Misalignment Tolerant Inductive Power Transfer (IPT) Systems

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Executive Summary

This report describes the design of the inductive power transfer system. The IPT system needs to charge the battery of the car with maximum efficiency and constant power. A buck converter is designed to achieve these requirements. The buck converters components are calculated, simulated and an exhaustive power loss calculation of these components is given.

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1 Problem Definition

1.1 Problem Scope

With all the new technological improvements in the electric vehicles world, different methods for charging cars are needed. Currently, electric vehicles are charged at EV charging stations through cable connections. New charging applications for these vehicles are required to make charging easier. Inductive power transfer systems are gaining popularity in the electric vehicle world. By leaving the car on a parking spot, it can be charged without the use of any cables. An important issue is the efficiency of the charging system. The position of the car while charging has a huge impact on how efficient the vehicle is charging. A perfectly working IPT system would be able to charge an electric vehicle with maximum efficiency and at certain power rate at any car position.

In this project, the focus will lay on designing an additional system to make an already existing IPT system charge the battery of an electric vehicle with maximum efficiency. In the next section a more detailed description of the problem and focus area of this system will be given.

1.2 Technical Review

The basic principle of an IPT system is shown in figure 1.1. By applying an alternating voltage on the primary coil and by bringing the secondary coil close to the primary coil, a current can be induced in the secondary coil. This induced current can flow through a certain load, which enables power to be transfered to the secondary side of the coil.

By installing the secondary coil at the bottom of the vehicle and the primary coil in the ground, as shown in figure 1.2 (a), the battery inside the electric vehicle can be charged. As mentioned in the previous section, the position of the car with respect to the coil in the ground affects the efficiency of the charging system.

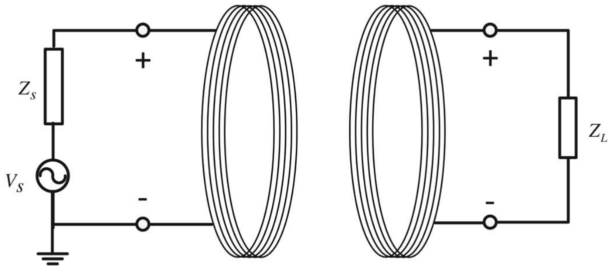
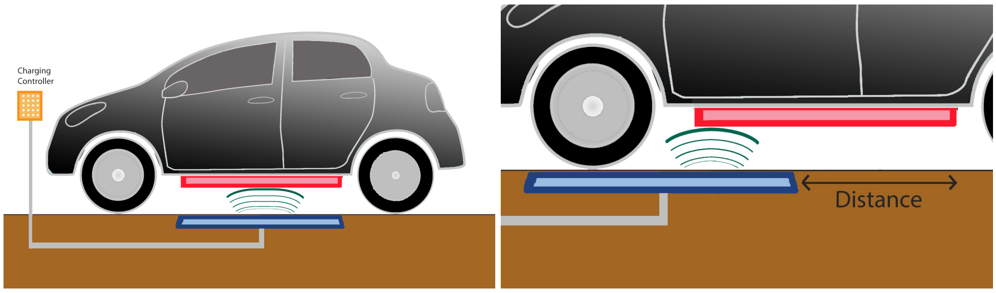


Figure 1.1: Inductive power transfer system configuration

In figure 1.2 (b) a misalignment in the x-direction is shown. Note that misalignment can also occur in the y-direction. Furthermore, the height of the car and thus the height of the coil (z-direction) can affect the efficiency as well. Increasing the misalignment distance in both x and y direction and the height between the two coils will result in low efficiency power transfer.



(a) Perfect aligned (b) Misaligned

Figure 1.2: Wireless charging setup

While the coils are at misaligned position, the battery needs to be charged with maximum efficiency. Several coil designs and control schemes are already proposed in literature [1] [2] [3]which deal with misalignment related designs for IPT systems.

In figure 1.3 the configuration of the already existing IPT systems is shown. The power supply on the the primary side is a DC voltage source. This DC voltage is converted to AC by an inverter to enable inductive power transfer. An AC current will be induced in the secondary coil. Since the battery on the secondary side needs to be charged with a DC voltage and DC current, the induced current needs to be rectified to DC by an AC-DC rectifier.

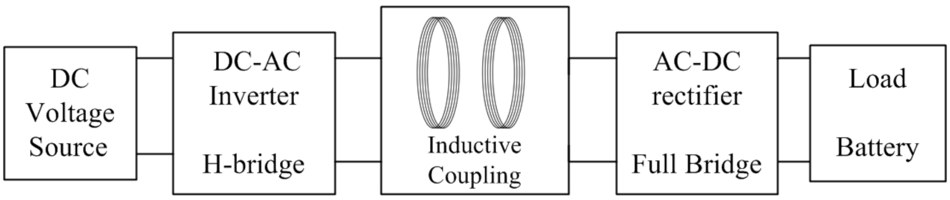


Figure 1.3: Inductive power transfer system configuration

In figure 1.4 a more specified configuration of the IPT system that is already been built is given.

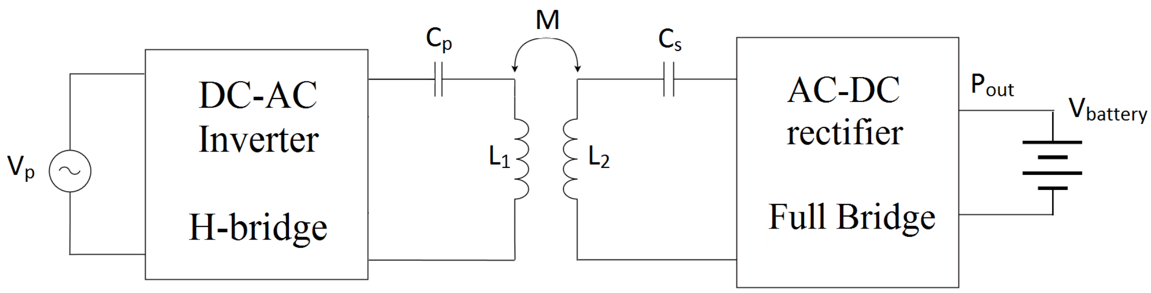


Figure 1.4: More specified configuration of the IPT system

As shown, both inductors with compensating capacitors are included, as well as the voltage source on the primary side and the battery on the secondary side.

The parameters of the circuit components of figure 1.4 are given in the following table:

Variable	**Value**	**Description**
$V_{battery}$	200V	The nominal battery voltage converter
P_{out}	8 kW	The power output of the battery
f	85 kHz	frequency of the primary voltage source (V_p)
k	$0.08 \leq k \leq 0.2$	The coupling coefficient range
L_1	200μH	Inductance at the primary side of the transformer
L_2	200μH	Inductance at the secondary side of the transformer
C_p	$\frac{1}{\omega^2 * L_1}$ F	Capacitance at the primary side of the transformer
C_s	$\frac{1}{\omega^2 * L_2}$ F	Capacitance at the secondary side of the transformer

Table 1.1: The design requirements

The mutual inductance M is equal to $k\sqrt{L_1 L_2}$. Note that since the inductance values and the coupling coefficient are known, the mutual inductance can be derived accordingly.

The next section gives a detailed description of the design requirements.

1.3 Design requirements

The following requirements are given by Soumya Bandhopadhyay.

1. The battery has to be charged with a constant power of 8 kW.
2. Additional systems that will be designed need to have minimum losses when implemented and used for the IPT system that has already been built.
3. Charging the battery must happen with maximum efficiency, that is, the ratio between P_{out} and P_{in} must be as close as possible to the value of 1.
4. Requirements 1 and 3 must both be met for misalignments with a coupling coefficient of $0.08 \leq k \leq 0.2$.

2 Design description feedback

2.1 Overview

The IPT system is able to charge the battery of an electric car without the use of a cable. The wireless charging of the battery will be done, regardless of the misalignment between the two coils, with the highest efficiency possible.

In figure 2.1 the schematic of the system can be seen. As explained in chapter 1, a system needs to be designed to make sure that battery can be charged with maximum efficiency. As shown in figure 2.1, the rectifier and the battery on the secondary coil will together be modeled as a load resistance R_{load}. In the next section, the best R_{load} value will be determined. Furthermore, a system needs to be designed to maintain that value at the input terminals of the rectifier. The main focus of this subgroup is to design such a system.

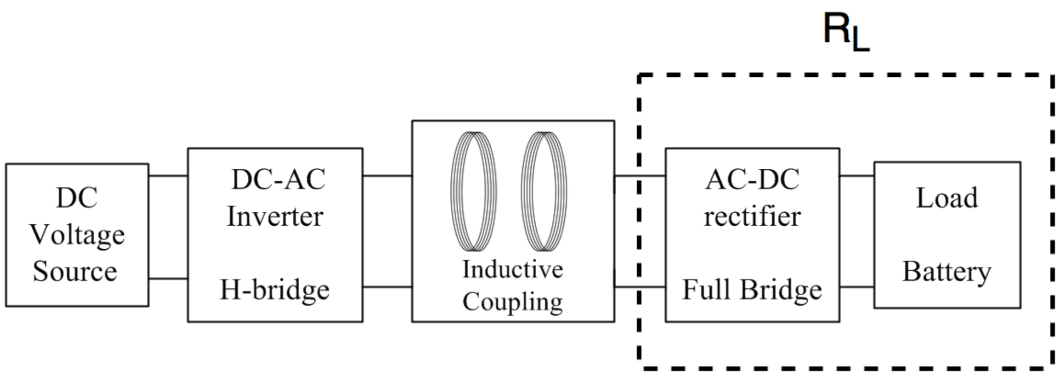


Figure 2.1: Block diagram of the system with R_{load}

2.2 Detailed description

In figure 2.1 the block diagram of the system can be seen. In the following sections each separate block, except for the car battery, will be discussed in detail. The understanding of these blocks is of great importance to come up with a solution to solve the inefficient charging problem of the battery.

2.2.1 DC Voltage Source and DC-AC Inverter

The inverter is already designed by the PhD group. This section will only give a brief explanation of the basics of this inverter.

The inverter can be seen in figure 2.2. The DC voltage at the input will be converted to an AC voltage at the output. If the switches S1 and S3 are switched on, the switches S2 and S4 are switched off and vice versa. This output voltage (u_1) will be a square wave with amplitude U_{dc}. The output voltage will be modeled as a sine wave with a rms value given by equation 2.1. This equation can be derived by using the Fourier series [4].

$$u_{1rms} = \frac{2\sqrt{2}}{\pi} \times U_{dc} \tag{2.1}$$

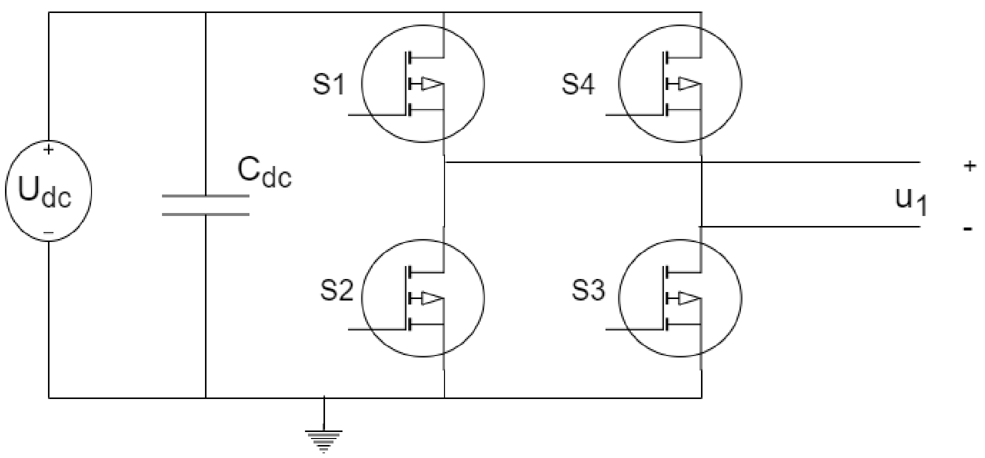


Figure 2.2: The inverter With DC input voltage U_{dc}

2.2.2 Inductive coupling and compensation

In figure 2.3 the two coils with the compensation can be seen, which is the circuit topology of the diagram given in figure 2.1. V_p is hereby the AC output voltage (u_1) as can be seen in figure 2.2. The reason why R_{load} in figure 2.1 is modeled as an resistor in figure 2.3 will become clear further down in this section.

