series. Furthermore it will enable the possibility to have a large TEG system with an output power exceeding the power needed of the vehicle. Another advantage is that the converter can produce multiple output voltages.

14.2. TEG system without a DC/DC converter

If no DC/DC converter is present the TEG system power output must be less than what the vehicle power demand is or else the voltage could rise to dangerous levels. When designing the configuration of the modules as few modules in series as possible should be used to get the highest efficiency. A way of avoiding large chains in series is to use a switching network which will switch between for example two different configurations. This way the TEG system will feed the truck with power at quite small voltage levels per TEG modules by connecting a large amount of TEG modules in series but if only one module brakes down the entire chain of modules in series will fail. When there are enough waste heat for the modules to produce a nominal voltage level the switching network will move towards a better configuration with fewer modules in series and more in parallel. This will for sure increase the performance but there is an added complexity.

APPENDIX

A) Demo converter calculations

Input voltage: Vin=20-40V (min 5V per module)
Switching frequency: f=50 000Hz (to meet power criteria)
Switching period: T=20*10^-6s
Output voltage: 26-30V
Power: 220W

Output filter

$$L=\frac{0.5\times V_{OUT}\times T}{I_{ON}}=\frac{0.5\times 30\times 20\times 10^{-6}}{(220/30)}=40\mu H$$

$$C=\frac{80\times 10^{-6}\times dI}{V_r}=\frac{80\times 10^{-6}\times 2\times (220/30)\times 0.1}{0.05}=2200\mu F$$

Bought and used values are 25µH and 2200µF

Wire

$$Circ.mil.req=\frac{500\times 0.98\times P_{OUT}}{V_{DC\min}}=5390$$ Wire no 13: 6.57Ω/km

$$Circ.mil.req=500\times 0.632\times I_{DC}=500\times 0.632\times 220/30=2317$$ Wire no 17: 16.61Ω/km

$$N_P=\frac{(V_{DC\min}-1)(0.8\times T)\times 10^8}{2\times A_e\times dB}=\frac{(20-1)(0.8\times 20\times 10^{-6})\times 10^8}{2\times 2.11\times 3200}=2.25$$

$$N_S=N_P\times\frac{\frac{V_{OUT}\times T}{2\times T_{ON}}+0.5}{(V_{DC\min}-1)}=2.25\times\frac{\frac{30\times 20\times 10^{-6}}{2\times 0.8\times 20\times 10^{-6}/2}+0.5}{(20-1)}=4.44$$

Bought and used wire is copper litz wire of the type “120”. AWG 13 is roughly 3 Litz wire in parallel and AWG 17 is just a single Litz wire.

Transformer radiated heat

Core: ETD49 ~900W 3F3 @ 50kHz

$$70\times 10^{-3}W/cm^3\times 24.2cm^3=1.7W$$

$$P_{TRAMSFORMERcopperloss}=I^2{}_{rms}\times R_{DC}=10.84^2\times(16.61+6.57)/1000=2.7\text{W}$$

$$R_{AC}=\kappa\times R_{DC}=1.70\times 0.77+1.20\times 1.95=3.7W$$

This is not entirely true since litz wire has been used and the total transformer loss is less than 10W.

Transistor and snubber (with no resistor)

$$V_{stress} = 2.6 \times V_{DC} = 2.6 \times 40 = 104V$$

$$I_{PFT} = \frac{3.13 \times P_O}{V_{DC\min}} = \frac{3.13 \times 220}{20} = 34.3A$$

$$C1 = \frac{I_P \times t_f}{2 \times 2 \times V_{DC\max}} = \frac{34.43 \times 74 \times 10^{-9}}{2 \times 2 \times 40} = 16nF$$

$$L1 = \left(\frac{F_r}{2\pi}\right)^2 \div C1 = \left(\frac{0.9 \times 74 \times 10^{-9}}{2\pi}\right)^2 \div 16 \times 10^{-9} = 11nH$$

$$P_{LOSSTRANSISTOR} = \frac{(I_P/2) \times (2 \times V_{DC\max}) \times t_f}{6 \times T} = \frac{(34.43/2) \times (2 \times 40) \times 120 \times 10^{-9}}{6 \times 20 \times 10^{-6}} = 1.5W$$

Input filter (LC-filter)

Crossover frequency should be at a low frequency; in this case it is 355Hz.