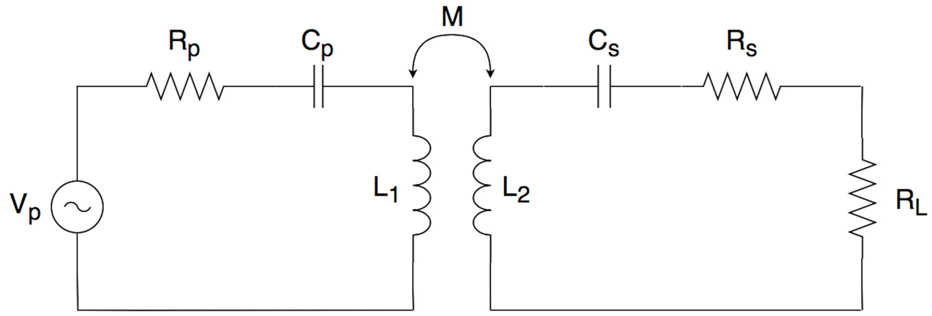


Figure 2.3: The circuit model with voltage source AC

Due to the AC voltage, a time-varying current will flow into inductor L_1, and as a result, this will create a varying flux around this inductor. According to Faraday's law, the voltage induced over the inductor will be equal to equation (2.2). Equation (2.2) can also be written as equation (2.3).

$$v = N\frac{\mathrm{d}\phi}{\mathrm{d}t} \tag{2.2}$$

$$v = L\frac{\mathrm{d}i}{\mathrm{d}t} \tag{2.3}$$

Two coils can be placed close to each other, as in the case of L_1 and L_2. The time-varying current through inductor L_1 will cause a flux which will link both coils, which induces a voltage at L_2. This induced voltage V_2 is given by equation (2.4). M is called the mutual inductance and is given by equation (2.5). This can be written as equation (2.6), since L_1 and L_2 are equal (see table 1.1).
The k in this equation is called the coupling coefficient, this is the ratio between the linked flux (the flux which will link both coils) and the total flux generated by inductor L_1.

$$v_2 = M\frac{\mathrm{d}i}{\mathrm{d}t} \tag{2.4}$$

$$M = k\sqrt{L_1 L_2} \tag{2.5}$$

$$M = kL \tag{2.6}$$

The capacitors C_p and C_s, with their modeled parasitic resistances R_p and R_s respectively, form the compensation network. Reactive compensation is implemented to ensure that the AC voltage and current are in phase, this will lead to charging the battery with high efficiency [5]. Reactive compensation can be achieved by ensuring that the summation of the impedances of the reactive elements is equal to "0", as can be seen in equation (2.7). Solving equation (2.7) will give an expression for the corresponding capacitor value (see equation (2.8)). The voltage and current will be in phase if C_p and C_s are chosen correctly (with the help of (2.8)). Zero phase shift means that the load (R_L in figure 2.3) is purely resistive [6, chapter 11, p. 471] and, therefore R_{load} in figure 2.1 can be modeled by a resistor (R_L), as can be seen in figure 2.3

$$\frac{1}{j\omega C} + j\omega L = 0 \tag{2.7}$$

$$C = \frac{1}{\omega^2 L} \tag{2.8}$$

2.2.3 Load resistance calculation

The battery of the car can be charged with maximum efficiency. This is the case when R_L (in figure 2.3) is equal to a certain value. This section will give a calculation for this optimal load resistance.

The circuit in figure 2.3 can be converted into the T-equivalent circuit using [6, chapter 13, p. 569]. The result can be seen in figure 2.4.

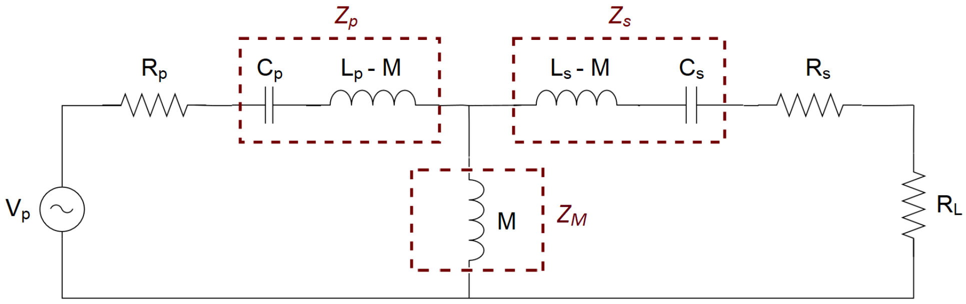


Figure 2.4: The T-equivalent circuit

In figure 2.4, L_p and L_s are equal to the L_1 and L_2 respectively.

This circuit can be simplified to figure 2.5 and the total impedance is equal to equation (2.9), where ω is the angular frequency in rad/s and M is the mutual inductance in Henry. Note that Z_{total} doesn't have any reactive component, since it has all been compensated. In order to calculate the optimal load resistance, the input power and the output power need to be determined.

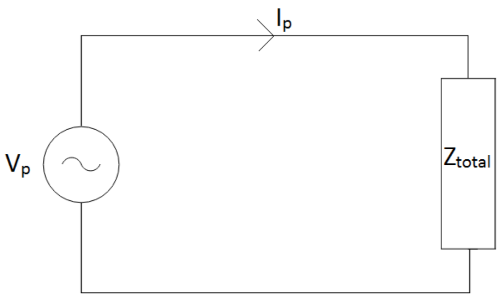


Figure 2.5: Simplified circuit with the total impedance

$$Z_{total} = R_p + \frac{\omega^2 M^2}{R_s + R_L} \tag{2.9}$$

Input power

Since the total impedance is known, the input power can be calculated using the rms input current and the total impedance as can be seen in equation (2.10).

$$P_{in} = |\boldsymbol{I_{p,rms}}|^2 \cdot Z_{total} \tag{2.10}$$

Where $\mathbf{I_{p,rms}}$ is the input voltage in phasor form.
Accordingly, equation 2.10 is equal to equation (2.11):

$$P_{in} = \frac{|\boldsymbol{V_{p,rms}}|^2}{|Z_{total}|^2} \cdot Z_{total} \tag{2.11}$$

where P_{in} is the input real power in Watt, $\mathbf{V_{p,rms}}$ the input voltage in phasor form, with amplitude in rms and Z_{total} the impedance in ohms.

Output power

In order to find the output power (which is the load power), the current through the load resistor R_L needs to be determined (see figure 2.4).

Applying nodal analysis on the circuit given in figure 2.4, the load current $\mathbf{I_L}$ can be expressed by equation (2.12).

$$\boldsymbol{I_L} = \frac{\boldsymbol{I_p} \cdot Z_M}{Z_M + Z_s + R_s + R_L} \tag{2.12}$$

Where both $\mathbf{I_p}$ and $\mathbf{I_L}$ are the currents through the Z_p and R_L in phasor form respectively.

$\mathbf{I_p}$ is given by equation (2.13):

$$\boldsymbol{I_p} = \frac{\boldsymbol{V_p}}{Z_{total}} \tag{2.13}$$

The output power can now be calculated and is given by equation (2.14).

$$P_{out} = |\boldsymbol{I_L, rms}|^2 \cdot R_L \tag{2.14}$$

Efficiency

The efficiency η is calculated by dividing the output power by the input power as can be seen in equation (2.15)

$$\eta = \frac{P_{out}}{P_{in}} \tag{2.15}$$

Substituting all the terms and simplifying eventually leads to equation (2.16).

$$\eta(R_L) = \frac{\omega^2 M^2 R_L}{({R_s}^2 + {R_L}^2 + 2R_L R_s)R_p + \omega^2 M^2 R_s + \omega^2 M^2 R_L} \tag{2.16}$$

Looking at equation (2.16), the only variable that is not fixed is the load resistance. By varying the load resistance R_L the efficiency can be tuned. The next step is to determine for which load resistance the efficiency is at its maximum. In order to do this the derivative of equation (2.16) with respect to R_L needs to be equal to zero (2.17).

$$\frac{d\eta(R_L)}{dR_L} = 0 \tag{2.17}$$

Solving equation (2.17) gives for R_L two expression for the roots. The positive one is the root that is needed and is given by equation (2.18).

$$R_L = \sqrt{\frac{\omega^2 M^2 R_s}{R_p} + {R_s}^2} \tag{2.18}$$

Assuming that $\omega M \gg R_s$ and $R_s = R_p$, the optimal load resistance is given by equation (2.19).

$$R_L \approx \sqrt{\omega^2 M^2} = \omega M = \omega k \sqrt{L_1 L_2} = \omega k L \tag{2.19}$$

So the load resistance for maximum efficiency depends on the mutual inductance (which depends on the position of the car) and the frequency of the primary voltage V_p (figure 2.4).

2.2.4 Basic rectifiers

A rectifier in brief will convert an AC input current into a DC output current. The rectifier is necessary in order to charge the battery of the car with DC current. In this section different rectifier topologies will be discussed.

Rectifier topologies

Figure 2.6 show a classification of the different rectifiers that can be used, this section will discuss these different rectifiers.

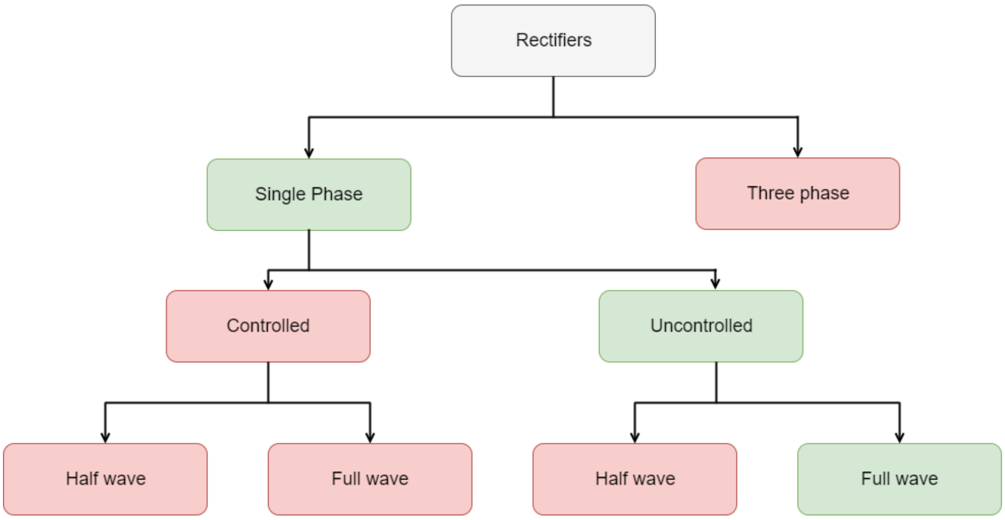


Figure 2.6: Rectifier classification, green is implemented for the IPT system

Single phase vs three phase

Rectifiers can be classified into single and three phase rectifiers. The AC current flowing out from inductor L_2 in figure 2.3 is single phase. In other words, the AC input current of the rectifier is single phase which means that, for this application, single phase rectifiers need to be chosen.

Half wave vs Full wave

Before the controlled and uncontrolled rectifiers are discussed, the difference between half and full waves will be discussed.

An example of a half wave rectifier can be seen in figure 2.7. In the positive cycle of the AC current (current has "positive" value), the diode D_1 will conduct and for the negative cycle the same diode will block the current. In this fashion only the positive half of the sine wave will pass through the rectifier. The output capacitor (C_{out}) will make this positive half sine wave a nearly constant DC current. The AC input current can be seen in figure 2.8 and the corresponding current after the diode can be seen in figure 2.9.

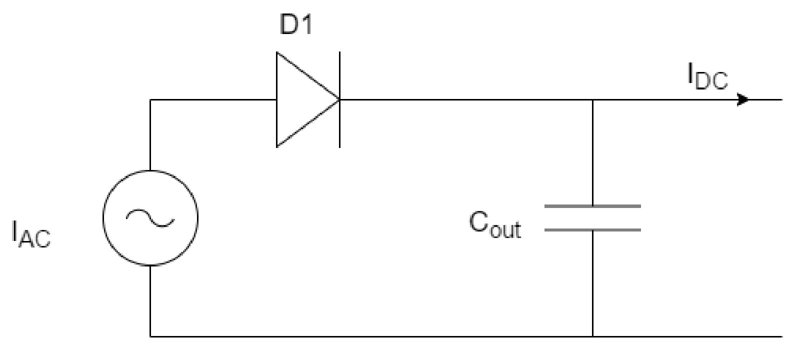


Figure 2.7: Uncontrolled half wave rectifier

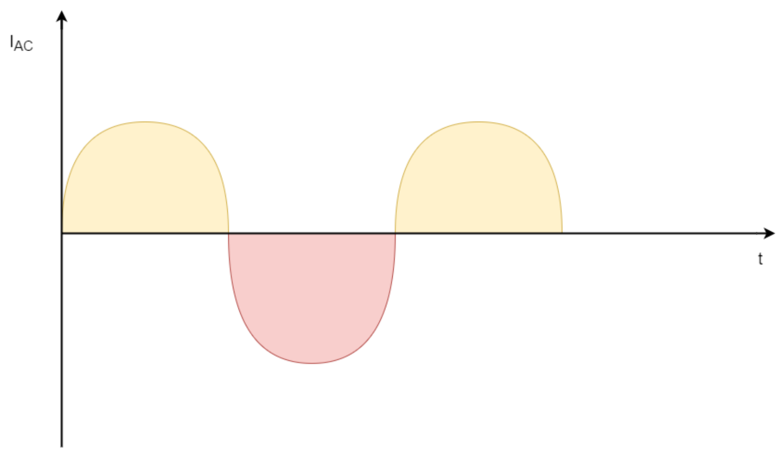


Figure 2.8: AC input current

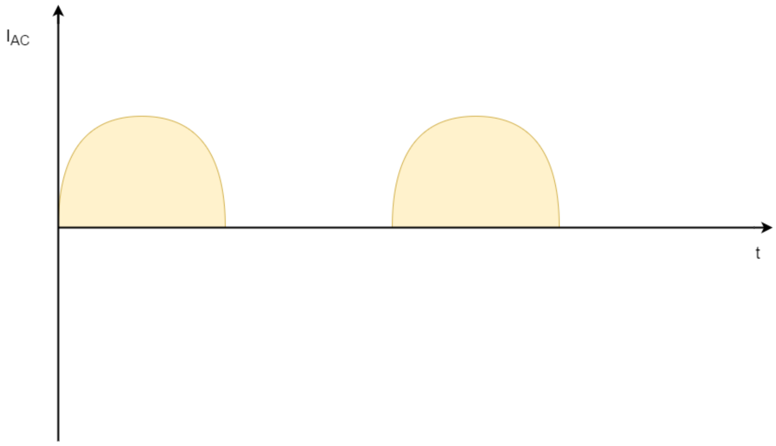


Figure 2.9: Current before the capacitor

The disadvantage of half wave rectifiers is low efficiency, due to the low output power (only delivered for the positive cycle of the sine wave). The main advantage is the simplicity of the circuit. Few components are necessary which makes it relatively cheap.

An example of a full wave rectifier can be seen in figure 2.10. In the positive cycle of the AC current (current has "positive" value) the diodes D_1 and D_4 will conduct and the diodes D_2 and D_3 will block the current and vice versa for the negative cycle of the AC current. In this fashion only the positive half of the sine wave will pass through the rectifier. The capacitor will make this positive half sine wave a nearly constant DC current.