$$\omega = \frac{1}{\sqrt{LC}} = 2\pi \times 355Hz$$

$$LC = \left(\frac{1}{2\pi \times 355}\right)^2 = 2 \times 10^{-7}$$

With 4.8Ω of source resistance in mind:

$$C = 2020\mu F$$

$$L = 100\mu H$$

Feedback, type III error amplifier {15}

$F_{CO} = f_{switching} \times 0.2$=50000*0.2=10kHz

$K = \frac{F_{CO}}{F_Z} = \frac{F_P}{F_{CO}}$ $F_Z = 2kHz$ and $F_P = 50kHz$

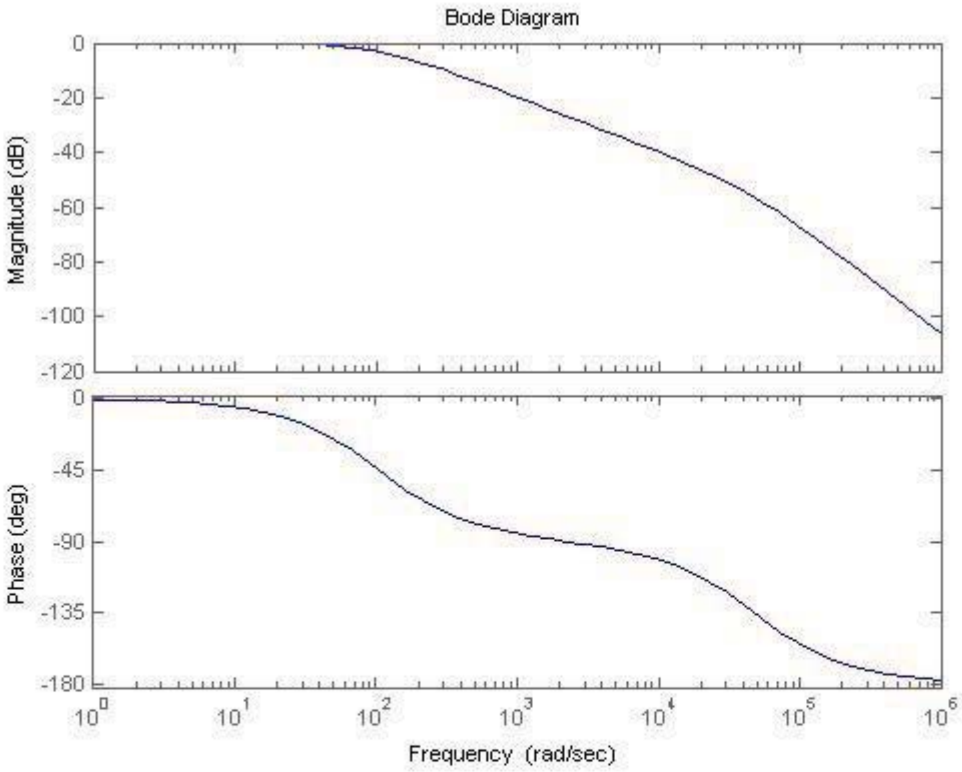
$R_1 = 1k\Omega$ and $R_2 = R_1 \times gain = 1000 * 32 = 32k\Omega$

$F_Z = \frac{1}{2\pi R_2 C_1} \rightarrow C_1 = \frac{1}{2\pi R_2 F_Z} = 2.5 \times 10^{-9}$ F

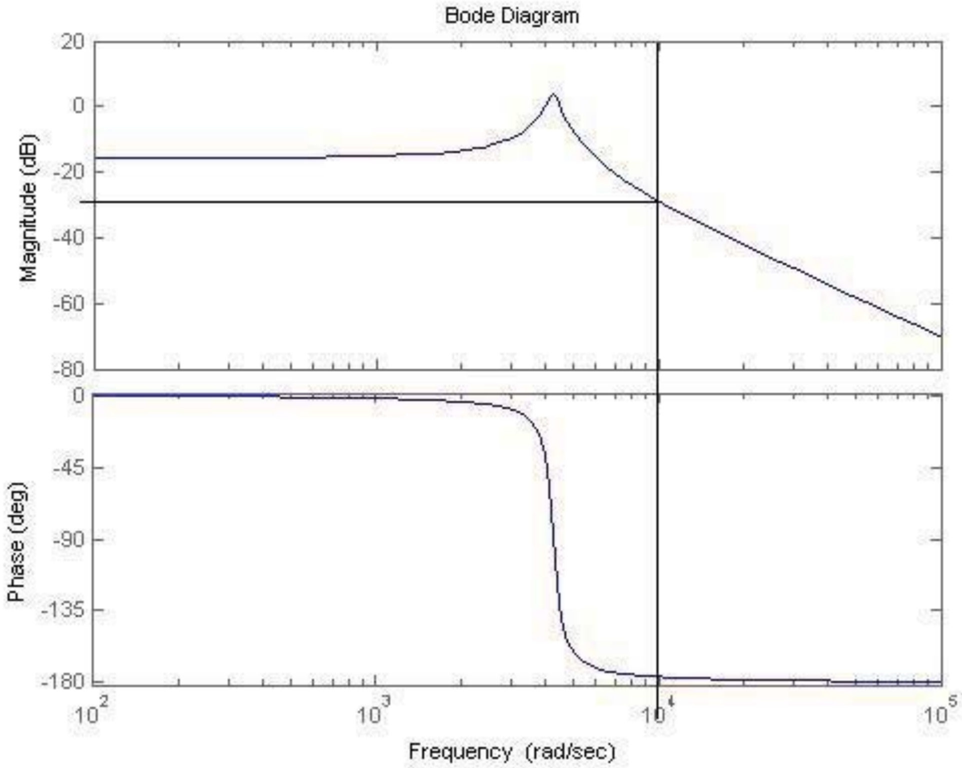
$F_Z = \frac{1}{2\pi R_1 C_3} \rightarrow C_3 = \frac{1}{2\pi R_1 F_Z} = 80 \times 10^{-9}$ F