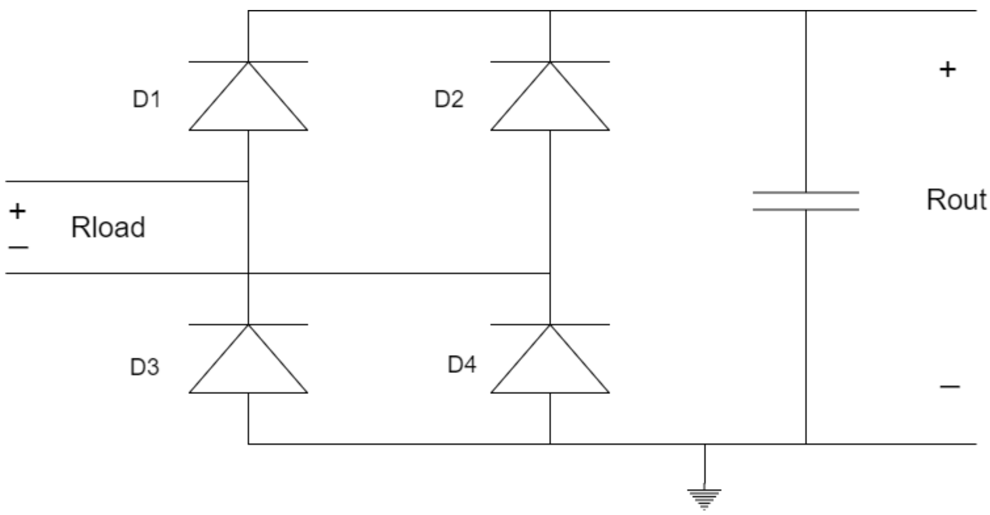


Figure 2.10: Uncontrolled full wave rectifier

The input AC current is obviously the same as for the half wave rectifier as can be seen in figure 2.8. The full wave rectifier will convert both the positive and negative cycle into a "DC" current the result can be seen in figure 2.11. This means that the average output current is higher with respect to the half wave rectifier.

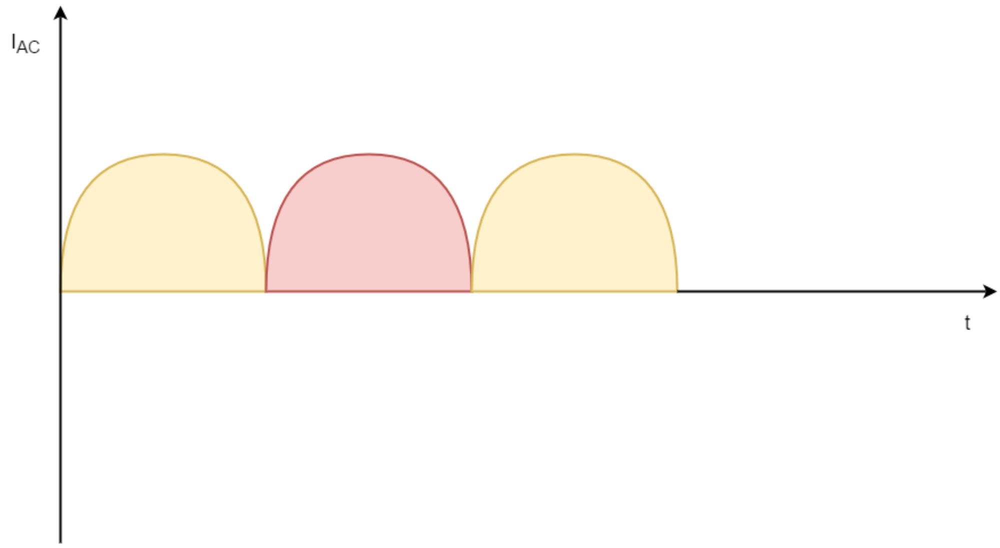


Figure 2.11: Current output (before capacitor)

It it is obvious that the full wave rectifier has a higher efficiency with respect to the half wave rectifier, therefore, it is reasonable to use a full wave rectifier for the IPT system.

Uncontrolled vs Controlled

So far, the single phase full wave rectifiers are qualified to be used in the IPT system. In figure 2.10 an uncontrolled single phase full wave rectifier can be seen. The diodes used in these rectifiers have a typical voltage drop of 0.6 V. One can imagine that this will decrease the efficiency of the rectifier. Schottky diodes could be used to reduce the voltage drop, which will cause a relative increase in the efficiency of the system.

A controlled single phase full wave rectifier can be seen in figure 2.12, the principle is the same as for the uncontrolled rectifier. The difference is that the MOSFETs are controlled whether they are switched on or off. Using MOSFETs has the advantage of low power losses due to low resistance. For this reason the voltage drop over the MOSFETs is less with respect to the diodes used in the uncontrolled rectifiers. Several MOSFETs can be placed in parallel to reduce the voltage drop even more.

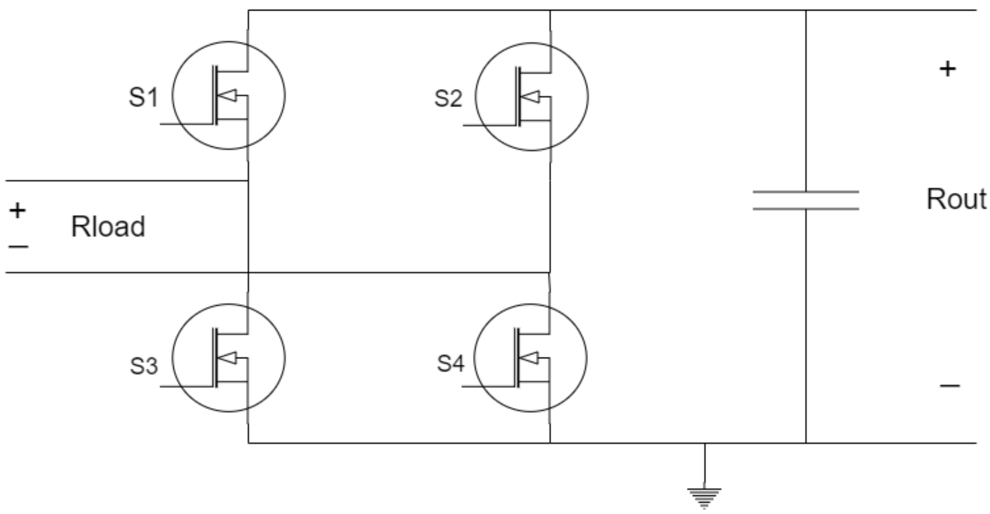


Figure 2.12: Controlled full wave rectifier

The controlled rectifier seems to be the best solution for the IPT system, but the only downside is that a control system is necessary to switch the MOSFETS synchronously. This control system is outside of the scope of this work package and therefore the work package will work with the uncontrolled single phase full wave rectifier (figure 2.10).

2.2.5 Rectifier solution

The rectifier in figure 2.10 will be used for the IPT system. This section will explain whether the current IPT system as can be seen in figure 2.1 is able to meet the following conditions:

1. Charge the battery of the car with maximum efficiency.
2. Charge the battery of the car with the required power (see table 1.1).

In subsection 2.2.3 R_{Load} (see input of the rectifier figure 2.10) needed to be approximately equal to ωM for maximum efficiency. The ratio between the input voltage and current needs to be equal to this R_{load}. However, reaching the optimal load resistance could be hard due to the sinusoidal (changing) input signals. It is relatively easier to control the DC voltage and current at the output of the rectifier. The relation between R_{load} and R_{out} is given by equation (2.20) [5, equation 5].

$$R_{load} = \frac{8}{\pi^2 \eta_{rect}} \frac{U_{out}^2}{P_{out}} \tag{2.20}$$

The output resistance can be written in the form as can be seen in equation (2.21).

$$R_{out} = \frac{U_{2,dc}^2}{P_{out}} \tag{2.21}$$

So R_{load} and R_{out} are related by equation (2.22), they are related by a constant, the efficiency of the rectifier and the R_{load} (ωM).

$$R_{out} = \frac{\pi^2 * \eta_{rect}}{8} \times R_{load} \tag{2.22}$$

So the battery of the car can be charged with maximum efficiency by changing the ratio between the output voltage and current, which are nearly constant signals.

The rectifier is connected to the battery of the car which means that the output voltage of the rectifier is fixed. The only parameter that can be changed to achieve the desired R_{out} is the output current of the rectifier. This current is obviously related by the AC input voltage V_p (figure 2.4) which is controllable. In other words, the output current of the rectifier can be tuned in such a way that the ratio of output voltage and current is equal to the desired R_{out}. The maximum efficiency charging condition is met, but the IPT system also needs to charge the battery with the desired power (see table 1.1).

Solving equation (2.20) for the output voltage will lead to equation (2.23), where R_{load} is equal to $\omega k\sqrt{L_1 L_2}$. Substituting the values of table 1.1 into this equation will lead to $U_{out} > V_{battery}$, this means that the output voltage of the rectifier needs to be equal to U_{out} to charge the battery with the desired power. The output voltage of the rectifier is equal to the battery voltage and, therefore, this current IPT system is not able to charge the battery with the required power.

$$U_{out} = \sqrt{\frac{\pi^2 * \eta_{rect}}{8} \times P_{out} \times \omega k\sqrt{L_1 L_2}} \tag{2.23}$$

2.2.6 DC-DC converter solution

To meet the two conditions mentioned in subsection 2.2.5, the output DC voltage and current ratio needs to be equal to R_{out} (equation (2.22)) and the output voltage of the rectifier needs to be equal to equation (2.23). These two conditions can be met by placing a power converter after the rectifier. This can be seen in figure 2.13.

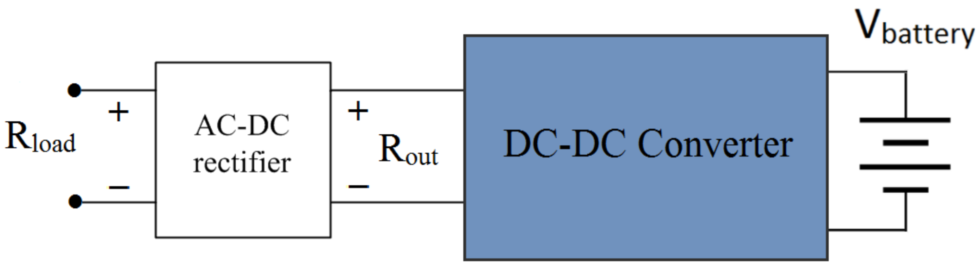


Figure 2.13: Rectifier connected to a DC-DC converter

The input current of the converter is DC and the output of the converter needs to be DC. The battery needs to be charged with DC current, so it is reasonable to use a DC-DC converter. The converter is able to change the ratio between its input voltage and current. This can be done by changing the duty cycle(see section 2.2.8).

In this way R_{out} (equation (2.22)) can be reached and therefore condition 1 is met. The converter is in the same way also able to achieve the voltage equation (2.23) and in case the primary voltage V_p (figure 2.4) is tuned according to equation (2.24) the battery will be charged with the required power. The DC-DC converter is a suitable solution, because both requirements can be achieved.

Where U_{out} is calculated in (2.23) [7, equation 12].

$$V_p = U_{out}\sqrt{\frac{L_1}{L_2}} \tag{2.24}$$

Two different DC-DC converters will be analyzed at surface level. These converters are the following:

1. Buck converter
2. Boost converter

Buck converter

A buck converter is able to reduce its input DC voltage to a lower output voltage. These are the basic relations in CCM (see section basic buck converter) assumed zero losses.

$$V_{out} = D \times V_{in} \tag{2.25}$$

$$I_{out} = \frac{I_{in}}{D} \tag{2.26}$$

D is defined as the duty cycle and this condition holds $0 \leq D \leq 1$ (see section basic buck converter CCM) and, therefore, equation (2.27) holds.

$$V_{in} \geq V_{out} \tag{2.27}$$

Boost converter

A boost converter is able to increase its input DC voltage to a higher output voltage. These are the basic relations in CCM assumed zero losses.

$$V_{out} = \frac{V_{in}}{1 - D} \tag{2.28}$$

$$I_{out} = I_{in} \times 1 - D \tag{2.29}$$

D is defined as the duty cycle and this condition holds $0 \leq D \leq 1$ and therefore equation (2.30) holds.

$$V_{in} \leq V_{out} \tag{2.30}$$

The input voltage range of the DC-DC converter will determine which converter is suitable for the IPT system. Note that the input voltage of the converter is equal to the output voltage of the rectifier. The input voltage of the converter is given by (2.23) and is given below, for convenience purposes.

$$U_{in,converter} = \sqrt{\frac{\pi^2 * \eta_{rect}}{8} \times \frac{P_{out}}{\eta_{conv}} \times \omega k L} \tag{2.31}$$

The coupling coefficient k is equal to $0.08 \leq k \leq 0.2$ (see table 1.1), so for the minimal k, the minimal $U_{in,converter}$ is given by (2.32). Note that η_{conv} is the converter efficiency.

$$U_{min,converter} = \sqrt{\frac{\pi^2 * \eta_{rect}}{8} \times \frac{P_{out}}{\eta_{conv}} \times \omega k_{min} L} = 290.41V \tag{2.32}$$

The maximum input voltage is given for the maximal k and is given by equation (2.33). Note that these calculations are under the assumption of η_{rect} and $\eta_{conv} = 1$.

$$U_{max,converter} = \sqrt{\frac{\pi^2 * \eta_{rect}}{8} \times \frac{P_{out}}{\eta_{conv}} \times \omega k_{max} L} = 459.18V \tag{2.33}$$

The input voltage of the converter is higher than the battery voltage (see table 1.1), so the buck converter will be a reasonable choice for the IPT system.

2.2.7 Buck modes of operation

The buck converter has two modes of operation, namely CCM and DCM. This section will give a brief description of this operations. Note that the buck converter needs to operate in steady state, resulting in a "nearly" constant output current. In case the reader is not familiar with the basics of the buck converter, it is suggested to read 2.2.8.

CCM

In CCM the current through the inductor will flow continuously during the entire switching period. The current through the inductor is equal to the average output current. The current through the output capacitor during one switching period is equal to zero. The inductor current through the inductor can be seen in figure 2.14.

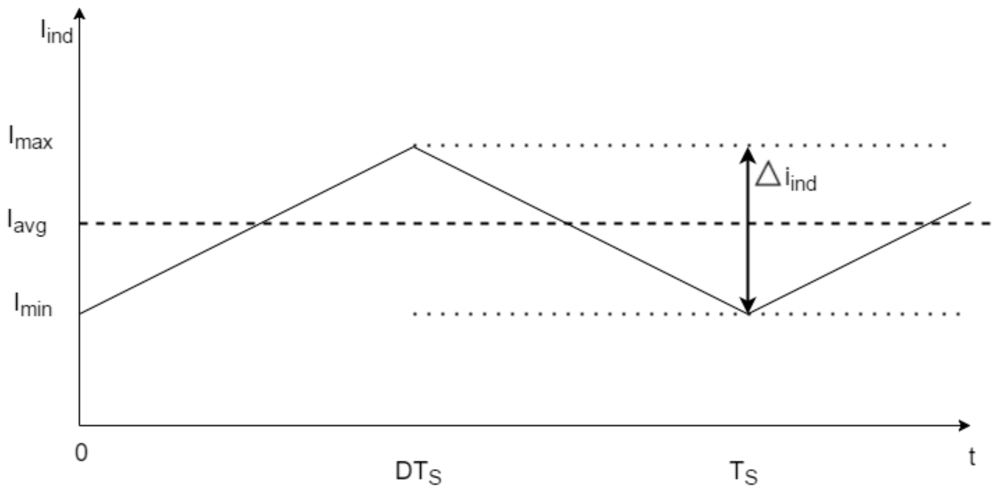


Figure 2.14: Inductor current in CCM

DCM

The buck converter will operate in DCM when the inductor current is zero for a portion of the switching period. The inductor current in DCM can be seen in figure 2.15.

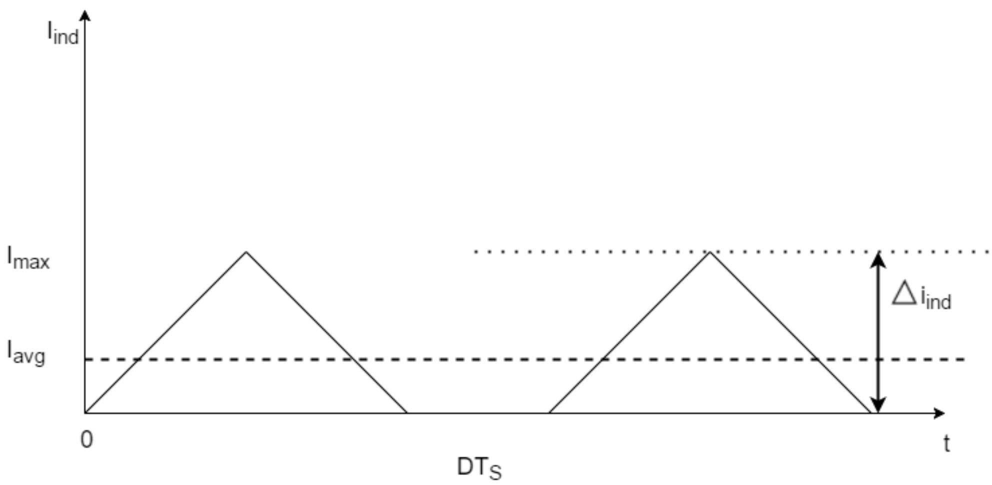


Figure 2.15: Inductor current in DCM

The ripple factor is defined by equation (2.34) [8, equation 8]

$$\gamma = \frac{\Delta i_{ind}}{I_{avg}} \tag{2.34}$$

A ripple factor less than two means that the buck converter works in CCM [8], so a buck converter working in CCM will cause lower stresses in the components.

The output/input voltage relation in CCM of the buck converter are given in subsection 2.2.6. The output/input voltage relation of the buck converter in DCM is given by equation (2.35) [9].

$$V_{out} = V_{in} \times \frac{2}{1+\sqrt{1+\frac{4\times K}{D^2}}} \tag{2.35}$$

where $K = \frac{2\times L}{R\times T_s}$

The output/input voltage relation in DCM is dependent on R which means dependent on the output resistance (load) of the buck converter.

The buck converter will be designed in CCM, because the components are relatively less stressed and the output/input voltage relation does not depend on the load of the buck converter.

2.2.8 Basic Buck converter in CCM

This section will explain the basic DC/DC converter concepts. This work package needs to design a buck converter for the IPT system, so the basics of the buck converter will be explained first.

The buck converter can be seen in figure 2.16. The converter is able to reduce the input DC voltage to a lower output voltage. The voltage can be reduced by controlling the switch. In case the switch is on for half a second and off for half a second, the average output voltage will be the half of the input voltage. This frequency is very low and, therefore, the variation of the voltage can be seen in the behavior of the load. Therefore, the switching frequency needs to be relatively high, in the order of hundreds of kilo hertz.

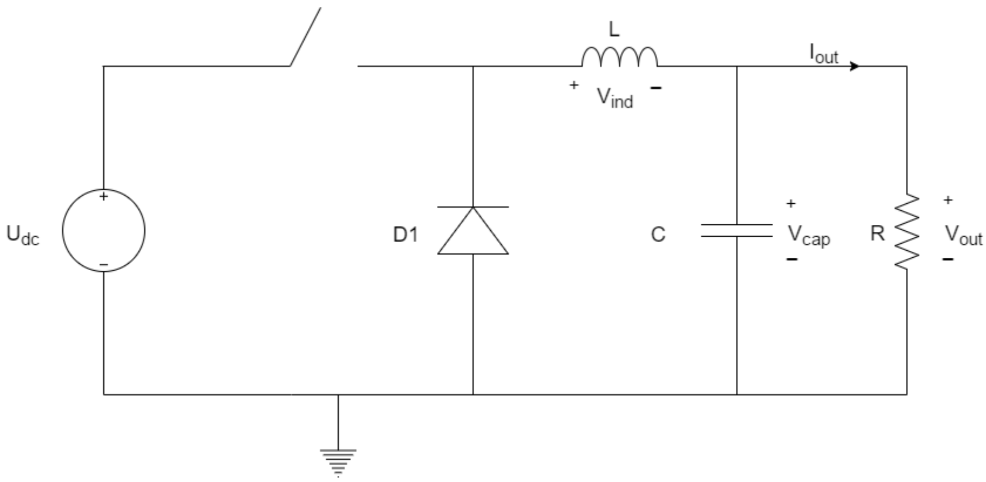


Figure 2.16: The buck converter

The amount of time the switch is on will influence how much the input voltage is reduced at the output. This on-time is related to the duty cycle as shown in equation (2.36).

Switching with such high frequencies will create undesired higher frequency components, which could damage the load [10, Chapter 6, p. 149].To protect the load from such frequency components, an LC low pass filter is used in the buck converter as can be seen in figure 2.16.

$$D = \frac{t_{on}}{t_{on} + t_{off}} \tag{2.36}$$

The buck converter has 2 situations, namely switch closed (situation 1) and switch open (situation 2). In case the switch is closed, the current will flow into the inductor, due to the sudden change of the current through the inductor. A voltage across the inductor will be induced. This results in a lower output voltage, due to the voltage drop over the inductor. The voltage drop will decrease as the switch stays closed for a longer time, the change of the current through the inductor will become less and, therefore, the output voltage will increase. The current flowing into the inductor is stored into its magnetic field. In case the switch is opened, the inductor will act as a current source to keep the voltage at the output constant. The diode will make a closed path possible for the inductor current [11, Chapter 7, p.164]

The two different situations will be analyzed for a better understanding of the buck converter. Before analyzing the converter some assumptions are made. The converter will work in CCM mode (see section 2.2.7), in other words the current through inductor L will never be zero. The converter is also in steady state, which means that the current through the inductor is constant and the voltage over the capacitor is also constant.

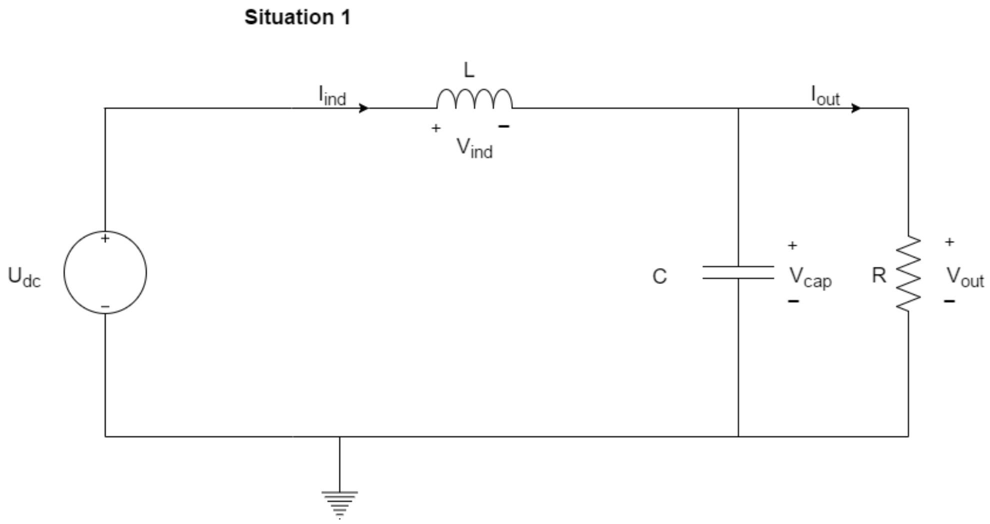


Figure 2.17: The buck converter switch closed

The buck converter with closed switch can be seen in figure 2.17. The voltage over the inductor is given by equation 2.37. This can also be written as equation 2.38. The inductor current slope can be written as equation 2.39.

$$U_{dc} - V_{cap} = V_{ind} \tag{2.37}$$

$$U_{dc} - V_{cap} = L\frac{\mathrm{d}i}{\mathrm{d}t} \tag{2.38}$$

$$s_1 = \frac{\mathrm{d}i}{\mathrm{d}t} = \frac{U_{dc} - V_{cap}}{L} \tag{2.39}$$

The buck converter with open switch can be seen in figure 2.18. The voltage over the inductor is given by equation (2.40). This can also be written as equation (2.41). The inductor current slope can be written as equation (2.42).

$$-V_{cap} = V_{ind} \tag{2.40}$$

$$-V_{cap} = L\frac{di}{dt} \tag{2.41}$$

$$s_2 = \frac{di}{dt} = \frac{-V_{cap}}{L} \tag{2.42}$$

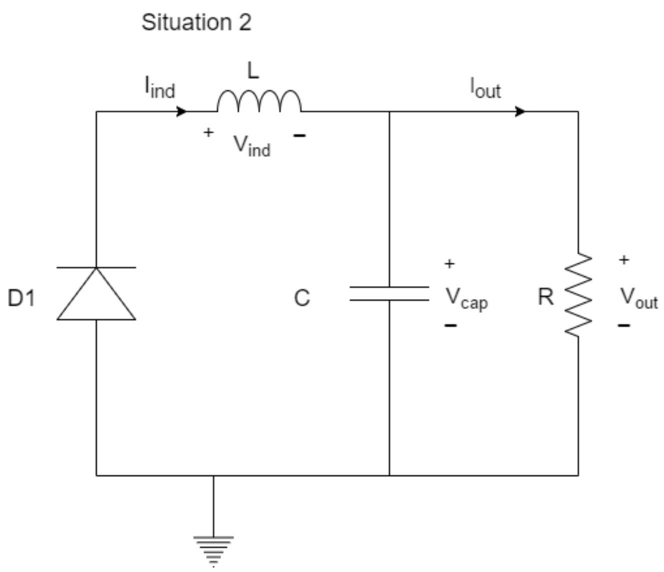


Figure 2.18: The buck converter switch open

In figure 2.19 the graphical representation of the inductor current can be seen. In the time interval from 0 till DT_s (equal to the on time of the switch), the inductor current will increase with slope s_1 as calculated in ((2.39)). In the time interval DT_s till T_s (switching period) the inductor current will decrease with slope s_2. The buck converter will work in steady state, so the current through the inductor needs to be constant. Therefore, equation (2.43) [10, Chapter 6, p.156] holds. Substituting the slopes will eventually lead to relation (2.44). It can be seen in 3.13 that the capacitor voltage is equal to the output voltage(V_{out}). Equation (2.44) shows that the output voltage can be regulated by changing the duty cycle.