$F_P = \frac{1}{2\pi R_2 C_2} \rightarrow C_2 = \frac{1}{2\pi R_2 F_P} = 9 \times 10^{-11}$ F

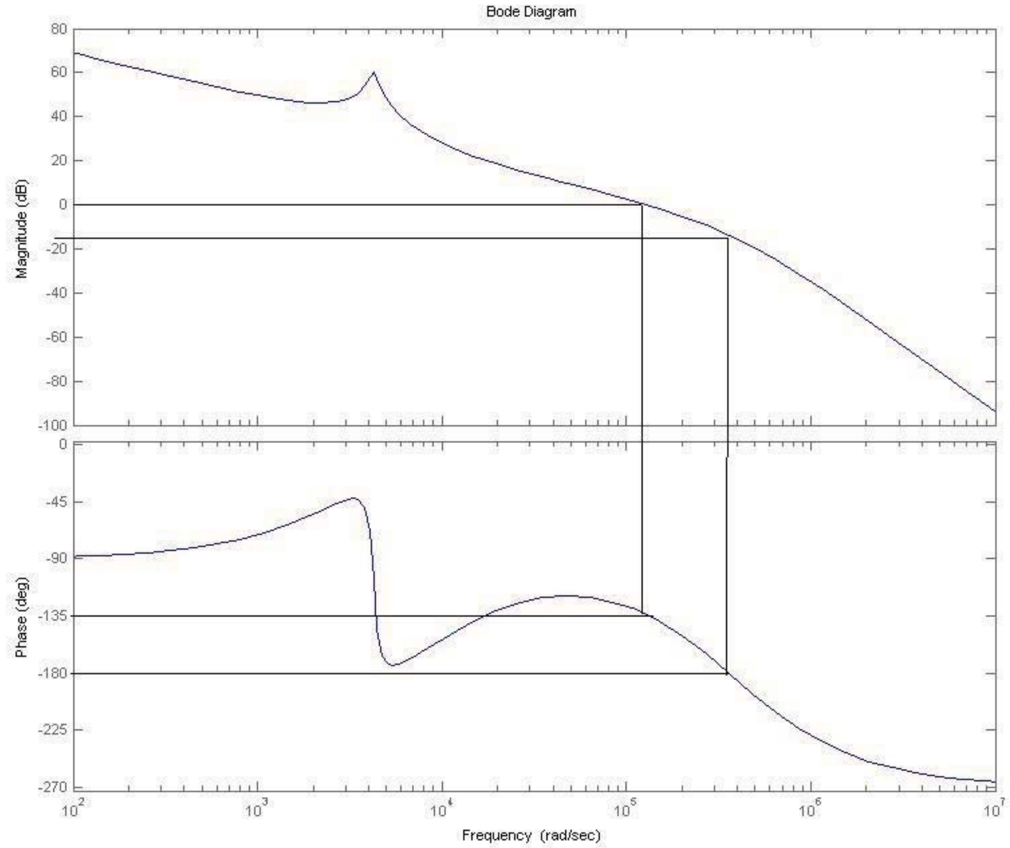
$$F_P = \frac{1}{2\pi R_3 C_3} \rightarrow R_3 = \frac{1}{2\pi C_3 F_P} = 40\Omega$$



Input filter with source resistance of 4x1.2=4.8Ω, L=100µH and C=2020µF



Output filter with diod resistance L=25µH and C=2200µF
Increase ~30dB to put cut off at 10kHz



Type 3 EA: R1=1kΩ, R2=32kΩ, R3=40Ω. C1=70nF, C2=3.5nF, C3=250pF
This gives a phase margin of 45° and a gain margin of 15dB. The values have been slightly enhanced to give even better feedback performance.

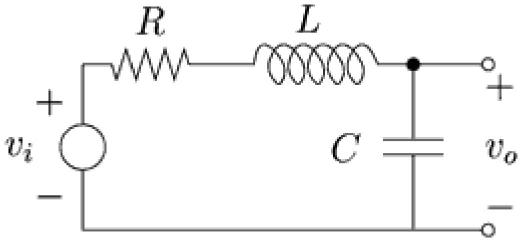
B) Stable feedback

The input filter consists of a RLC network. The resistance is of course not desirable but unavoidable since it is the source resistance of the TEG.

The transfer function of an RLC network is (Vi to Vo)

$$H_{IN}\langle s\rangle = \frac{1}{LCs^2 + CRs + 1}$$

when we have the following setup

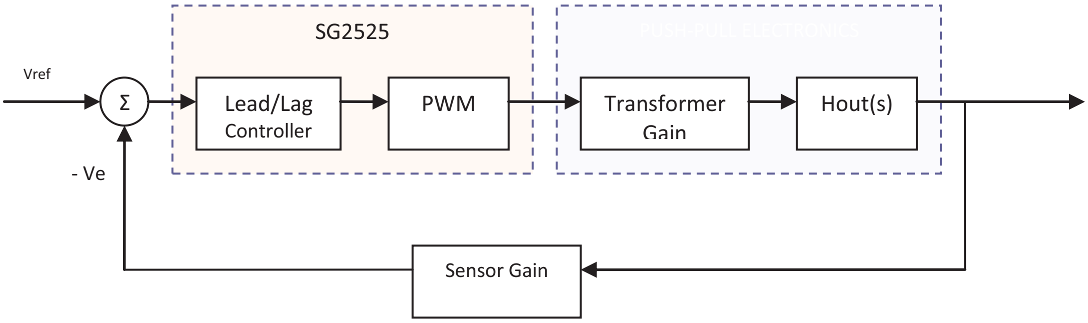


The output filter is a LC filter which yields the following transfer function.

$$H_{IN}\langle s\rangle = \frac{1}{LCs^2 + 1}$$

This means that a resonance frequency can be found at $f = \frac{1}{2\pi\sqrt{LC}}$

The transformer placed in between the two filters can be viewed as a simple gain function.



The complete control system

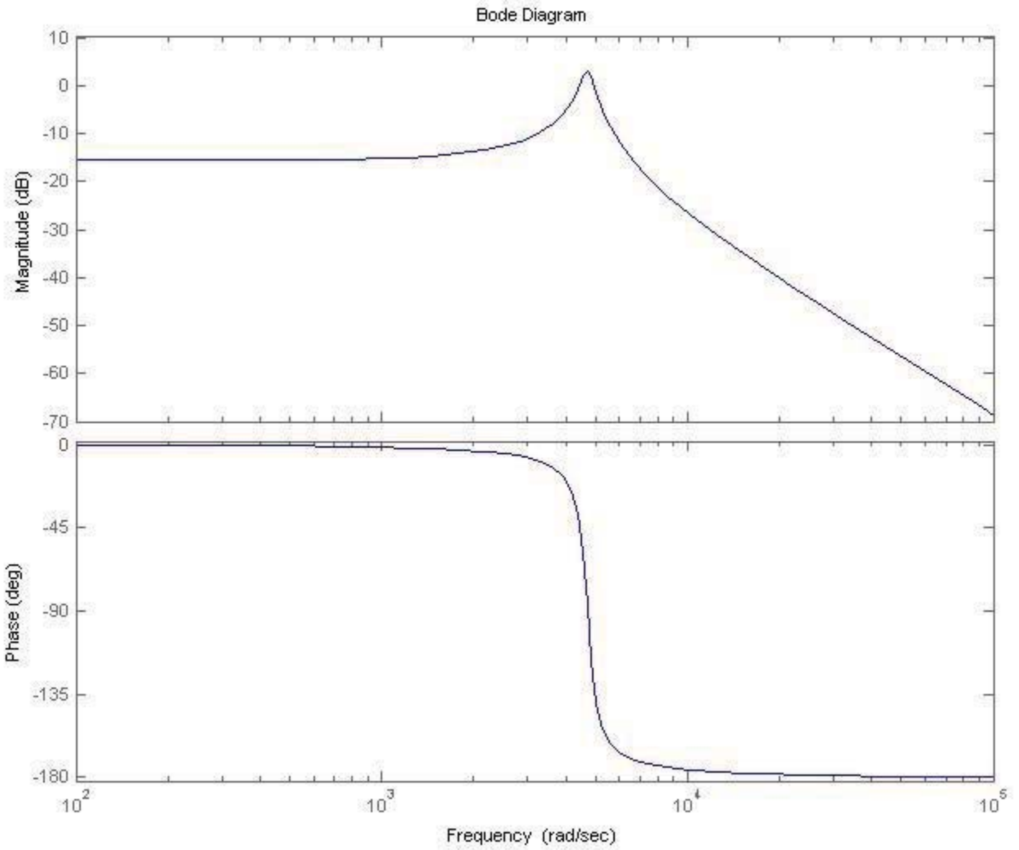
The controller is a type III error amplifier. This kind of amplifier is required when the slope is 40dB/decade after the cross over frequency.