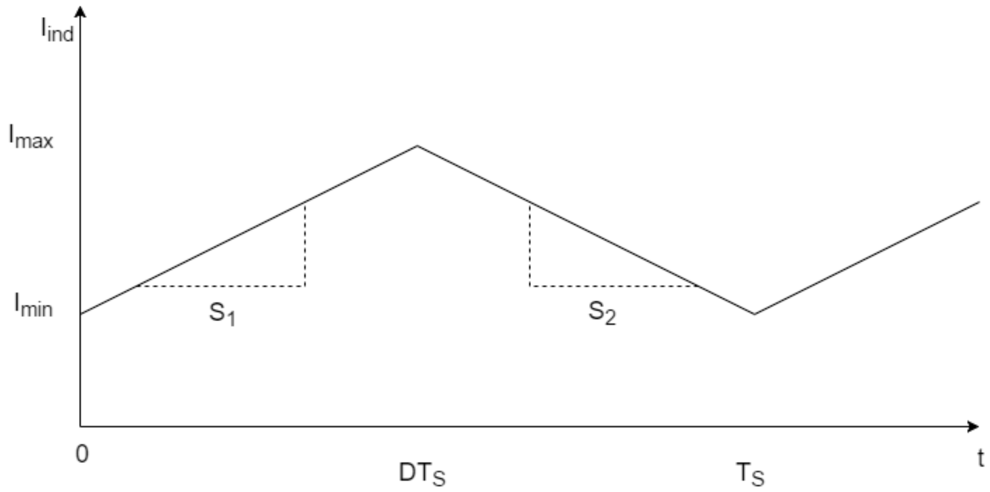


Figure 2.19: Graphical inductor current

$$S_1 DT_s + S_2(1-D)T_s = 0 \tag{2.43}$$

$$D \times U_{dc} = V_{cap} \tag{2.44}$$

2.2.9 IPT buck converter

In the previous section the basic buck converter was explained. The buck converter in this IPT system has some differences with respect to the basic buck converter. The IPT system buck converter can be seen in figure 2.21. The IPT system with suggested solution can be seen in 2.20.

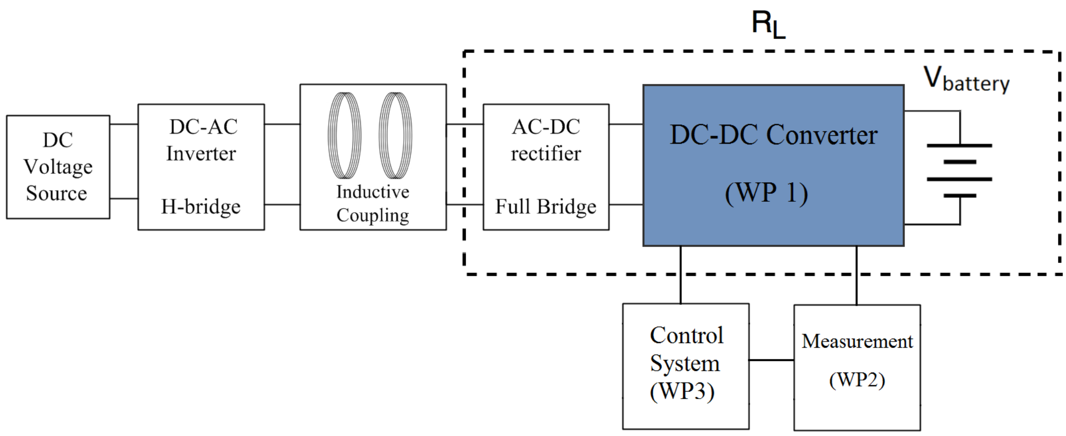


Figure 2.20: IPT system with additional systems to reach high efficiency

The circuit before the buck converter as can be seen in figure 2.20 can be modeled as an DC current source, in reality it is an absolute sine (current direct after the rectifier). The R_{cin},R_{cout},R_{ind} and R_{bat} are the parasitic resistances. Note that parasitic resistances are also present in the general buck converter. The output of the IPT buck converter is the model of a charging battery. The battery needs to have a constant voltage. This is modeled by a voltage source at the output (V_{bat}). The battery needs to be charged only, so discharging is avoided by placing a diode (D_2) in series with the voltage source. The capacitor C_{in} is of vital importance for the functioning of the buck converter. Note that this capacitor is the capacitor after the rectifier (figure 2.10). The current will flow through the capacitor in case the switch is open. Without the capacitor the current will not have a path to flow through.

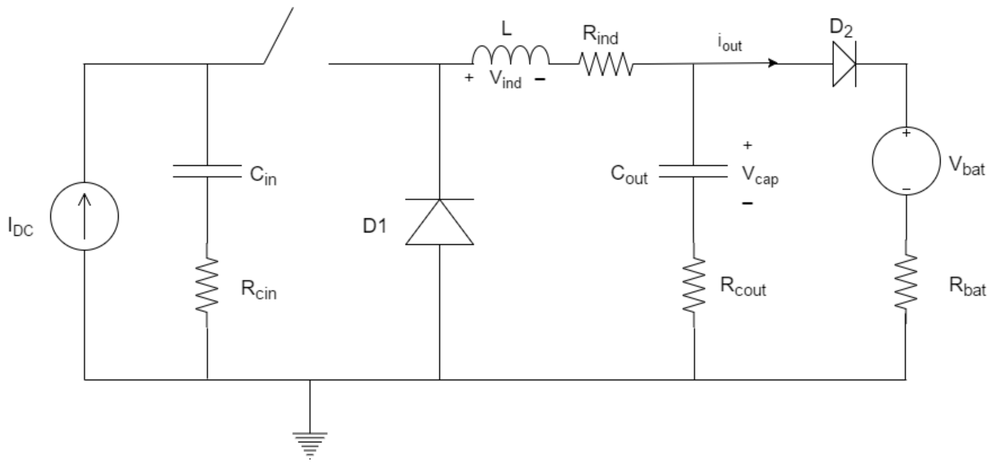


Figure 2.21: The IPT buck converter

The IPT buck converter has a fixed output voltage and this means that the input voltage (voltage over C_{in}) can be regulated by changing the duty cycle. Equation (2.44) will become now (2.45). The duty cycle will determine how much of the input current will flow into C_{in} and, therefore, the input voltage (voltage over the C_{in}) can be regulated. The input voltage, however, will be higher in case a higher input current is used at the same duty cycle. The reason for this is that relatively more current can flow into the internal resistance of the battery which results in a higher battery voltage.

So in summary the amount of current flowing through the capacitor (C_{in}) can be regulated by changing the duty cycle. This implicitly regulates the voltage over C_{in}. So the IPT buck converter is able to change the ratio between the input voltage and current, and, therefore, the resistance value calculated with equation (2.19) and (2.22) can be reached. The battery will be charged with maximum efficiency in case this value is reached.

$$V_{Cin} = \frac{V_{out}}{D} = \frac{V_{bat} + (I_{out} \times R_{bat})}{D} \tag{2.45}$$

2.2.10 Buck converter components calculation

In this section the calculations for the components used in the buck converter are given. The design requirements given by the supervisor S. Bandyopadhyay can be found in table 1.1. The requirements important for the converter design can be found in table 2.1.

Variable	Value	Description
$V_{battery}$	200V	The nominal battery voltage converter
P_{out}	8 kW	The power output of the battery
I_{out}	40 A	The current output of the battery
Δi_{ind}	$0.2 I_{out}$	The inductor ripple current
v_{Cout} ripple percentage	$\leq 5\%$	The voltage ripple over the output capacitor
V_{in} range of V_{Cin}	290.41 V- 459.18 V	See below for calculation

Table 2.1: The design requirements for buck design

With the help of the parameters listed in 2.1, the components for the buck converter can be designed [12].

Inductor

The two different situations explained in subsection 2.2.8 converter are necessary for the inductor design. For situation 1 the equations for the IPT buck converter are given by (2.46), (2.47) and 2.48. Note that the only difference is the replacement of U_{DC} with V_{Cin}. Situation 2 of the IPT buck converter is exactly the same as for the general buck converter, see subsection 2.2.8 for these equations.

$$V_{Cin} - V_{cap} = V_{ind} \tag{2.46}$$

$$V_{Cin} - V_{cap} = L\frac{\mathrm{d}i}{\mathrm{d}t} \tag{2.47}$$

$$s_1 = \frac{\mathrm{d}i}{\mathrm{d}t} = \frac{V_{Cin} - V_{cap}}{L} \tag{2.48}$$

The inductor value is calculated based on the inductor current ripple [13], so there will be given an expression for the inductor current ripple.

The graphical representation of the inductor current can be seen in figure 2.19. The inductor ripple is defined as follows (2.49) which is equal to equation (2.50). Modifying (2.50) will result in equation (2.51), where $T_s = \frac{1}{f_s}$.

$$\Delta i_{ind} = I_{max} - I_{min} \tag{2.49}$$

$$\Delta i_{ind} = \frac{V_{Cin,max} - V_{out}}{L_{buck}} \times DT_s \tag{2.50}$$

$$L_{buck} = \frac{V_{Cin,max} - V_{out}}{\Delta i_{ind}} \times \frac{D}{f_s} \tag{2.51}$$

All parameters are known except the switching frequency (f_{sw}). Note that the duty cycle can be calculated with the help of equation (2.45). The switching frequency needs to be minimal in the range of hundreds of kHz as explained in section 2.2.8.

A switching frequency too high affect the efficiency of the converter. The switching loss is proportional to the switching frequency [14]. A switching frequency too low means a higher buck inductor value, resulting in more losses due to the inductor. So a trade off has to be made. In consultation with work package 3 the switching frequency of 500 kHz is chosen(This was necessary for the FPGA implementation, see [15]).

Output Capacitor

The calculation of the capacitor value is based on the output capacitor current i_{Cout}, which flows into C_{out} as can be seen in 2.21. The capacitor current is given by equation (2.52). This means that the inductor current in figure 2.19 is shifted down with its average current. The capacitor current can be seen in figure 2.22. The blue part of the figure represents the amount of charge (in a switching cycle) that builds up in the capacitor [10, Chapter 6, p.160].

$$i_{Cout} = i_{ind} - i_{out} \tag{2.52}$$

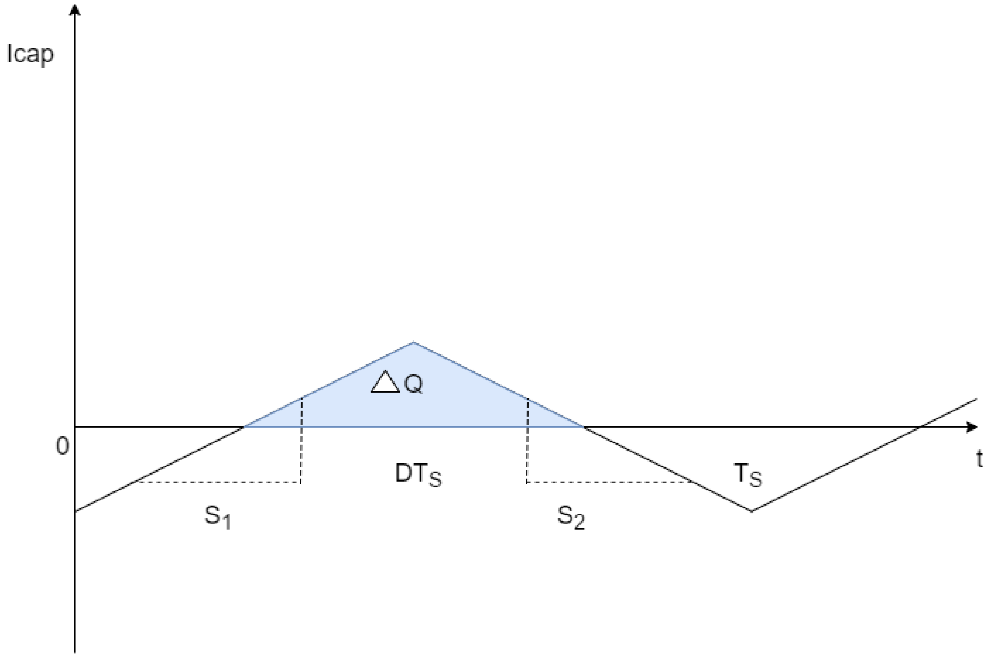


Figure 2.22: The output capacitor current

The capacitor value can be calculated with equation (2.53). ΔV_{Cout} is given by (2.54). The voltage ripple percentage can be found in table 2.1. The input capacitor of the buck converter is part of the rectifier and its design is out of the scope of this work package. The value is chosen in such a way that the simulations can function properly.

$$C_{out} = \frac{\Delta Q}{\Delta V_{Cout}} \tag{2.53}$$

$$\Delta V_{Cout} = \text{voltage ripple percentage} \times V_{out} \tag{2.54}$$

2.2.11 Buck converter components choice

This section will give a brief overview of the components that can be chosen for the IPT buck converter, this will be done in a general way.

Output capacitor

A capacitor can be modeled as shown in figure 2.23. The ESR is defined as the parasitic resistance of the capacitor. The ESL is the parasitic inductance of the capacitor. A value too high can cause spikes at the load transient response for high frequencies.

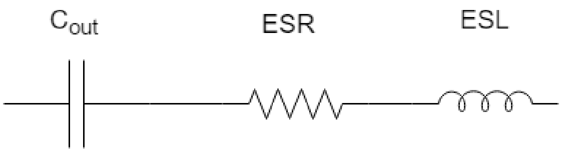


Figure 2.23: Capacitor model

Electrolytic capacitors

1. Stable capacitance at high bias voltage.
2. Large capacitors for low cost
3. High ESR an ESL, this results in high power loss and the transient response is slow [16].

Ceramic capacitors

1. Low ESR and ESL, this is great for the efficiency and the transient response of the system.
2. Limitation on the capacitor size, large capacitors can store more energy [16].
3. Capacitance can be reduced at high bias voltages, the effective capacitance can become less than half the rated capacitance. The capacitor is not able to store enough energy anymore.
4. Ceramic capacitors are relatively expensive.

Polymer and Tantalum capacitors

1. Low ESR and ESL, not lower than ceramic capacitors.
2. Available in large value.
3. Very expensive

The electrolytic capacitors are not suitable for the IPT buck converter, due to the high power loss and slow transient response. Ceramic capacitors bias voltages will reduce its capacitance and, therefore, the energy storage capability will become insufficient, so this is also not very pleasant. So at first glance it is not more than reasonable to opt for either the polymer or tantalum capacitors, despite the high price. An alternative, however, could be the use of the combination of the electrolytic and ceramic capacitor as explained in [16], where this combination could be better than either the polymer or tantalum capacitors.

Inductor
Inductors used for buck converters can be classified into three groups as can be seen in table 2.2 [17].