To be able to analyze the system the transfer function of the type 3 error amplifier must be derived.

$$H_{PI}\langle s\rangle = \frac{Z2}{Z1} = \frac{((\frac{1}{C_2 s}) + R_2)^{-1} + (\frac{1}{C_1 s})^{-1})^{-1}}{R_1} = \frac{\left(\frac{C_2 s + C_1 s(1 + R_2 C_2 s)}{1 + R_2 C_2 s}\right)^{-1}}{R_1} = \frac{1 + R_2 C_2 s}{R_1((C_1 + C_2)s + R_2 C_1 C_2 s^2)}$$

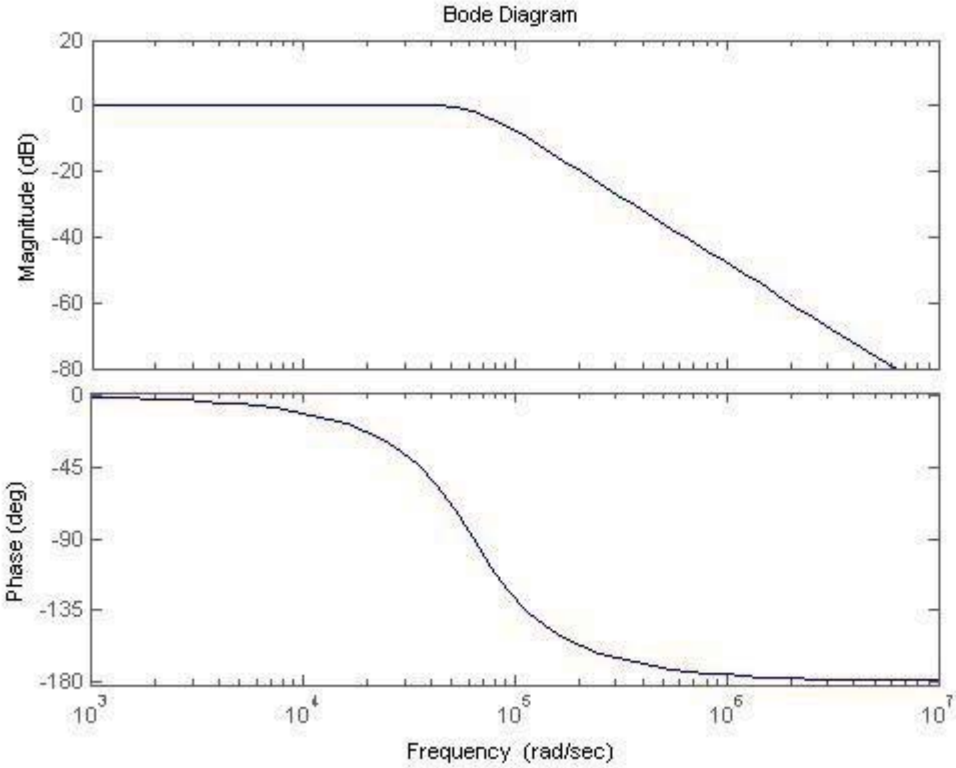
Choosing the cross over frequency at 20% of switching frequency $f_{CO} = 50000 * 1/5 = 10000 Hz$

Now looking at the bode plot from the output filter, figure 4, we can see that we need to boost with 60dB in order to get the cross over freq at 0dB. Sensor gain is 1/6 to ensure that the feedback is <5V.