	Wire wound ferrite	**Metal composite**	**Multilayer**
Inductance value	High	Medium	Low
DC resistance	low	High	High
DC behavior at saturation	Inductance rapidely reduced	Inductance gradually reduced	Inductance rapidly reduced
Performance*	Poor	Good	Good
Applications	Medium current < 1 MHz	low voltage > 1MHz	small current > 3 MHz

Table 2.2: The inductor types for the buck converter

**At high temperature*

By analyzing some of the performance characteristics it can be concluded that the wire wound ferrite inductor is the most suitable for the IPT buck converter. It has a low DC resistance which means relative less power dissipation, resulting in a relative increase in efficiency of the overall system. The inductance value is high and it is able to handle medium current, so overall the wire wound ferrite inductor is the most appropriate choice for the IPT buck converter.

Switch

The following points need to be taken into consideration for choosing the right MOSFET.

1. Low on Resistance of the MOSFET, $R_{DS,ON}$ needs to be low to minimize the conduction losses
2. Low FOM(figure of Merit) it is equal to the product of $R_{DS,ON}$ and Q_G (gate charge)
3. Low internal series resistance to minimize the power losses
4. Low parasitic inductance, this will optimize the switching speed and minimizes the voltage stresses of the inductor during switching transients.
5. Low thermal resistance, at high temperatures this can cause undesired power losses.

The explanation of these point in depth can be found in [18].

Diode

The most common diode used in a buck converter is the Schottky diode. The voltage drop of this diode is smaller with respect to other diodes. This diode is selected based on the forward voltage and the reverse leakage current specifications. It is not possible to decrease the forward voltage of the Schottky diode below 0.3 V. This is due to its physical limitations.

An alternative for Schottky diodes are MOSFETs. The $R_{DS,ON}$ is very low which means that the voltage drop over the MOSFET can be smaller with respect to the diode. However, the MOSFET needs to be controlled complementary with respect to the switch of the buck converter. It could be dangerous when both the switch and the MOSFET were on at the same time, which would cause a short circuit. To avoid this, a control system is necessary which makes the design more complicated, but more efficient

2.2.12 Power loss calculation of the buck converter

This section will give the general formulas which can be used to calculate the power loss of the buck converter.

Inductor

The power losses for the inductor will be given below with the help of [19].

Inductor core loss

$$P_{core} = k_0 \times f_e^{(k_f-1)} \times B_{pk}^{K_b} \times f_0 \times 10^{-14} \tag{2.55}$$

K_0 = Core constant
K_b = flux density constant
K_f = frequency constant
f_0 = switching frequency
f_e = effective frequency
B_{pk} = maximum flux density

$$f_e = \frac{f_0}{2\pi \times (D - D^2)} \tag{2.56}$$

$$B_{pk} = \frac{E_{Tckt}}{E_{T100}} \times 100 \tag{2.57}$$

E_{T100} = Constant which is dependent on the inductor value and size
E_{Tckt} = The V- μs product of the buck converter

$$E_{Tckt} = \frac{V_{out} + V_{diode,drop}}{f_0} \times (1 - f_0) \times 10^6 \tag{2.58}$$

The inductor core loss can be calculated by using this equations above.

AC power loss

$$P_{AC} = K_1 \times \Delta i_{ind}^2 \times \sqrt{f_0} \times R_{oper} \tag{2.59}$$

K_1 = Core constant
Δi_{ind} = inductor ripple current (see table 2.1)
R_{oper} = operational resistance, temperature corrected resistance

$$R_{oper} = R_{max} \times 243.5 + \frac{T_{amb} + T_{rise}}{259.5} \tag{2.60}$$

DC power loss

$$P_{DC} = I_{out}^2 \times DCR \tag{2.61}$$

DCR = The DC resistance of the inductor

The total power loss is equal to equation (2.62).

$$P_{tot} = P_{core} + P_{AC} + P_{DC} \tag{2.62}$$

Switch

The losses calculation for the switch (high side) is based on [13].

conduction losses

$$P_{HS,cond} = I_{out}^2 \times R_{DSON} \times D \tag{2.63}$$

The conduction losses occur in case the switch is in the on state.

gate losses

$$P_{HS,Gate} = Q_{GS,HS} \times V_{GS} \times f_s \tag{2.64}$$

The Gate losses are proportional to the switching frequency.

output capacitor losses

The output capacitor C_{oss} of the MOSFET is parasitic, the capacitor will be charged every cycle.

$$P_{oss,HS} = 0.5 \times Q_{oss_H S} \times V_{in} \times f_s \tag{2.65}$$

Diode losses

The forward diode conduction is as follows:

$$P_{frwd} = V_{frwd} \times I_{out} \times (1 - D) \tag{2.66}$$

This loss only occurs when the switch of the buck converter is switched off.

Capacitor losses

The DC power dissipation is given below.

$$P_{DC} = \Delta i_{ripple} \times ESR \tag{2.67}$$

3 Evaluation

3.1 Overview

This chapter will explain all the testing results regarding the buck converter that was designed. Different simulations were evaluated to verify the calculations and the choices that were made. The simulation were made in Simulink using Matlab. Three types of simulation results will be shown. The first one is the verification of the maximum efficiency point at $R_{load} = \omega$M, by simulating the circuit given in figure 1.4. The second one is the simulation of the DC-DC converter (see figure 2.21) with a DC current source as an input and a battery as an output (see figure 2.21), to verify that the input voltage of the DC-DC converter can be brought to desired voltage level by varying the duty cycle of the switch. The last one is to verify the proper working of the DC-DC converter when integrated in the IPT system.

3.2 Testing and Results

3.2.1 Simulation 1 : Maximum efficiency at ωM

In figure 3.1, the configuration of the simulation is shown. All the component values that were used in this simulation can be found in the table 1.1 in subsection 1.2. By calculating the input power and the output power, and dividing these two values using the subsystem blocks, the efficiency was calculated. This was done for different mutual inductances while certain resitance values were swept. The efficiency was sent to the workspace of Matlab and saved in an empty vector. After finishing the simulation, the vector values were plotted against the resistor values. The graph in figure 3.2 shows the result of this simulation. This simulation was created in corporation with the Controller Design group [15].

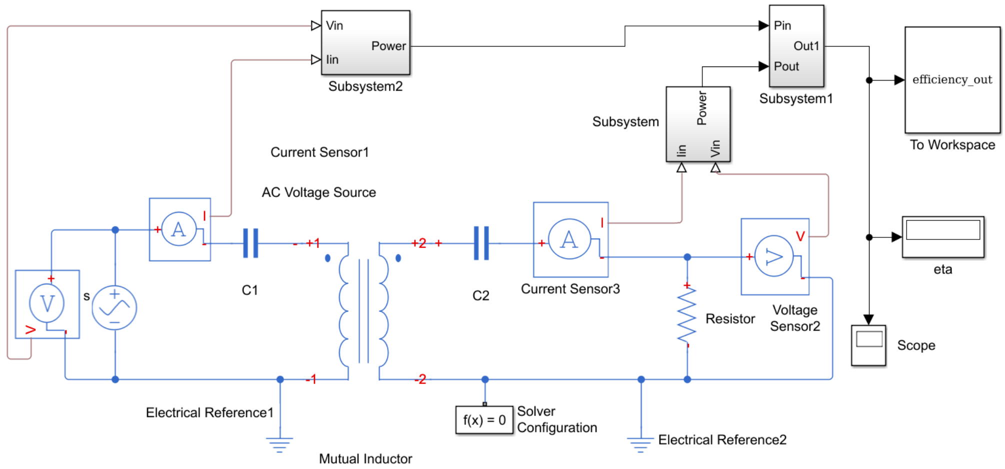
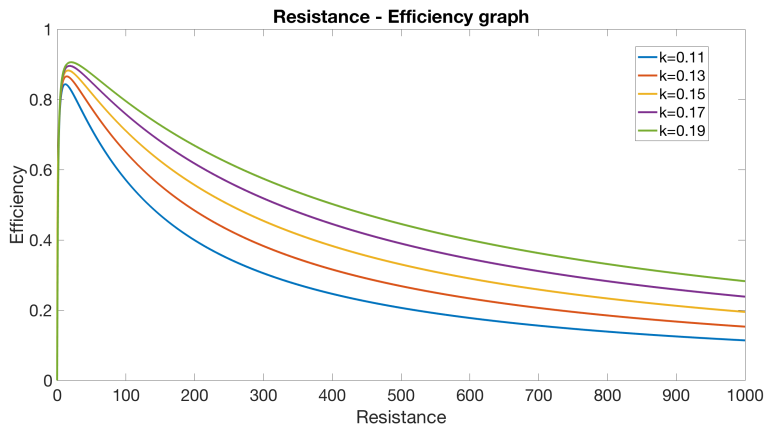
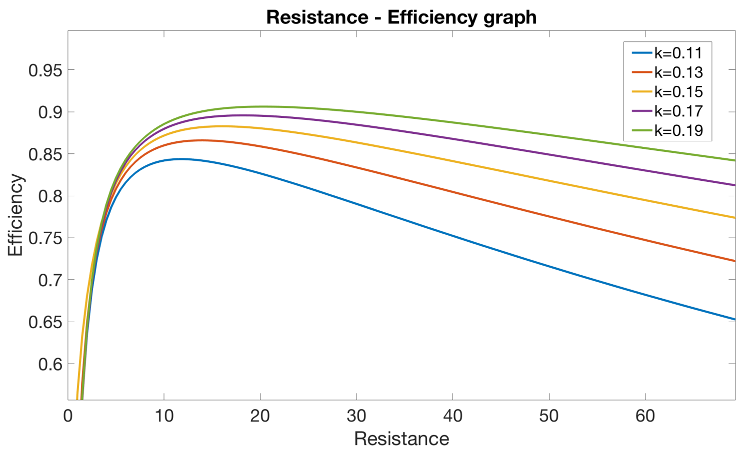


Figure 3.1: Efficiency simulation for variable R_{load}



(a) Resistance - Efficiency Graph



(b) Resistance - Efficiency Graph zoomed in

Figure 3.2: Simulation Results Resistance-Efficiency

k	**maximum efficiency**	R_{load} **Simulation**	R_{load} **calculated**
0.11	0.844	12.0 Ω	11.75 Ω
0.13	0.866	14.0 Ω	13.89 Ω
0.15	0.883	15.5 Ω	16.02 Ω
0.17	0.896	18.0 Ω	18.16 Ω
0.19	0.906	20.5 Ω	20.29 Ω

Table 3.1: Resistance-Efficiency table

Table 4.1 shows the maximum efficiency for all the k values The corresponding resistance value is almost the same as the calculated resistance. This means that the calculations done in the design section were correct.

The small difference between the values in table is due to the fact that Matlab uses discrete variables to calculate a certain value. The distance to the next possible permissible value needs to be chosen to be able to run the simulation. The smaller the distance, the more Matlab needs to calculate, but the more accurate the graph will be. This obviously increases the simulation time. For this simulation the resistance values between 0 and 1000 with steps of 0.5 Ω were chosen. By taking smaller steps, the simulated results would be more close to the calculated values, however, this would increase the simulation time tremendously.

The Matlab code for plotting this graph is shown in the appendix.

3.2.2 Simulation 2 : DC-DC converter with DC current input

In figure 3.3, the simulation of the DC-DC converter is shown. A DC current source was used as an input and a battery, modeled by a DC voltage source in series with a resistor, was used as the output of the DC-DC converter. For different duty cycles the input voltage was measured. Also, this was done for different input currents. Same method as described in the previous section was used to sweep a variable (this case duty cycle) to see the behavior of the system in Matlab.

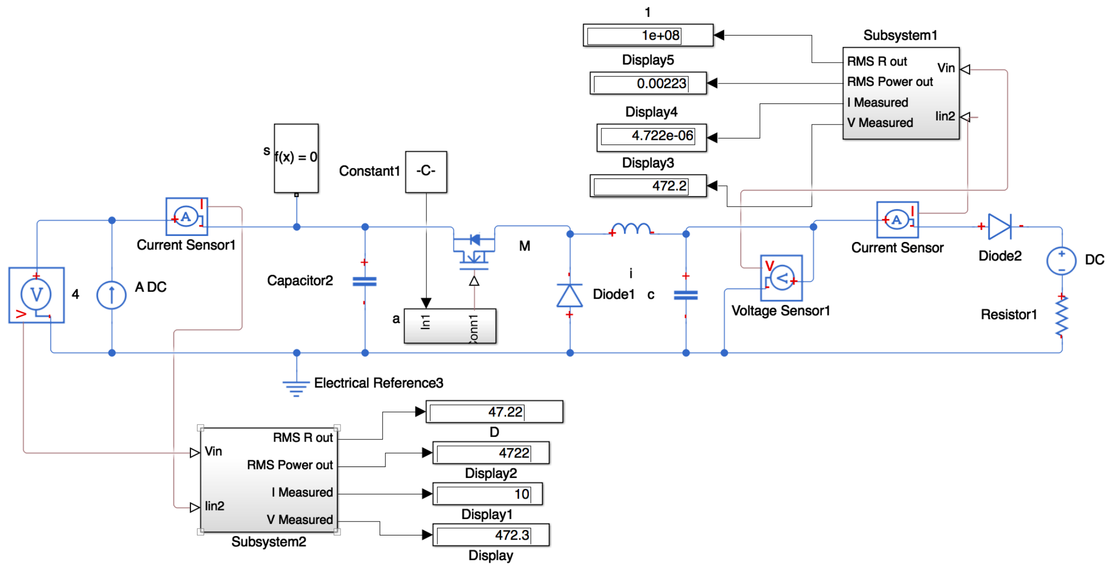
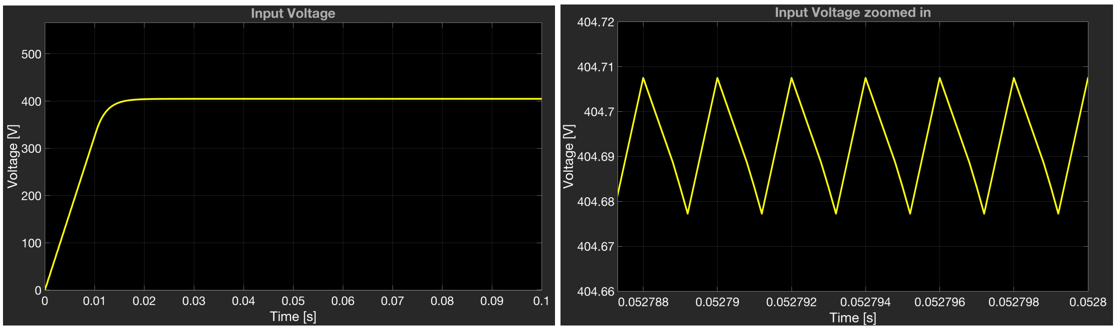