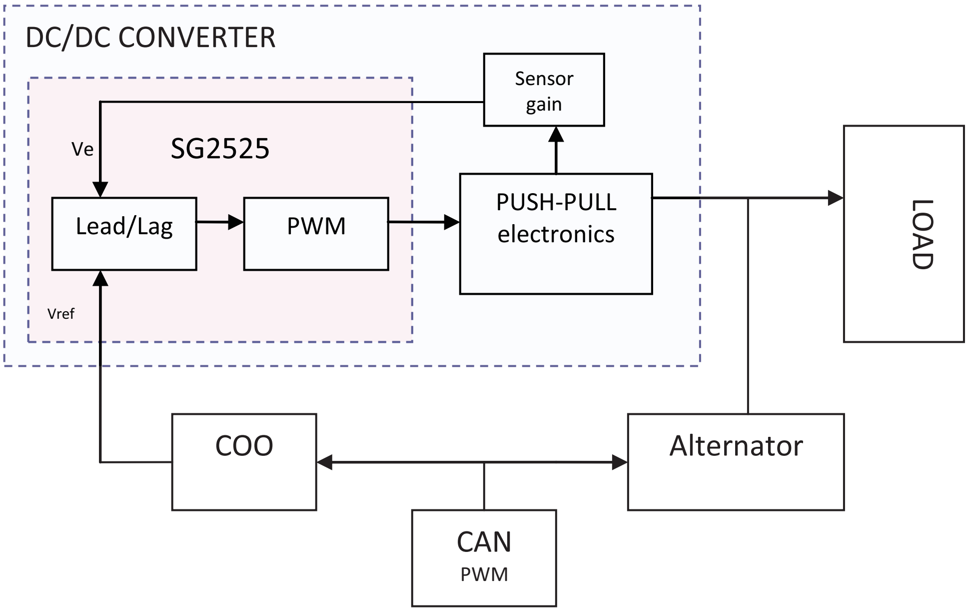


The output filter with sensor gain.

Keeping $f_{CO} < f_{INPUTresonance}$ will result in a positive phase margin, ensuring stability[1]. The input filter does not need damping since the high source resistance will act as a damper.



C) System overview



D) Pulse width modulated signal to analogue signal

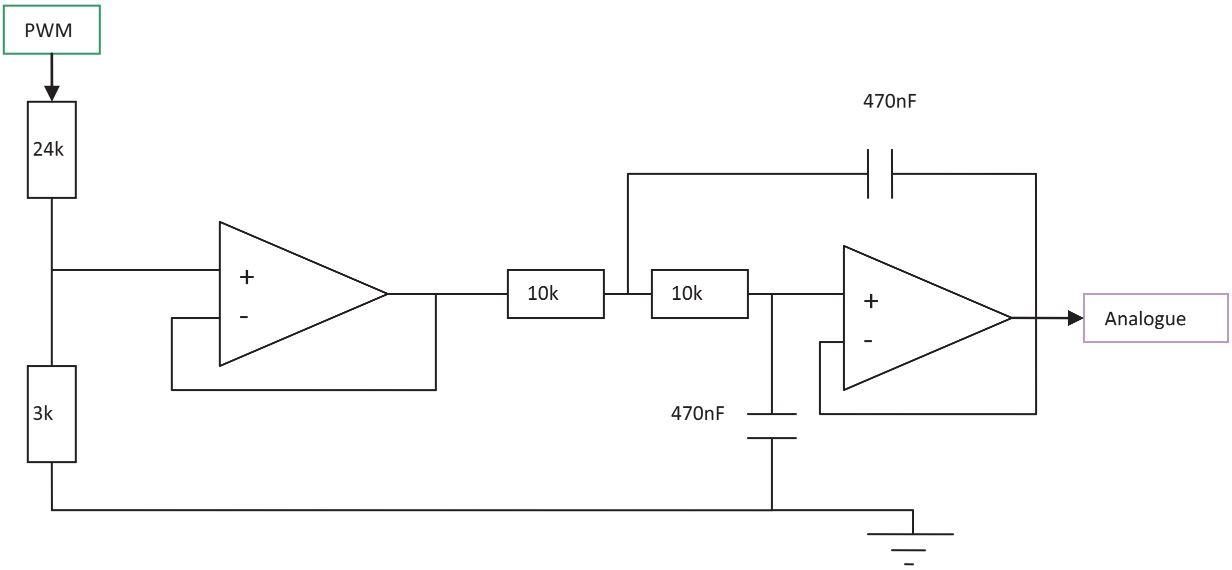
To be able to control the DC/DC converter via the coordinator a circuit must be constructed so that a PWM signal is transformed into an analogue signal fed into non inverted input of the regulator of the converter.