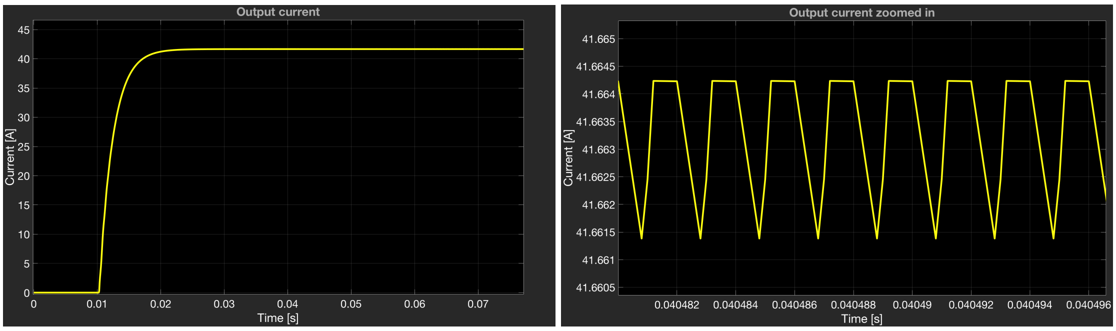
Figure 3.3: DC-DC converter simulation with DC current source input



(a) Input Voltage D = 0.6

(b) Input Voltage zoomed in D = 0.6

Figure 3.4: Input voltage of the Converter at duty cycle 0.6



(a) Output current (b) Output current zoomed in

Figure 3.5: Output current of converter with dutyc cycle 0.6

Figure 3.4 shows that an almost constant voltage can be maintained at the input of the converter. The voltage ripple is in the range of mV, which is according to the supervisor acceptable. The same is true for the output current, as shown in figure 3.5. The current ripple is also in the range of mA. Both requirements of maintaining an almost constant input voltage and output current are therefore met.

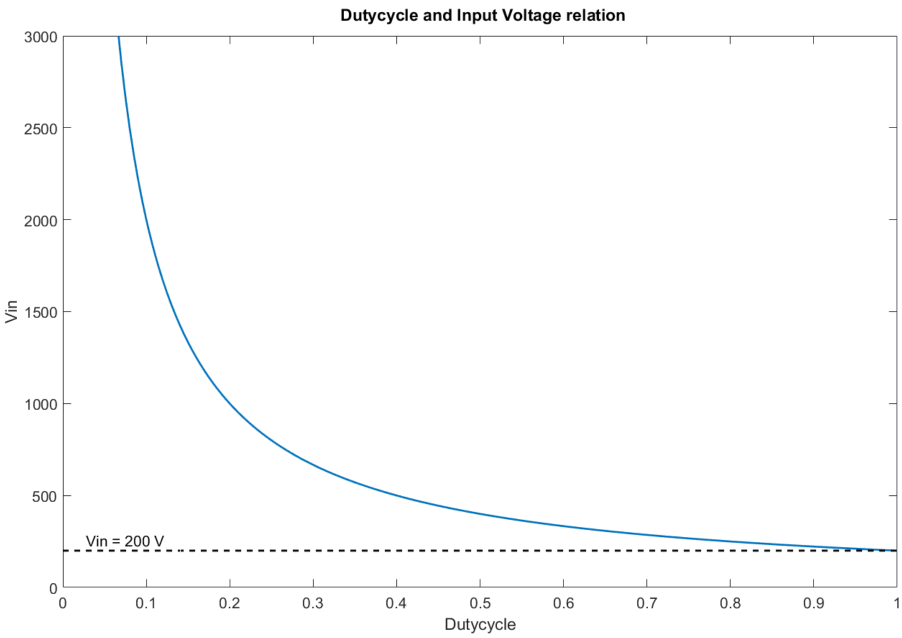


Figure 3.6: Dutycycle - Input Voltage relation of the converter

As shown in figure 3.6 , varying the duty cycles perfectly changes the input voltage to any desired value while the input current remains the same. As a result, every desired ωM value at the input can be reached .
The Matlab code can be found in the appendix.

3.2.3 Simulation 3 : DC-DC converter and IPT system integration

The IPT system was fully built together with the DC-DC converter, as shown in figure 3.7. This simulation was created in corporation with the Controller Design group [15]. Note that the input voltage source on the primary side of the circuit consists of a controlled AC voltage source . The AC output is a square wave, which is the same as the output of the inverter with a DC input voltage.

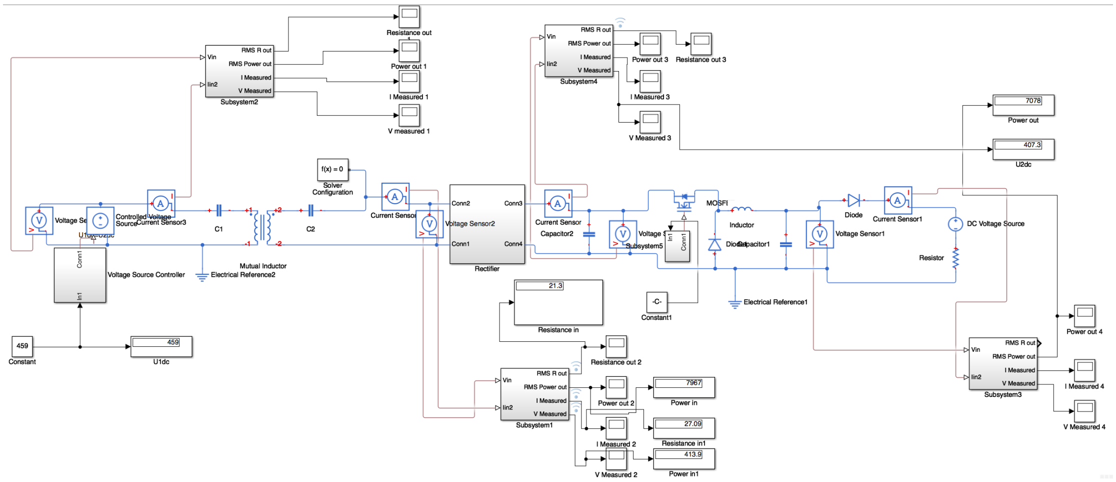


Figure 3.7: Simulation of the IPT system with DC-DC converter

The figures 3.8 until 3.12 are showing the behavior of the system for k = 0.2 with an input voltage of 459.18 V. According to the WPA 3 group, this input voltage value should deliver 8 kW to the whole system. Looking at figure 3.8 this is indeed true. The system power input is 7993 W, which is roughly 8 kW.

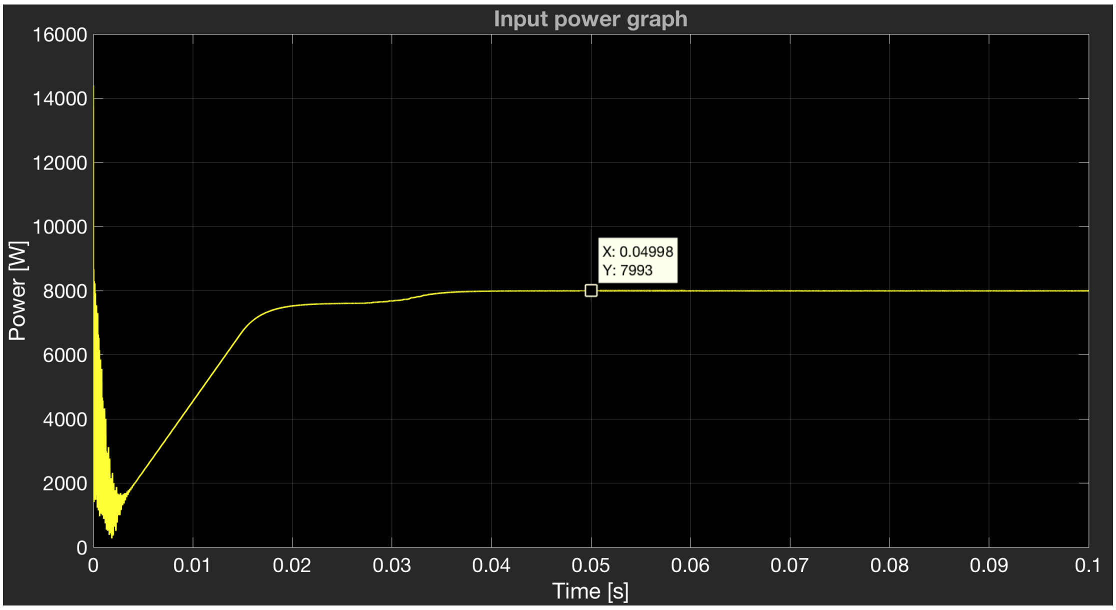


Figure 3.8: Input power graph for k = 0.2

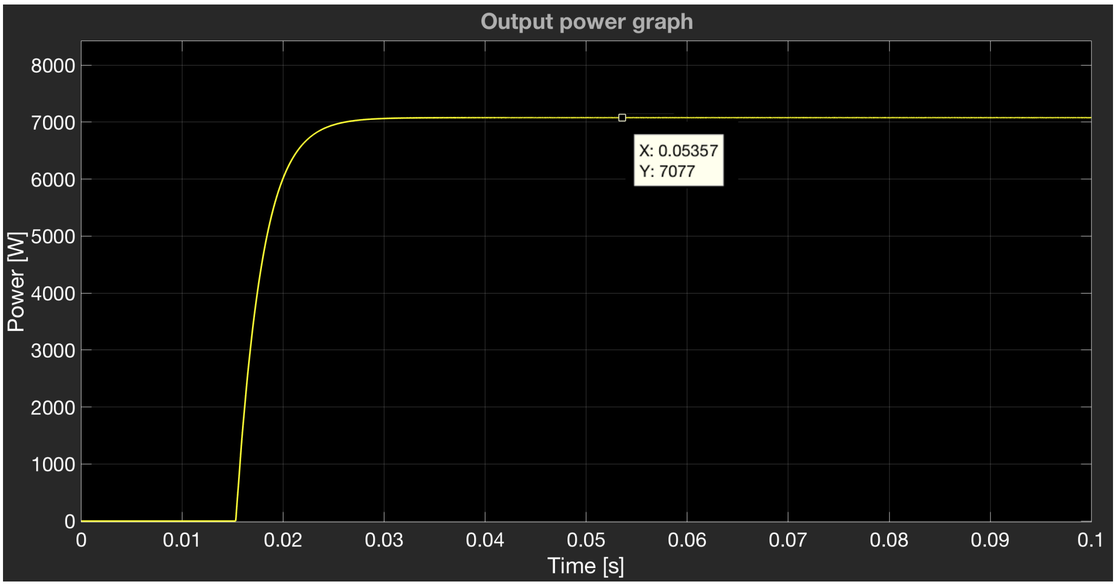


Figure 3.9: Output power graph for k = 0.2

The output power is 7077 W as shown in figure 3.9. Accordingly, the efficiency of the system is 88%. Note, that R_{load} is also roughly equal to the value of ωM, which is in this case 21.36 Ω. (see figure 3.10).

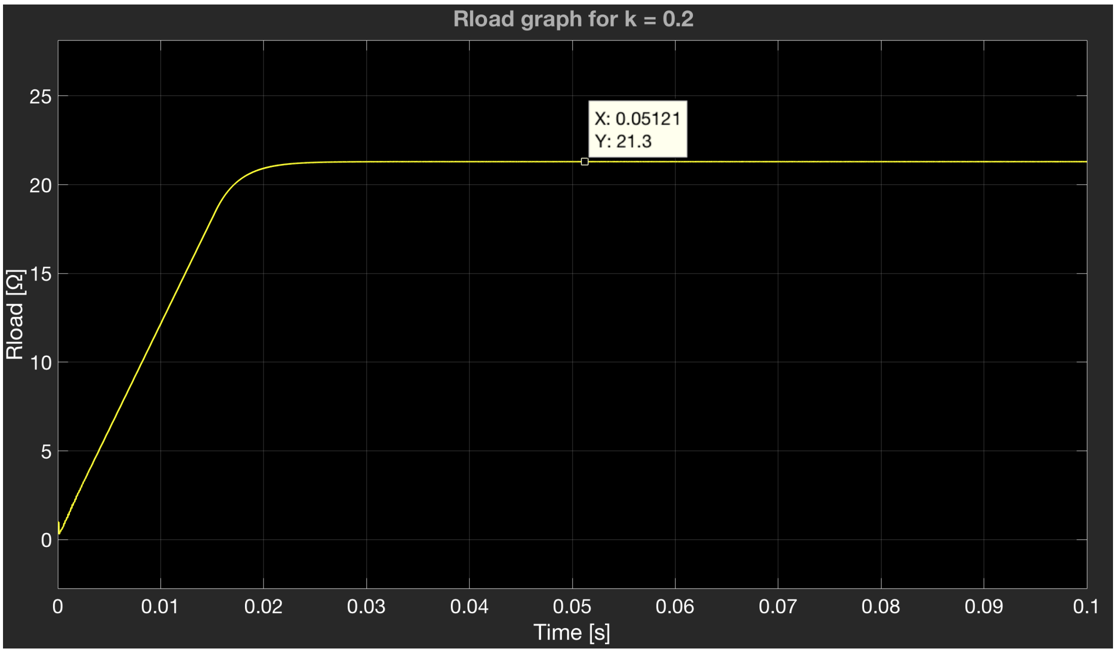


Figure 3.10: R_{load} graph for k = 0.2

To reach the value of $R_{load} = \omega$M, the duty cycle of the switch was set to a value of 0.59. Looking at the input and output voltage of the converter and dividing these two values gives a ratio of 0.586 (see figure for voltage values). This is also correct according to formula 2.25. Furthermore, the output current is almost constant as shown in figure 3.12a, caused by a very small current ripple in the range of mA (figure 3.12b).