The coordinator produces a 400Hz signal with maximal amplitude of 30V (minimum 24V). The circuit consists of two parts; First the PWM is scaled down with a voltage follower down to roughly 3V. Secondly, the scaled PWM is filtered through a Sallen Key low pass filter.

The duty cycle will determine the voltage that will be fed into the non inverted input and the DC/DC converter output can be calculated via the following formula: $V_{OUT} = V_{SYSTEM} \times 0.4 \times D \times K$ where V_{OUT} = DC/DC output voltage, V_{SYSTEM} = ECU working voltage, D=duty cycle in percent and K= (calibrating factor to correct measured discrepancy on converter) .

The operational amplifier used is LM2904 and a supply voltage of minimum +15V should be used.

To ensure that the converter will feed the vehicle system an offset must be added.



Colors used represent the colors used on actual circuit, e.g. the PWM signal from the ECU should be connected to the green cable.

E) PUSH-PULL DESIGN FORMULAS {15}

Filter design (SPSD p.65)

$$L = \frac{0.5 \times V_{OUT} \times T}{I_{ON}}$$

$$T = \frac{1}{f_S}$$

and

$I_{DC} = I_{MIN} = 0.1 \times I_{ON}$, Ion is nominal output current

$$C = \frac{80 \times 10^{-6} \times dI}{V_r}$$

$dI = 2 \times I_{DC\min} = 2 \times I_{MIN} = 2 \times 0.1 \times I_{ON}$ inductor ramp amplitude, V_r is the voltage ripple peak2peak

Transformer heat loss (SPSD p.272)

$$P_{TRANSFORMERloss} = Corematerial \times volume$$

Core material is chosen and volume is set by power output boundaries.

Transformer core

Select from table depending on output power requirement

Transformer copper, skinning & proximity losses (SPSD p.298, p.304)

$$P_{TRAMSFORMERcopperloss} = I^2{}_{rms} \times R_{DC}$$

R_{DC} = wire resistance and

$$I_{rms} = 0.632 \times \frac{1.56 \times P_O}{V_{DC\min}}$$

$$R_{AC} = \kappa \times R_{DC}$$

κ is retrieved from table 7.6 or table 7.7

$$\frac{h \times \sqrt{F_l}}{\Delta}$$

See figure 7.9 p.313 for

values. h= 0.866d,

Δ =skindepth,

$F_l = \frac{N_l \times d}{w}$

d= wire diameter,

w=layer width,

N_l =number of turns per layer

Primary turns selection (SPSD p.53-54)

$$N_P = \frac{(V_{DC\min} - 1)(0.8 \times T) \times 10^8}{2 \times A_e \times dB}$$

T=switcing period, A_e =iron area, dB flux change = 3200 G

Secondary turns selection (SPSD p.39-40)

$$N_S = N_P \times \frac{\frac{V_{OUT} \times T}{2 \times T_{ON}} + 0.5}{\left(V_{DC\min} - 1\right)}$$

because $T_{ON} = 0.8 \times T / 2$ On time no more than 80% to guarantee flux reset

$$V_{OUT} = \frac{\left[\left(V_{DC\min} - 1\right)\left(\frac{N_S}{N_P}\right) - 0.5\right] \times 2 \times T_{ON}}{T}$$

Primary wiresize (SPSD p.57-58)

$$Circ.mil.req = \frac{500 \times 0.98 \times P_{OUT}}{V_{DC\min}}$$

500 circular mils per rms ampere is chosen but as low value as 300 might work. 1circ.mil=area of circle with 1/1000 of an inch in diameter

Secondary wiresize

$$Circ.mil.req = 500 \times 0.632 \times I_{DC}$$

$I_{DC} = P_{OUT} / V_{OUT}$

Transistor (SPSD eq 2.15)

$V_{stress} = 2.6 \times V_{DC}$ Conservative stress calculation

$$T_{ON} = \frac{0.8 \times T}{2}$$

@50kHz

$$T_{ON} = \frac{0.8 \times 20 \times 10^{-6}}{2} = 8 \times 10^{-6}\,\mathrm{S}$$

$$I_{PFT} = \frac{3.13 \times P_O}{V_{DC\min}}$$

I_{PFT} is peak current.