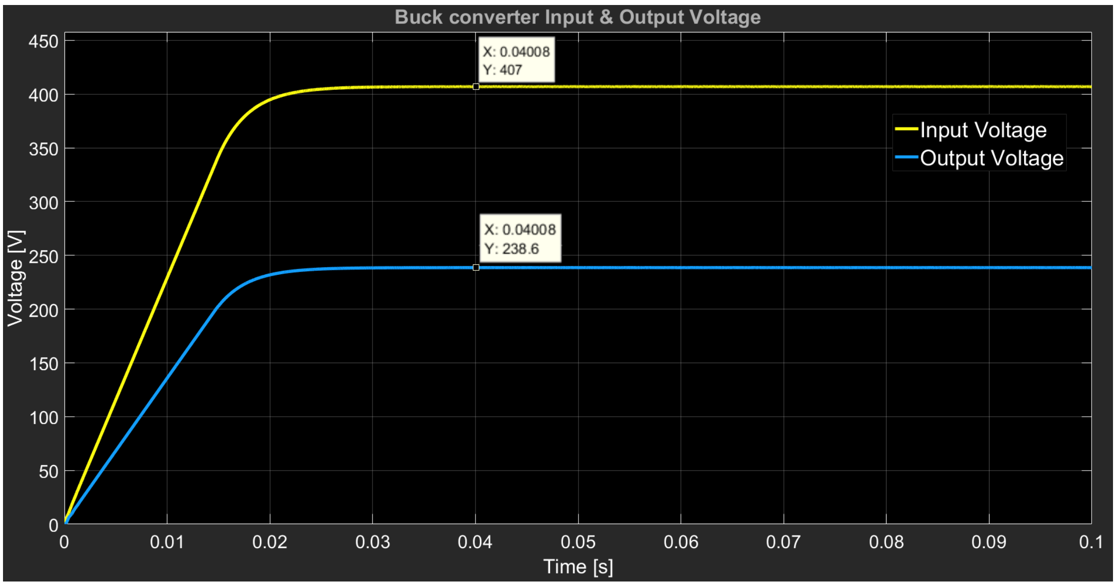
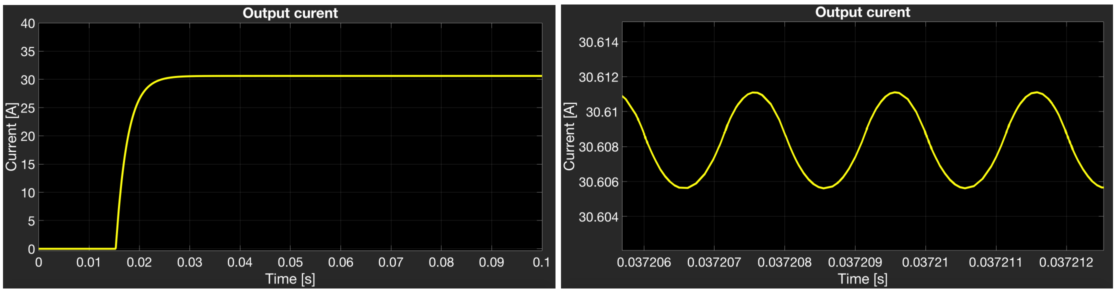


Figure 3.11: Input and Output voltage of the DC-DC converter



(a) Output current for k = 0.2 (b) Output current zoomed in for k = 0.2

Figure 3.12: Output current through battery

Simulation for k = 0.08

All the graphs plotted for k = 0.2 were also plotted for the value of k = 0.08, the minimum value of k , giving the same results as for k = 0.2. This time the input voltage was 290 V, which was again the voltage needed to have an 8 kW power input. The efficiency was 87.5 % and most importantly, R_{load} was 8.55 Ω (see figure 3.13), which is roughly the same value as the calculated R_{load} being 8.545 Ω.

This means that the designed DC-DC converter is capable of reaching and maintaining all the ωM values for the required coupling coefficient range of $0.08 \leq k \leq 0.2$ at the input of the rectifier. As a result, the IPT system is able to charge the battery with maximum efficiency at desired power rate.

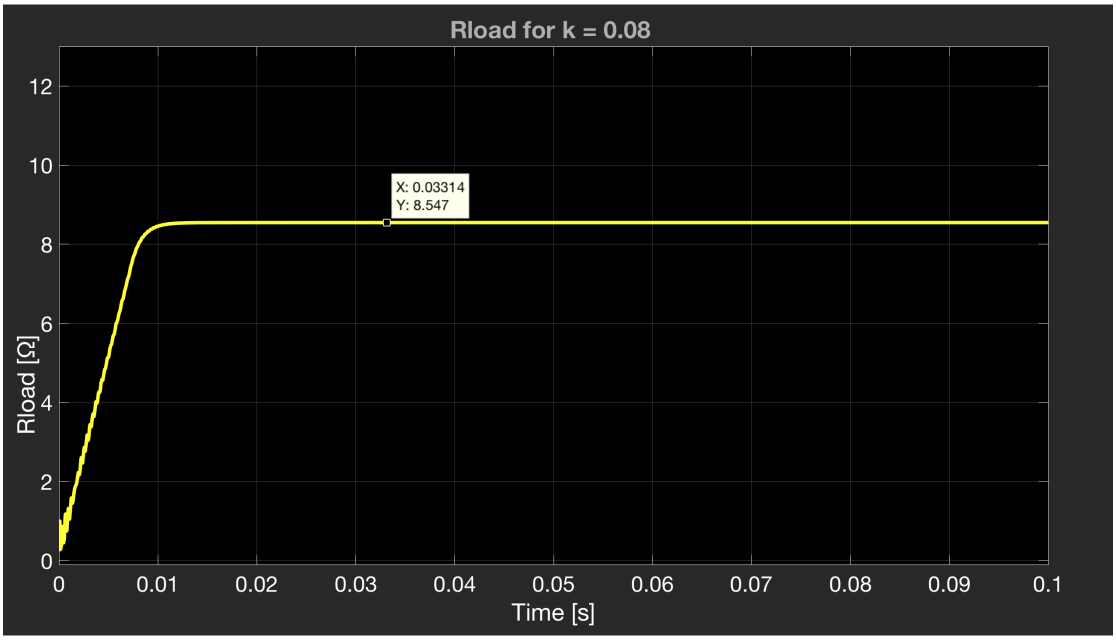


Figure 3.13: R_{load} for k = 0.8

3.3 Prototype

Given the time in which the design had to be finished, no prototype could have been built. However, all the design specifications are finished and verified. The components that are needed for the DC-DC converter can be ordered. Within the upcoming week there might be time to build a prototype before the final symposium. Primarily, this must be discussed with the supervisors.

3.4 Assessments

Looking at the overall results, the DC-DC converter does its job by fulfilling all the requirements. However, the DC-DC converter works manually, which means that one needs to tune the duty cycle and reach ωM himself. This system only is not sufficient to fully operate autonomously. An additional control system is required to make the DC-DC converter work for all the permissible misalignments.

Furthermore, the capacitor C_{in} between the rectifier and the buck converter as shown in figure 2.21, can be charged to a certain voltage level that might exceed the maximum operating voltage of the capacitor. This can happen when the duty cycle is close to the value of 0 resulting in an always open switch. Eventually, this can cause the capacitor to blow up. An additional safety system might be needed to avoid this situation.

3.5 Next Steps

The first thing that needs to be done is building the prototype, integrating this with the system and testing the overall performance of the IPT system. Furthermore, a control system is needed as mentioned in the previous section.

Since the control of DC-DC converter needs to have some input parameters to control accordingly, an additional measurement system needs to be built that can perfectly measure the misalignment and calculate the necessary input parameters for the control system. Currently, these input parameters need to be tuned manually, which can be prevented by adding this measurement system.

Also, the car will not be able to charge properly if the coupling coefficient is not between $0.08 \leq k \leq 0.2$. This measurement system can also create an alert that reminds the driver to adjust the position of the car until reaching a coupling coefficient value within the given range. An additional system can be designed for this purpose as well.

Furthermore, the IPT system technology can be used for charging the car battery while driving. The primary coil must be implemented in the road, which enables the driver to constantly charge the battery and at the same time consume power. As a result, the car will have a longer distance range [20] [21].

A Matlab Code simulations

A.1 Simulation 1 : Maximum efficiency at ωM

```
clear all;

%Set some constants
f=85000;
w=f*2*pi;
Ltransformer=200e-6;
Ctransformer=1/(w^2*Ltransformer);

%Create the sweeping variables
resistance=[0:0.5:1000];
k_values=[0.11:0.02:0.19]
results=zeros(length(resistance),length(k_values))
h = waitbar(0/length(resistance),'Simulating results')

%Sweep over numerous resistances for different values of k
 for j=1:length(k_values)
     k=k_values(j);
 for n=1:length(resistance)
    waitbar(n / length(resistance),h,strcat('Number of k:', '[',num2str(j),
    '/',num2str(length(k_values)),']'));
    R= resistance(n);
    disp(R);
    sim('effienciency');
    results(n,j)=efficiency_out.Data(2);

 end

```

```
 end

%Plot the results
for n=1:length(k_values)
plot(resistance,results(:,n),'DisplayName',strcat(
                        'k=',num2str(k_values(n))));
hold on;
end
hold off
title('Resistance vs Efficiency')
xlabel('Resistance')
ylabel('Efficiency')
legend('show')
```

A.2 Simulation 2 : DC-DC converter with DC current input

```
clear all;

%%%%% Before the buck
f=85000;
k=0.2;
w=2*pi*f;
Ltransformer=200e-6;
Ctransformer=1/(w^2*Ltransformer);

%%%%%% Inverter %%%%%%
f_sw_inv=f;

%%%% BUCK CONSTANTS
V_in_max= 2200;
V_out=200;
f_sw=500e3;
LIR=0.3;
P_out= 8000;
V_ripple=10e-3;

%The calculation for the ripple current/Inductor value
I_out = P_out/V_out;
I_ripple = LIR*I_out;
L= ((V_in_max-V_out)*V_out)/(V_in_max*f_sw*I_ripple);
I_max = I_out+(I_ripple/2);
I_min= I_out-(I_ripple/2);
```

```

%Calculation for the Capacitor value due to the ripple voltage
%integrating the inductor current will give the charge
%i.e. calculate the surface Area
Q_delta = ((1/2)^3)*(I_ripple/f_sw);
C_out= Q_delta/V_ripple;
V_ripple_percentage= V_ripple/V_out;


%The LC filter cut off frequency
w_cut_off = 1/(sqrt(L*C_out));

%Boundary current
D= (V_out/V_in_max);
I_b= V_in_max*(D-D^2)/(2*L*f_sw);
R_load= V_out/I_b;

%determine the input capacitance
C_in = D*(1-D)*I_out/(V_ripple*f_sw);

%paper design Note Buck converter
%Conclusion the same value as the Power electronics book
C_out_paper= (1-D)/(V_ripple_percentage*8*L*(f_sw^2));

%Create the sweeping variables
dutycycle=[0:0.01:1];
results=zeros(length(dutycycle),1)

%Sweep over numerous resistances for different values of k
 for n=1:length(dutycycle)

     D= dutycycle(n);
     disp(D);
     sim('buckconverter');
     results(1,n)=Vin.Data(2);

 end
%Plot the results
plot(dutycycle,results)
title('Dutycycle vs Vin')
xlabel('Dutycycle')
ylabel('Vin')
```

A.3 Simulation 3 : DC-DC converter and IPT system integration

```
clear all;

%%%%% Before the buck
f=85000;
k=0.2;
w=2*pi*f;
Ltransformer=200e-6;
Ctransformer=1/(w^2*Ltransformer);

%%%%%% Inverter %%%%%%
f_sw_inv=f;

%%%% BUCK CONSTANTS
V_in_max= 2200;
V_out=200;
f_sw=500e3;
LIR=0.3;
P_out= 8000;
V_ripple=10e-3;

%The calculation for the ripple current/Inductor value
I_out = P_out/V_out;
I_ripple = LIR*I_out;
L= ((V_in_max-V_out)*V_out)/(V_in_max*f_sw*I_ripple);
I_max = I_out+(I_ripple/2);
I_min= I_out-(I_ripple/2);

%Calculation for the Capacitor value due to the ripple voltage
%integrating the inductor current will give the charge
%i.e. calculate the surface Area
Q_delta = ((1/2)^3)*(I_ripple/f_sw);
C_out= Q_delta/V_ripple;
V_ripple_percentage= V_ripple/V_out;


%The LC filter cut off frequency
w_cut_off = 1/(sqrt(L*C_out));

%Boundary current
D= (V_out/V_in_max);
```

```
I_b= V_in_max*(D-D^2)/(2*L*f_sw);
R_load= V_out/I_b;

%determine the input capacitance
C_in = D*(1-D)*I_out/(V_ripple*f_sw);

%paper design Note Buck converter
%Conclusion the same value as the Power electronics book
C_out_paper= (1-D)/(V_ripple_percentage*8*L*(f_sw^2));
```

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