Assuming 80% efficiency (SPSD Eq.2.28)

Snubber network (SPSD p. 419)

$$C1 = \frac{I_P \times t_f}{2 \times 2 \times V_{DC\max}}$$

I_P is the peak current at turnoff $I_P = \frac{3.13 \times P_O}{V_{DC\min}}$ (SPSD p.415). t_f is transistor fall time

$$3 \times R1 \times C1 = t_{ON\min}$$

$t_{ON\min} = T / V_{INflux}$ Where V_{INflux} is the total flux from nominal input on the form 1.x

$$P_{LOSSR1} = \frac{0.5 \times C1 \times (2 \times V_{DC\max})^2}{T}$$

$$P_{LOSSTRANSISTOR} = \frac{(I_P / 2) \times (2 \times V_{DC\max}) \times t_f}{6 \times T}$$

Snubber network –nondissipative

(SPSD p.421)

$$L1 = \left(\frac{1}{2 \times F_r \times \pi} \right)^2 \div C1$$

Replace R1 with L1.

$$F_r = \frac{1}{0.9 \times t_{ON\min}}$$

The constant 0.9 is somewhat arbitrary chosen. F_r should be ”slightly less” than $t_{ON\min}$

LC input filter design

$$f = \frac{1}{2\pi \times \sqrt{LC}}$$

f=20% - 25% of switching freq.

$$H\langle s \rangle = \frac{1}{1 + CR_S s + LCs^2}$$

Transfer function with source resistance, R_S .

PWM module

SG2525 or UC2525AN

No need to use gate driver with these modules

Feedback EA Type II

(SPSD p.449, EA type 2)

$$F_{CO} = \frac{1}{2\pi \times \sqrt{L_{OUT}C_{OUT}}}$$

$L_{OUT}C_{OUT}$ are the values from the output filter

$$F_{esr} = \frac{1}{2\pi \times R_{esr}}$$

R_{esr} is the resistance in the conductor $\sim 65 \times 10^{-6}\,\Omega$

$F_{CO} / F_{esr} = \{table 12.2\}$ To see phase lag

360-45-phase lag $= \{table 12.1\}$ Use table 12.1 to calculate K

$$F_Z = \frac{1}{2\pi \times R2 \times C1}$$

Where $F_Z = F_{CO}$/K

$$F_{PO} = \frac{1}{2\pi \times R2 \times C2}$$

Where $F_{PO} = F_{CO} \times K$

Feedback EA Type II (SPSD p.456, EA type 3)

$$F_{CO} = f_{switching} \times 0.2$$

$$K = \frac{F_{CO}}{F_Z} = \frac{F_P}{F_{CO}}$$

K= 2, 3, 4, 5, 6 if lag is 196, 164, 146, 136, 128

$R_1 = 1k\Omega$ Arbitrary chosen

$R_2 = R_1 \times gain$ gain= gain needed to lift output filter @ F_{CO} to 0 dB

$$F_{Z1} = \frac{1}{2\pi R_2 C_1}$$

$$F_{Z2} = \frac{1}{2\pi R_1 C_3}$$

$$F_P = \frac{1}{2\pi R_2 C_2}$$

$$F_{Z3} = \frac{1}{2\pi R_3 C_3}$$

Table 1

converter output A	Load Ω	converter input V	TEG output A	Vref V	Current needed by the system A	system V	Converter output V	Generator output A
0	7	25	0	2,3	3,73	29,2	28	3,73
0	7	25	0	2,325	3,73	29,2	28,3	3,73
0,1	7	25	0,2	2,35	3,69	29	28,6	3,59
3,87	7	25	5,4	2,374	3,65	28,8	28,888	-0,22
3,93	7	25	5,5	2,402	3,81	29,2	29,224	-0,12
3,97	7	25	5,6	2,424	3,84	29,4	29,488	-0,13
4,01	7	25	5,8	2,451	3,87	29,7	29,812	-0,14
3,99	7	25	5,7	2,451	3,86	29,6	29,812	-0,13
0	10	25	0	2,3	2,92	29,2	28	2,92
0	10	25	0	2,325	2,91	29,2	28,3	2,91
0,07	10	25	0,01	2,35	2,88	29,1	28,6	2,81
3,05	10	25	4,3	2,374	2,84	28,8	28,888	-0,21
3,09	10	25	4,4	2,401	2,87	29,2	29,212	-0,22
3,1	10	25	4,4	2,423	2,89	29,4	29,476	-0,21
3,15	10	25	4,5	2,451	2,92	29,8	29,812	-0,23
3,11	10	25	4,5	2,451	2,92	29,7	29,812	-0,19

The system is representing the vehicle

Vref is a converter setting

Generator delivers 28.0 V (PWM controlled)

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